Encoding and Modulating

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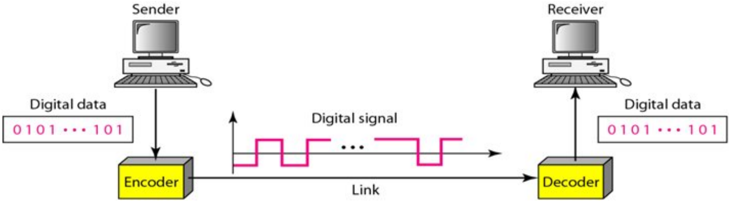
Digital to Digital Conversion

- The technique that we will see for digital to digital conversion is called Line coding.
- Converting a string of 1's and 0's (digital data) into a sequence of signals that denote the 1's and 0's.
- For example a high voltage level (+V) could represent a "1" and a low voltage level (0 or -V) could represent a "0".



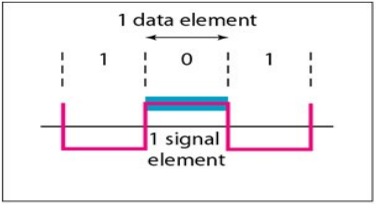
Mapping Data symbols onto Signal levels

- A data symbol (or element) can consist of a number of data bits:
  - 1, 0 or
  - 11, 10, 01, ...
- A data symbol can be coded into a single signal element or multiple signal elements:
  - $1 \rightarrow +V$, $0 \rightarrow -V$
  - $1 \rightarrow +V$ and $-V$, $0 \rightarrow -V$ and $+V$
- The ratio 'r' is the number of data elements carried by a signal element.

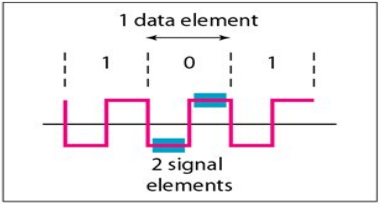
Data Rate and Signal Rate

- The data rate defines the number of bits sent per sec (bps). It is often referred to the bit rate.
- The signal rate is the number of signal elements sent in a second and is measured in bauds. It is also referred to as the modulation rate.
- Goal is to increase the data rate whilst reducing the baud rate.
  - ✓ Increasing data rate increases rate of transmission
  - ✓ Decreasing baud rate decrease the bandwidth requirement

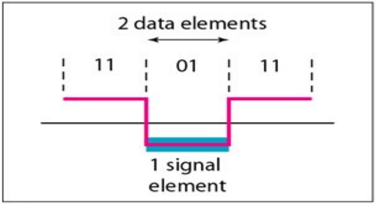
Data Rate and Signal Rate



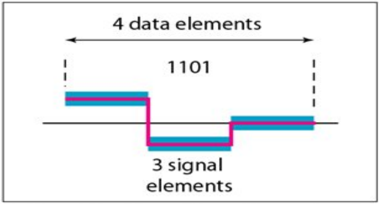
a. One data element per one signal element ($r = 1$)



b. One data element per two signal elements $\left(r = \frac{1}{2}\right)$



c. Two data elements per one signal element ($r = 2$)



d. Four data elements per three signal elements $\left(r = \frac{4}{3}\right)$

Baseline Wandering

- Baseline wandering: A receiver will evaluate the average power of the received signal (called the baseline) and use that to determine the value of the incoming data elements.
- If the incoming signal does not vary over a long period of time, the baseline will drift and thus cause errors in detection of incoming data elements.
- A good line encoding scheme will prevent long runs of fixed amplitude.

DC Components

- DC Components: When the voltage level remains constant for long periods of time, the spectrum creates very low frequencies. These frequencies around 0 is called DC component.
- Many channels may not support the low frequencies.
- E.g. telephone line cannot pass frequencies below 200 Hz.
- This will require the removal of the DC component of a transmitted signal.

Self Synchronization

- Self Synchronization: The clocks at the sender and the receiver must have the same bit interval.
- If the receiver clock is faster or slower it will misinterpret the incoming bit stream.

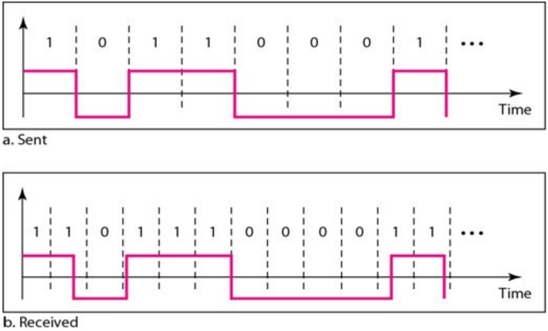


Figure: Effect of lack of synchronization

Self Synchronization

- **Problem:** In a digital transmission, the receiver clock is 0.1 percent faster than the sender clock. How many extra bits per second does the receiver receive if the data rate is 1 kbps? How many if the data rate is 1 Mbps?
- **Solution:** At 1 kbps, the receiver receives 1001 bps instead of 1000 bps.

