William Stallings
Data and Computer Communications

Chapter 5

Data Encoding

Encoding Techniques

- ⌘ **Analog data, analog signal**
- ⌘ **Digital data, digital signal**
- ⌘ **Analog data, digital signal**
- ⌘ **Digital data, analog signal**

Signal Encoding Techniques

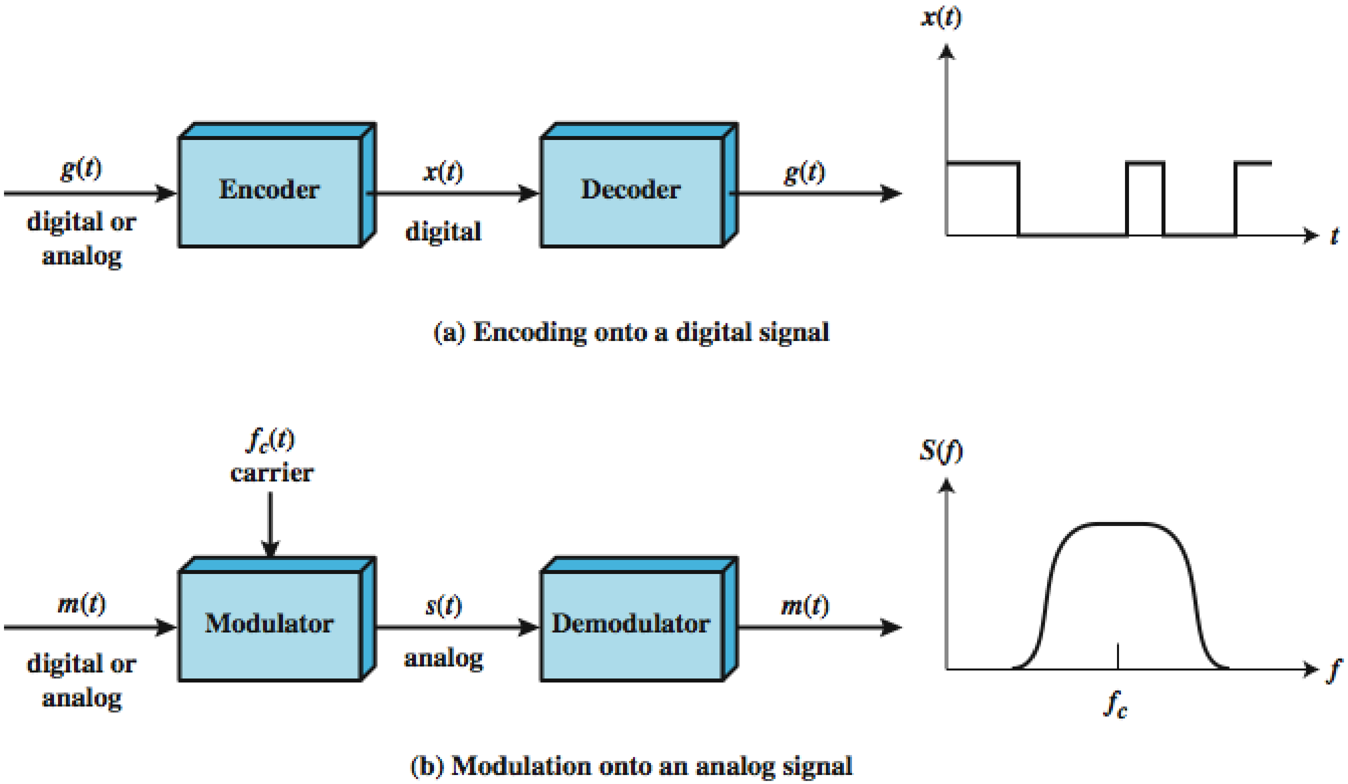
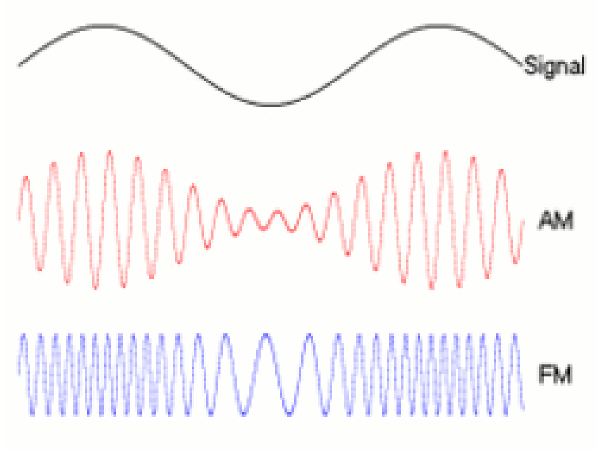