1000 bits sent	1001 bits received	1 extra bit

- At 1 Mbps, the receiver receives 1,001,000 bps instead of 1,000,000 bps.

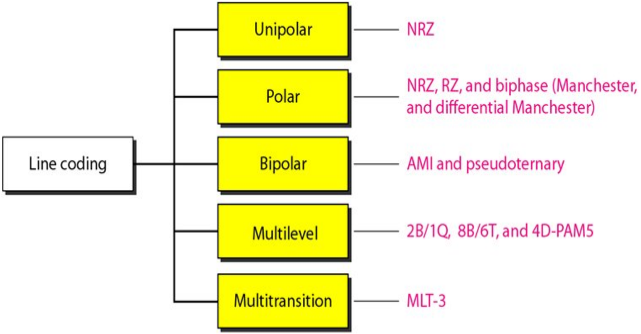
1,000,000 bits sent	1,001,000 bits received	1000 extra bits

Other Line Encoding Requirements

- Error detection: Errors occur during transmission due to line impairments.
- Noise and interference: There are line encoding techniques that make the transmitted signal "immune" to noise and interference.
- Complexity: The more robust and resilient the code, the more complex it is to implement and the price is often paid in baud rate or required bandwidth.

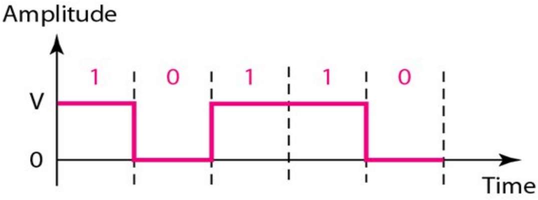
Line Coding Schemes

- Line coding schemes can be roughly divided into 5 broad categories



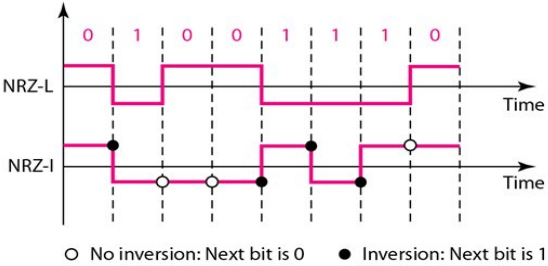
Unipolar - NRZ

- All signal levels are on one side of the time axis: either above or below
- NRZ: Non Return to Zero scheme is an example of this code. The signal level does not return to zero during a symbol transmission.
- Scheme is prone to baseline wandering and DC components. It has no synchronization or any error detection.
- It is simple.



Polar - NRZ

- The voltages are on both sides of the time axis.
- Polar NRZ scheme can be implemented with two voltages. E.g. +V for 1 and -V for 0.
- There are two versions:
  - ✓ NRZ - Level (NRZ-L) positive voltage for one symbol and negative for the other
  - ✓ NRZ - Inversion (NRZ-I): the change or lack of change in polarity determines the value of a symbol. E.g. a "1" symbol inverts the polarity a "0" does not.

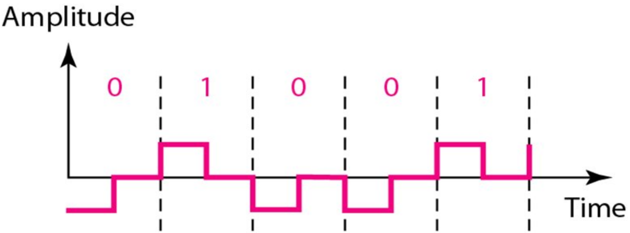


Polar - NRZ-L & NRZ-I

- In NRZ-L the level of the voltage determines the value of the bit.
- In NRZ-I the inversion or the lack of inversion determines the value of the bit.
- NRZ-L and NRZ-I both have a DC component problem and baseline wandering, it is worse for NRZ-L. Both have no self synchronization & no error detection. Both are relatively simple to implement.

Polar RZ

- The Return to Zero (RZ) scheme uses three voltage values. $+$, 0, $-$.
- Each symbol has a transition in the middle. Either from high to zero or from low to zero.



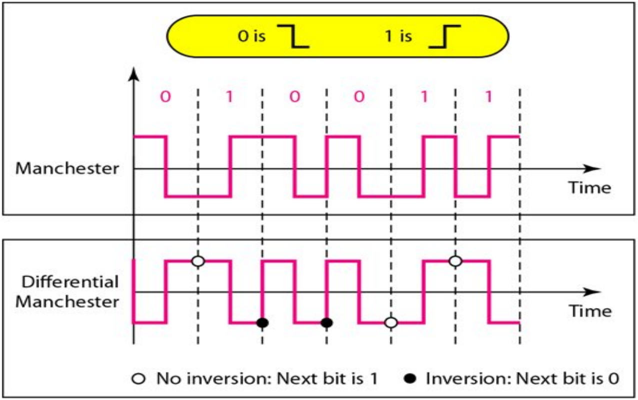
Polar RZ

- This scheme has more signal transitions (two per symbol) and therefore requires a wider bandwidth.
- No DC components or baseline wandering.
- Self synchronization - transition indicates symbol value.
- More complex as it uses three voltage level.
- It has no error detection capability.

Polar - Biphase: Manchester and Differential Manchester

- Manchester coding consists of combining the NRZ-L and RZ schemes.
  - Every symbol has a level transition in the middle: from high to low or low to high. Uses only two voltage levels.
- Differential Manchester coding consists of combining the NRZ-I and RZ schemes.
  - Every symbol has a level transition in the middle. But the level at the beginning of the symbol is determined by the symbol value. One symbol causes a level change the other does not.

Manchester and Differential Manchester



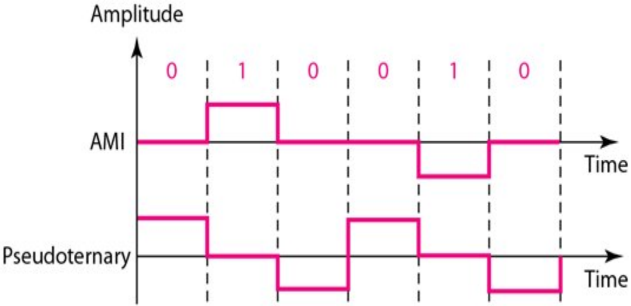
Manchester and Differential Manchester

- In Manchester and differential Manchester encoding, the transition at the middle of the bit is used for synchronization.
- The minimum bandwidth of Manchester and differential Manchester is 2 times that of NRZ.
- No DC component and no baseline wandering.
- None of these codes has error detection.

Bipolar - AMI and Pseudoternary

- Code uses 3 voltage levels: $+$, 0, $-$, to represent the symbols (note not transitions to zero as in RZ).
- Voltage level for one symbol is at "0" and the other alternates between $+$ & $-$.
- Bipolar Alternate Mark Inversion (AMI): the "0" symbol is represented by zero voltage and the "1" symbol alternates between $+V$ and $-V$.
- Pseudoternary is the reverse of AMI.

Bipolar - AMI and Pseudoternary

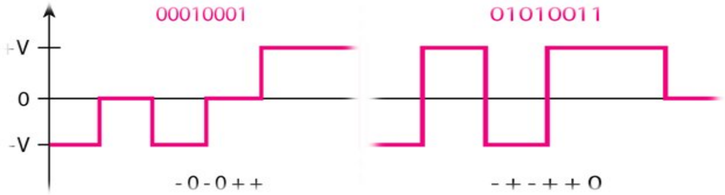


Bipolar Characteristics

- It is a better alternative to NRZ.
- Has no DC component.
  - Long sequence of 1's: the voltage alternates between +ve and -ve.
  - Long sequence of 0's: the voltage remains constant, but its amplitude is zero, which is same as no DC component.
- Has no self synchronization because long runs of "0"s results in no signal transitions.
- No error detection.

Multilevel Schemes

- In these schemes we increase the number of data bits per symbol thereby increasing the bit rate.
- Since we are dealing with binary data we only have 2 types of data element 1 or 0. We can combine the 2 data elements into a pattern of "m" elements to create 2^m symbols.
  - ✓ Example: Total number of 8 bit patterns using 0 and 1 are $2^8 = 256$
- If we've L signal levels, we can use "n" signal elements to create L^n signal elements.
  - ✓ Example: If we have 3 signal levels $(+, 0, -)$ and 6 signal elements... we can create $3^6 = 478$ signal elements.



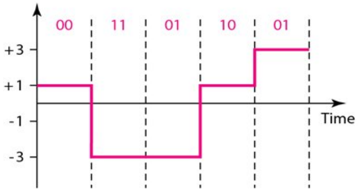
Multilevel Schemes Characteristics

- Now we have 2^m symbols and L^n signals.
- If $2^m > L^n$ then we can not represent all data elements, we don't have enough signals.
- If $2^m = L^n$ then we have an exact mapping of one symbol on one signal.
- If $2^m < L^n$ then we have more signals than symbols and we can choose the signals that are more distinct to represent the symbols and therefore have better noise immunity and error detection as some signals are not valid.

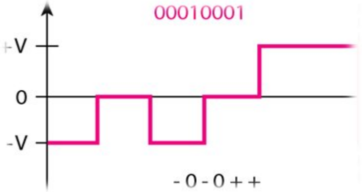
In *mBnL* schemes, a pattern of *m* data elements is encoded as a pattern of *n* signal elements in which $2^m \leq L^n$.

Representing Multilevel Codes

- The notation *mBnL*, where
  - m is the length of the binary pattern,
  - B represents binary data,
  - n represents the length of the signal pattern and
  - L the number of levels.
- L = B binary, L = T for 3 ternary, L = Q for 4 quaternary.



m = 2, n = 1, L = 4



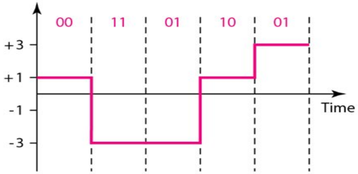
m = 8, n = 6, L = 3

Multilevel 2B1Q Scheme

- 2B1Q scheme: m = 2, n = 1 and L = 4 (quaternary)
- No redundancy as $2^2 = 4^1$.
- Sends data twice faster than NRZ-L.
- But receiver has to discern four different threshold.
- Used in DSL (Digital Subscriber Line) technology to provide high speed connection to the internet.