Figure 5.1 Encoding and Modulation Techniques

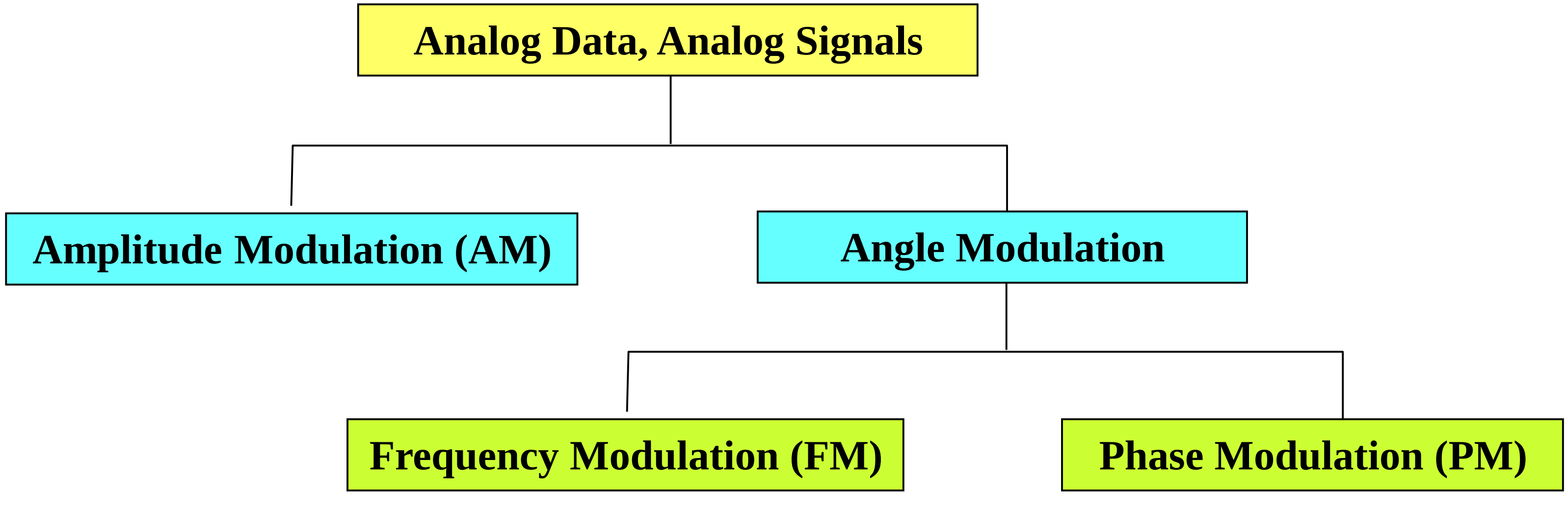
Encoding Techniques

Analog Data, Analog Signal



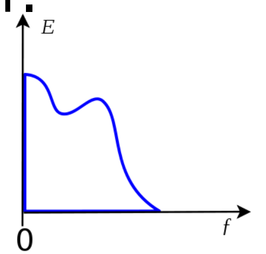
Analog Data, Analog Signals

- **Types of Modulation**
  - Amplitude
  - Frequency
  - Phase



Analog Data, Analog Signals

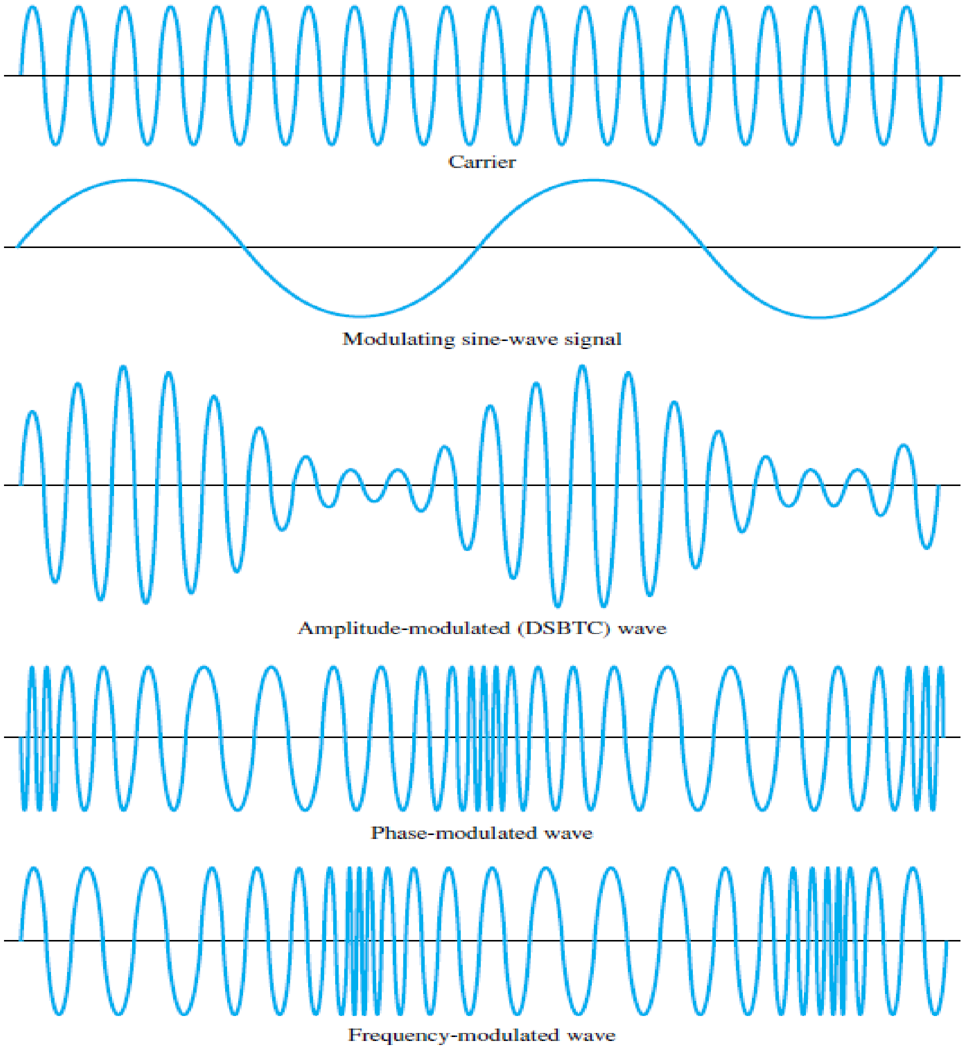
- **modulate carrier frequency f_c with input analog signal $m(t)$ to produce a signal $s(t)$ whose bandwidth is usually centered on f_c**
- why modulate analog signals?
  - **Higher frequency can give more efficient transmission**. For wireless transmission, it is impossible to transmit **baseband signals**; the transmitted antennas would be many kilometers in diameter.



Baseband Signal

  - Permits **frequency division multiplexing** (chapter 8)

Analog Modulation

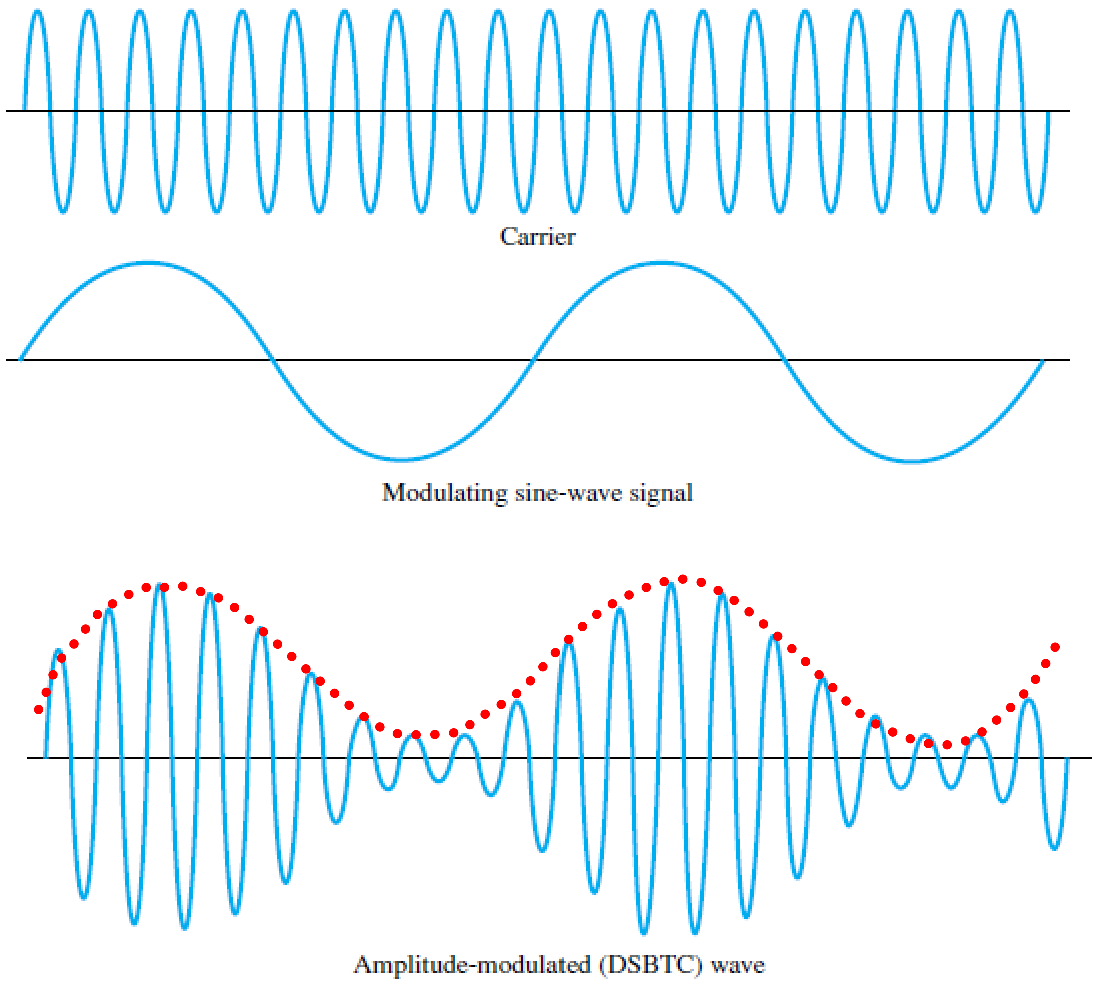


Amplitude Modulation

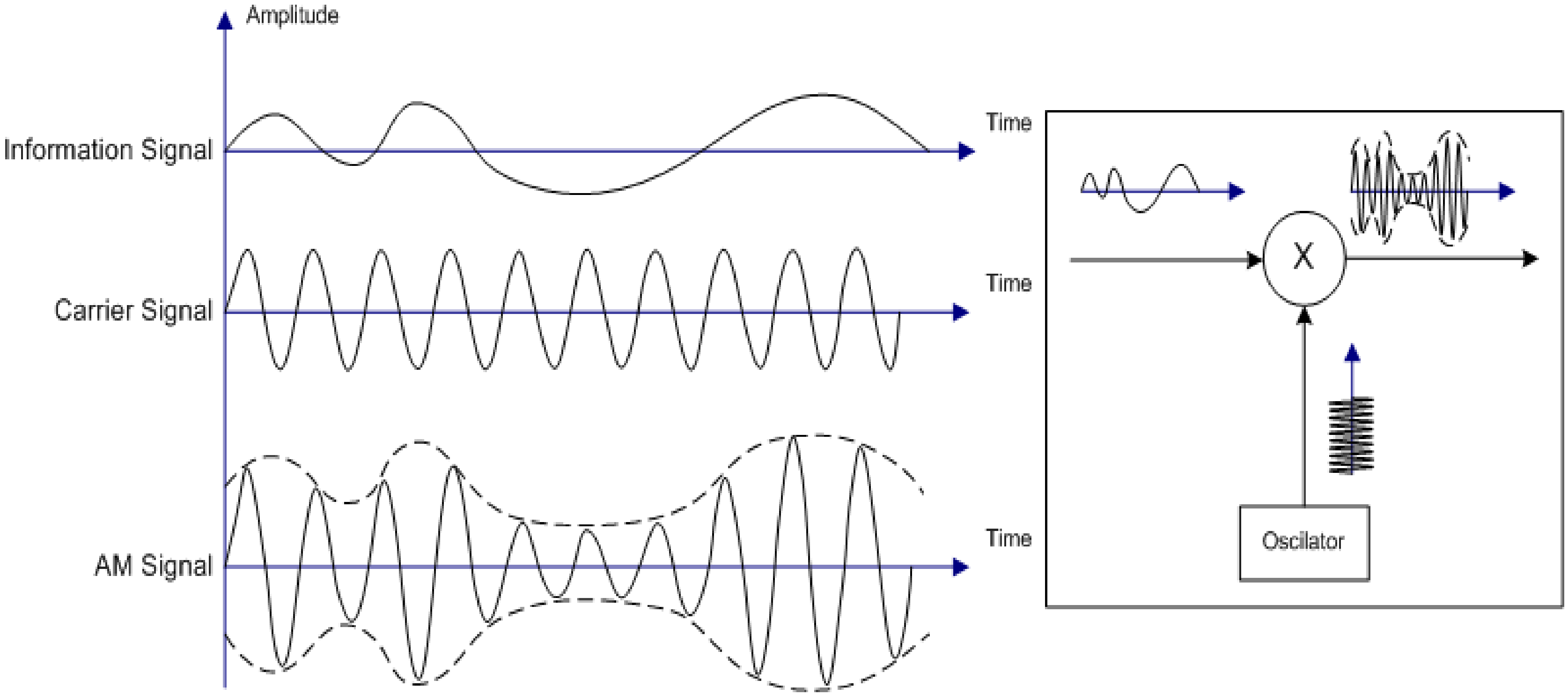