	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

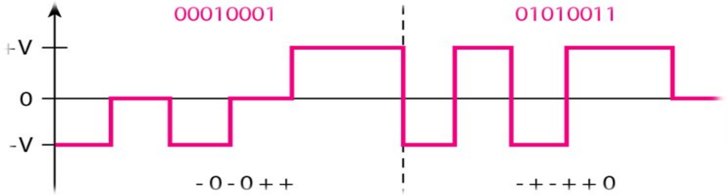


Assuming positive original level

Multilevel 8B6T Scheme

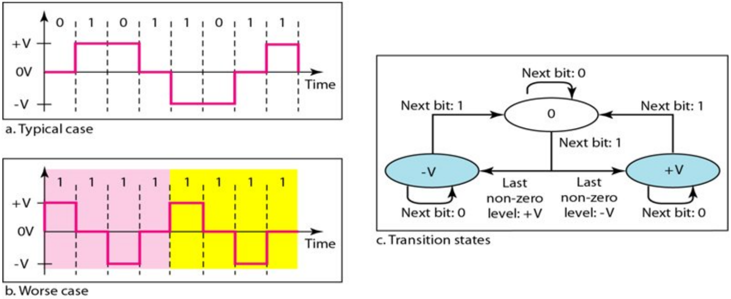
- Used in 100Base-4T cable.
- Encode 8 bits as a pattern of 6 signals, where the signal has three levels (ternary).
- $2^8 = 256$ different data pattern.
- $3^6 = 478$ different signal pattern.
- $478 - 256 = 222$ redundant signal elements to provide:
  - ✓ Synchronization.
  - ✓ Error Detection.
  - ✓ DC Balance.

Multilevel 8B6T Scheme



Multiline Transmission: MLT-3

- If the next bit is 0, there is no transition
- If the next bit is 1 and the current level is not 0 $\longrightarrow$ the next level is 0
- If the next bit is 1 and the current level is 0 $\longrightarrow$ the next level is the opposite of he last nonzero level.



a. Typical case
b. Worse case
c. Transition states

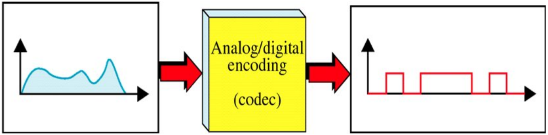
- No self-synchronization for long 0's.

Summary of line coding schemes

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

Analog to Digital Conversion

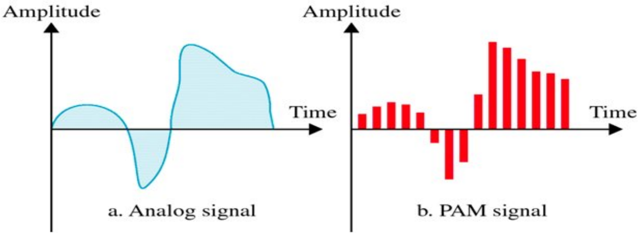
- To send human voice... we need to digitize it.
- This requires a reduction of potentially infinite number of values of an analog message so that it can be represented as a digital stream with a minimum loss of information
- We need an analog-to-digital converter called codec (coder-decoder)



Pulse Amplitude Modulation (PAM)

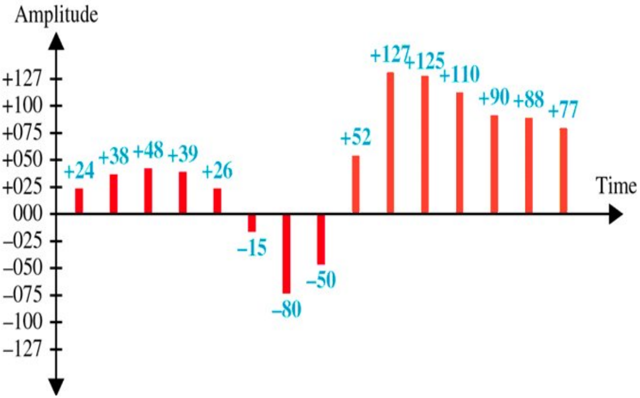
- The first step of analog-to-digital conversion is called Pulse Amplitude Modulation (PAM).
- It takes an analog signal, samples it, and generates a series of pulses.
- Sampling means measuring the amplitude of the signal at equal intervals.
- PAM uses a technique called sample and hold. That is, at a given moment, the signal level is read, then held briefly.

Pulse Amplitude Modulation (PAM)



Pulse Code Modulation (PCM)

- PCM modifies the pulses created by PAM to create digital signal.
- PCM first quantizes the PAM pulses. That is, it assigns integral values in a specific range to sampled instance.



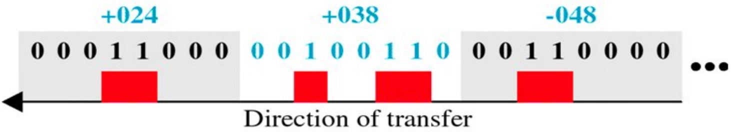
Quantizing Using Sign and Magnitude

+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

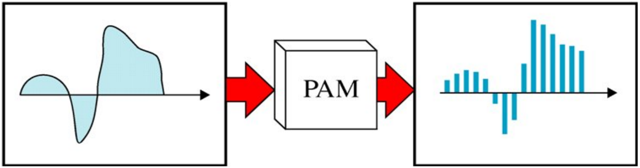
Sign bit
+ is 0 − is 1

Pulse Code Modulation PCM

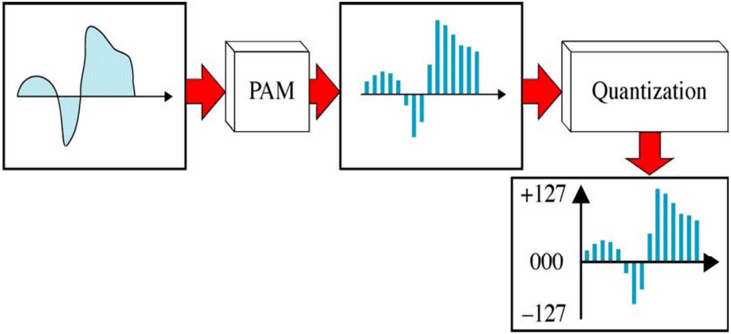
- The binary digits are then transformed into digital signals using one of the digital-to-digital encoding techniques.
- PCM is actually has four separate processes:
  - ✓ PAM
  - ✓ Quantization
  - ✓ Binary encoding
  - ✓ Digital to digital encoding