Phase Modulation

Frequency Modulation

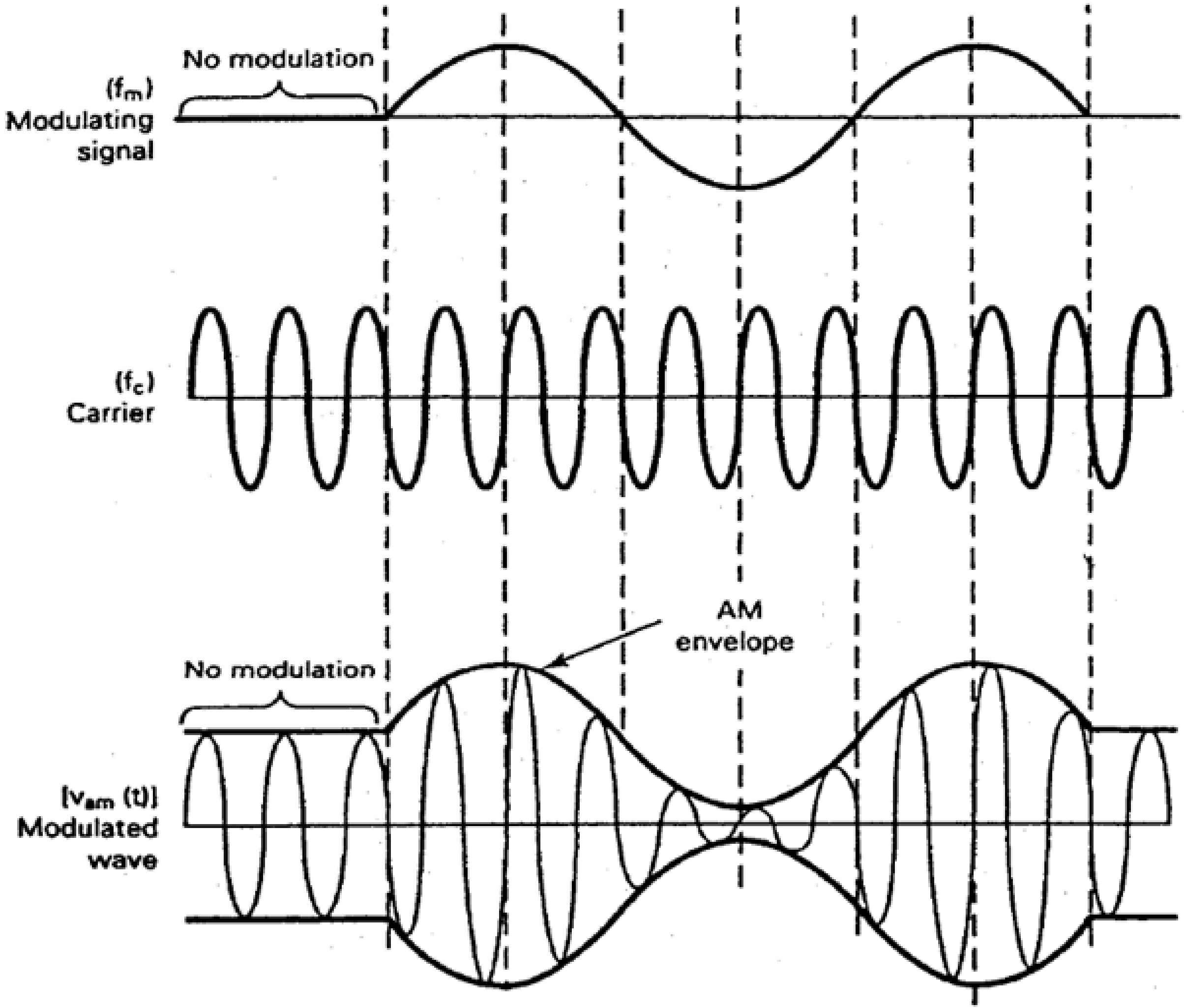
Amplitude Modulation (AM)