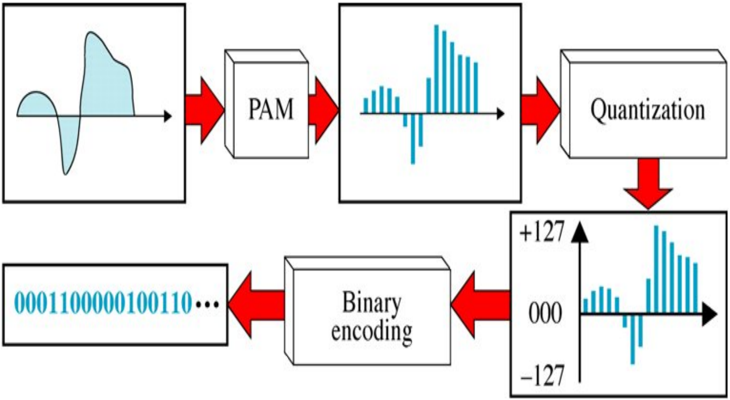
From Analog to PCM



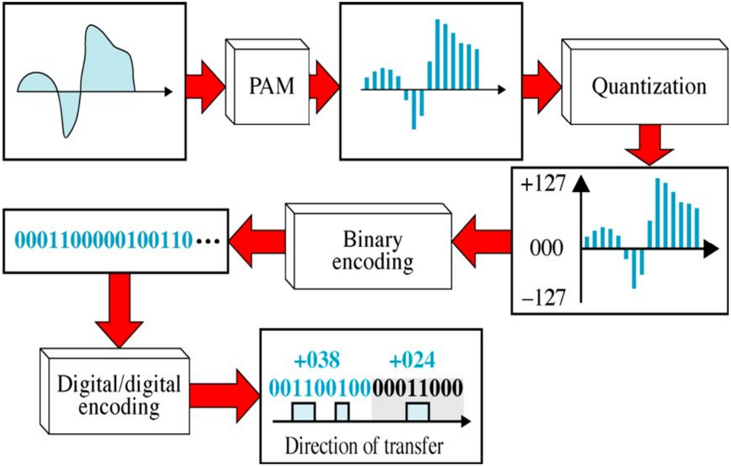
From Analog to PCM



From Analog to PCM



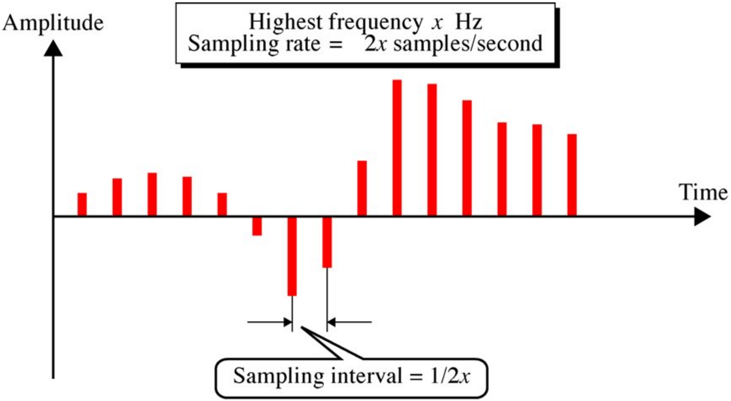
From Analog to PCM



Nyquist Theorem

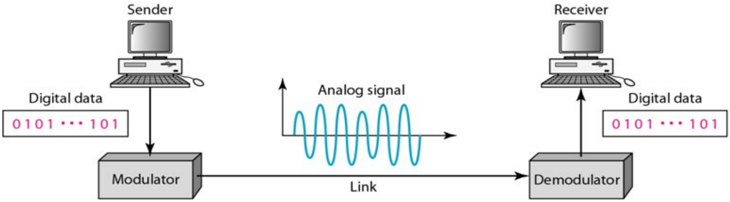
- The accuracy of analog-to-digital conversion depends on number of samples taken.
- So, how many samples are sufficient?
- According to Nyquist theorem, to ensure the accurate reproduction of an original analog signal using PAM, the sampling rate must be at least twice the highest frequency of the original signal.
- E.g. if we want to sample telephone voice with maximum frequency 4000 Hz, we need a sampling rate of 8000 samples per second.

Nyquist Theorem

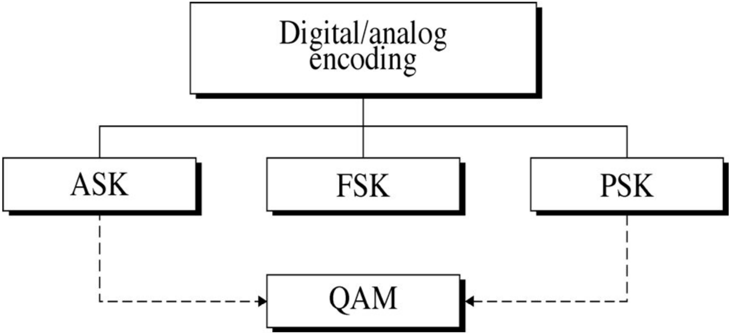


Digital to Analog Conversion

- For carrying digital data over analog line we need modem - modulation demodulation
- Used to connect a digital computer to an analog phone system

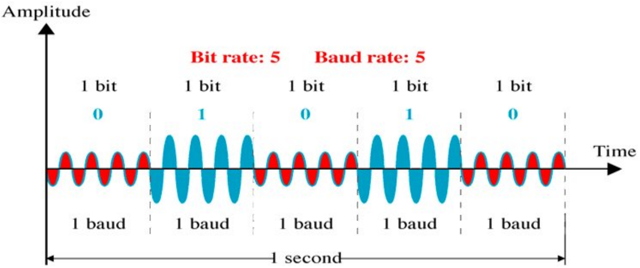


Digital to Analog Conversion



Amplitude Shift Keying (ASK)

- ASK: Two binary numbers (0, 1) represented by two different amplitudes of the carrier wave.
  - ✓ Strength of carrier signal is varied to represent binary 1 or 0
  - ✓ Both frequency & phase remain constant while amplitude changes

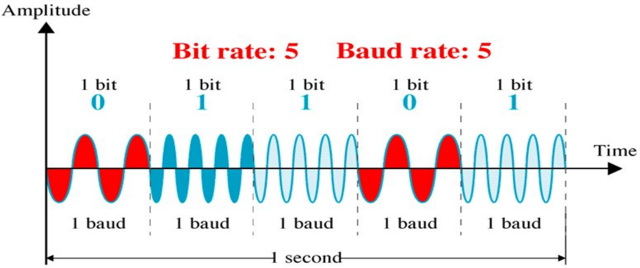


Amplitude Shift Keying (ASK)

- Multilevel ASK
  - There are more than two levels.
  - We can use 4, 8, 16 or more amplitudes for the signals and modulate the data using 2, 3, 4 or more bits at a time.
- Advantage: simplicity
- Disadvantage: Susceptible to noise. Noise usually (only) affects the amplitude, therefore ASK is the modulation technique most affected by noise
- Used to transmit digital data over optical fiber.

Frequency Shift Keying (FSK)

- ∝ The frequency of the carrier signal is varied to represent data.
- ∝ Both peak amplitude and phase remains constant.

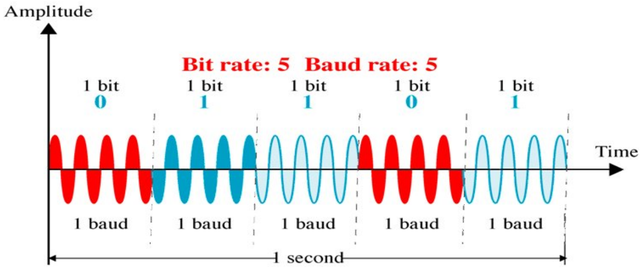


Frequency Shift Keying (FSK)

- Multilevel FSK
  - We can use four different frequencies to send 2 bits at a time.
- Less susceptible to error than ASK - receiver looks for specific frequency changes over a number of intervals, so voltage (noise) spikes can be ignored
- Requires more bandwidth
  - FSK spectrum is 2 times that of ASK spectrum

Phase Shift Keying (PSK)

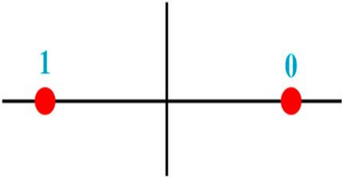
- The phase of the carrier is varied to represent two or more different signal elements.
- Both amplitude and frequency remains constant.
- PSK is more common than ASK and FSK.



PSK Constellation

Bit	Phase
0	0
1	180

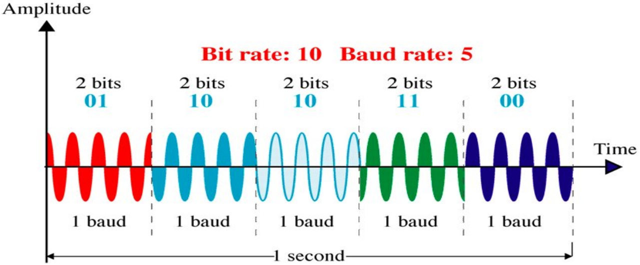
Bits



Constellation diagram

Phase Shift Keying (PSK)

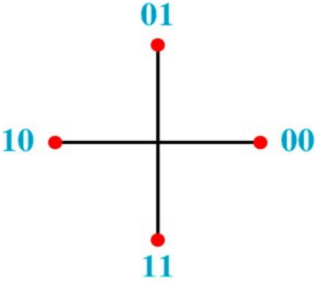
- PSK is not susceptible to noise degradation as affects ASK
- Nor has the bandwidth limitations of FSK. This means that the small variations in the signal can be detected reliably by the receiver.
- We can use 4 phase shifts to represent two bits.



4-PSK Constellation

Dibit	Phase
00	0
01	90
10	180
11	270

Dibit
(2 bits)

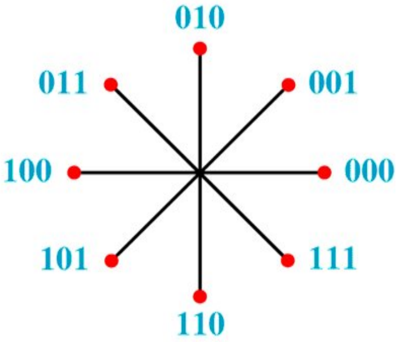


Constellation diagram

8-PSK Constellation

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

Tribits
(3 bits)

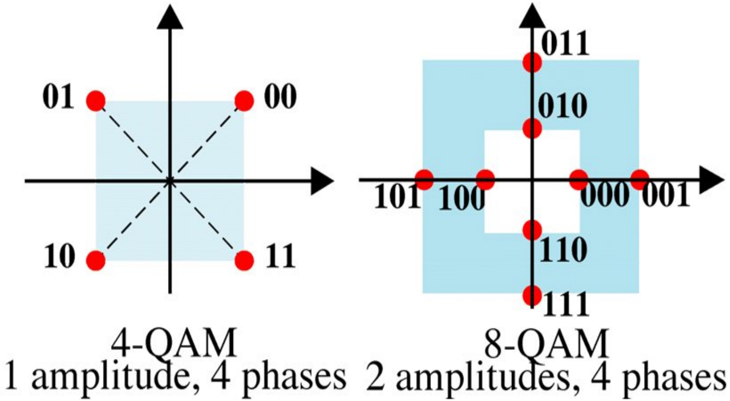


Constellation diagram

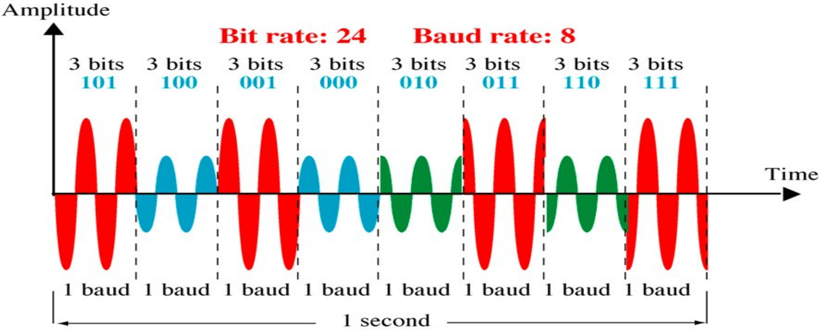
Quadrature Amplitude Modulation (QAM)

- PSK is limited by the ability of the equipment to distinguish small differences in phase. This limits potential bit rate.
- QAM combines ASK and PSK.
- The minimum bandwidth requirement for QAM is same as that for ASK and PSK.