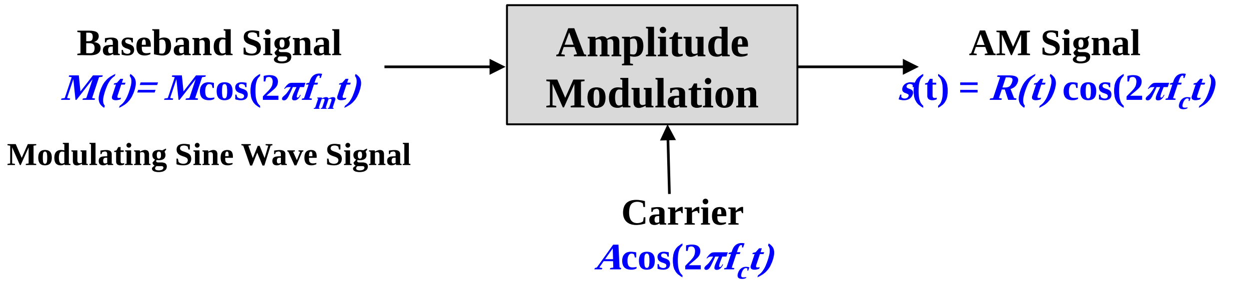
Amplitude Modulation (AM)