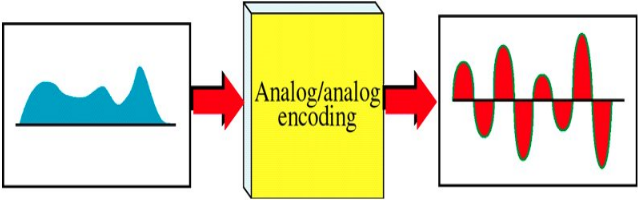
4-QAM and 8-QAM Constellation



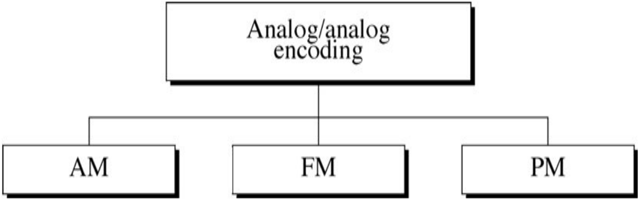
8-QAM Signal


Amplitude
Bit rate: 24
Baud rate: 8
3 bits
101
3 bits
100
3 bits
001
3 bits
000
3 bits
010
3 bits
011
3 bits
110
3 bits
111
Time
1 baud
1 baud
1 baud
1 baud
1 baud
1 baud
1 baud
1 baud
1 second

Analog to Digital Conversion

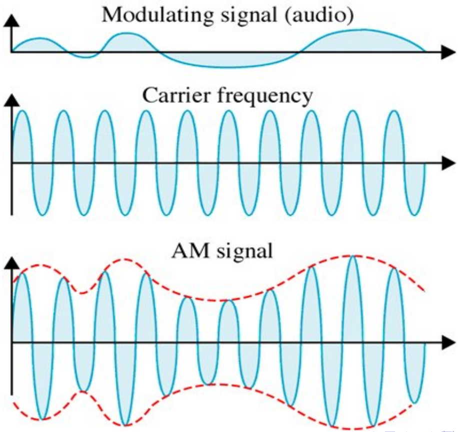


Analog to Digital Conversion



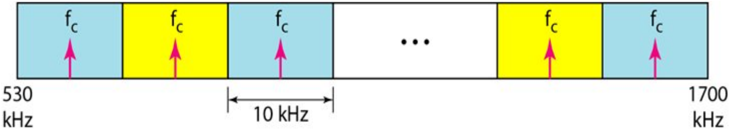
Amplitude Modulation

- In AM, the carrier signal is modulated so that its amplitude varies with the changing amplitude of the modulating signal.
- The phase and the frequency remains the same.



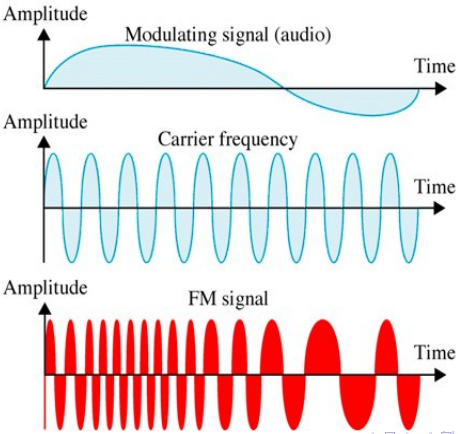
AM Bandwidth

- The bandwidth of an AM signal is twice the bandwidth of the modulating signal
- The bandwidth of an audio signal (speech & music) is usually 5kHz. Therefore an AM radio station needs a minimum bandwidth of 10kHz
- AM stations are allowed carrier frequencies anywhere between 530kHz and 1700kHz.
- Each station's carrier frequency must be separated by at least 10Hz to avoid interference.



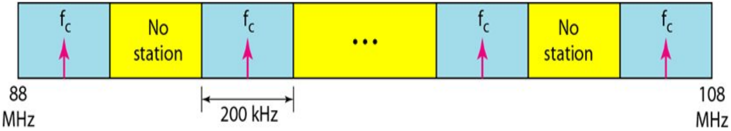
Frequency Modulation

- The frequency of the carrier signal is modulated to follow the changing voltage level (amplitude) of the modulating signal.
- The peak amplitude and the phase of the carrier signal remain constant.



FM Bandwidth

- The bandwidth of an FM signal is equal to 10 times the bandwidth of the modulating signal.
- The bandwidth of an audio signal broadcast (in stereo) is almost 15kHz. Thus, each FM radio station needs a minimum bandwidth of 150kHz.
- The Federal Communication Commission (FCC) allows 200KHz for each station to provide guard band.
- FM stations are allowed carrier frequencies anywhere between 88 and 108 MHz.



Phase Modulation

- The phase of the carrier signal is modulated to follow the changing voltage level (amplitude) of the modulating signal.
- The peak amplitude and frequency of the carrier signal remain constant.
- The bandwidth is higher than for AM.

Summary

- ∝ Digital-to-Digital Conversion :
  - ✓ NRZ, NRZ-L, NRZ-I, RZ, Manchester, Differential Manchester, AMI and Pseudoternary, 2B1Q, 8B1Q, MLT-3
- ∝ Digital-to-Analog Conversion :
  - ✓ PCM
- ∝ Analog-to-Digital Conversion :
  - ✓ ASK, FSK, PSK, QAM
- ∝ Analog-to-Analog Conversion :
  - ✓ AM, FM, PM