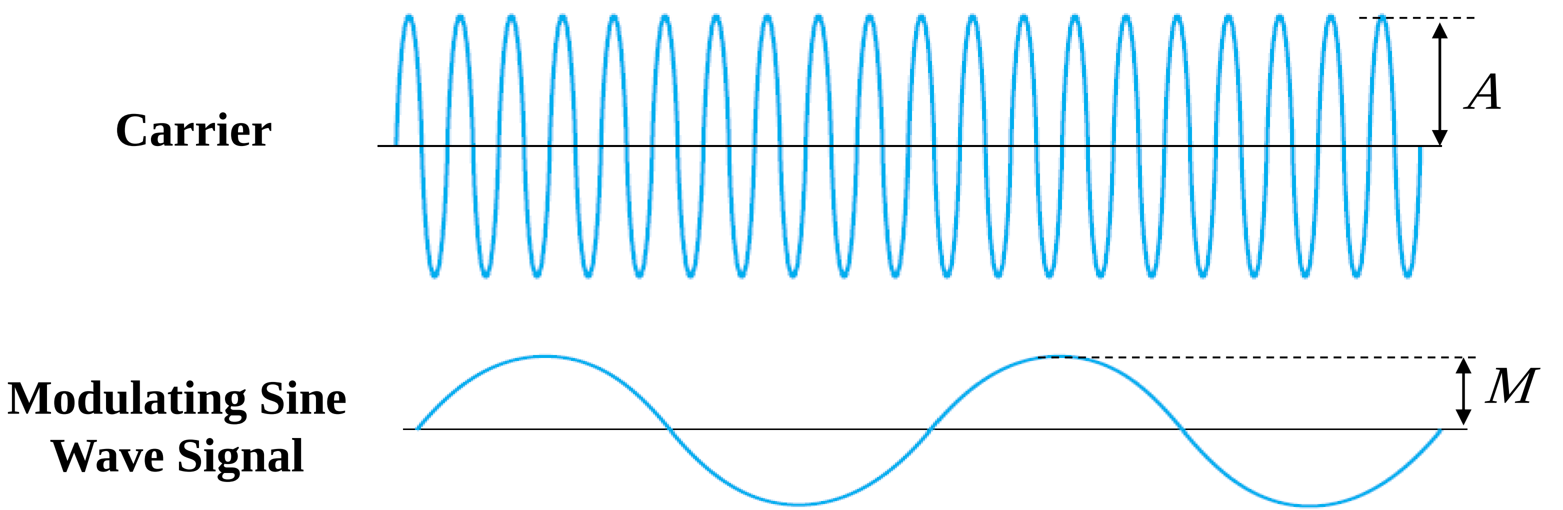


Amplitude Modulation (AM)



Amplitude Modulation (AM)





$M \leq A$

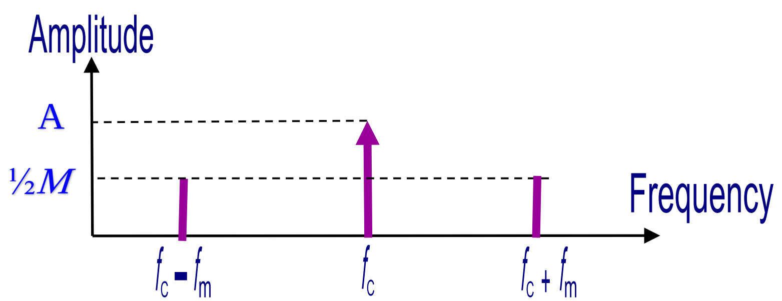
$f_m << f_c$

Modulation Index = n_a = M /A

Amplitude Modulation (AM)

- In AM, the **amplitude of the carrier is varied according to the baseband signal**.
- Amplitude of AM wave is $R(t) = A + M\cos(2\pi f_m t)$
- AM signal is $s(t) = R(t)\cos(2\pi f_c t) = (A+m(t))\cos(2\pi f_c t)$
- $s(t) = (A + M\cos(2\pi f_m t))\cos(2\pi f_c t)$
- $s(t) = A\cos(2\pi f_c t) + M\cos(2\pi f_m t)\cos(2\pi f_c t)$ $\quad \cos A.\cos B = \frac{1}{2}\cos(A-B) + \frac{1}{2}\cos(A+B)$
- $s(t) = A\cos(2\pi f_c t) + ½\, M\cos(2\pi(f_c + f_m)t) + ½\, M\cos(2\pi(f_c - f_m)t)$
- AM signal consists of 3 frequencies:

  Carrier: f_c, **Upper Sideband:** $f_c + f_m$, **Lower Sideband:** $f_c - f_m$



Amplitude Modulation (AM)

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- Amplitude of AM wave is $R(t) = A + M\cos(2\pi f_m t)$
- AM signal is $s(t) = R(t)\cos(2\pi f_c t) = (A + M\cos(2\pi f_m t))\cos(2\pi f_c t)$
- $s(t) = A(1 + M/A\cos(2\pi f_m t))\cos(2\pi f_c t)$
- $s(t) = A(1 + n_a\cos(2\pi f_m t))\cos(2\pi f_c t)$ $\rightarrow \cos A.\cos B = \frac{1}{2}\cos(A-B) + \frac{1}{2}\cos(A+B)$
- $s(t) = A\cos(2\pi f_c t) + ½\, A\, n_a\cos(2\pi(f_c + f_m)t) + ½\, A\, n_a\cos(2\pi(f_c - f_m)t)$
- AM signal consists of 3 frequencies:

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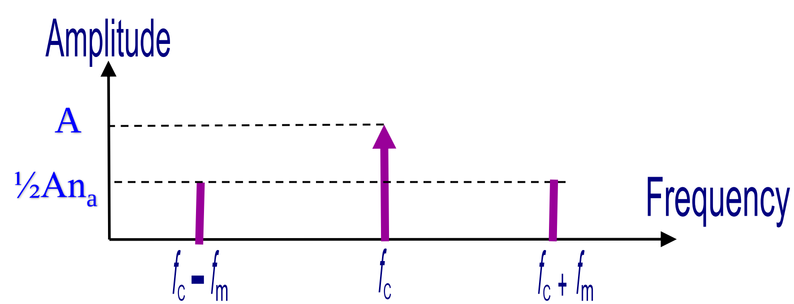
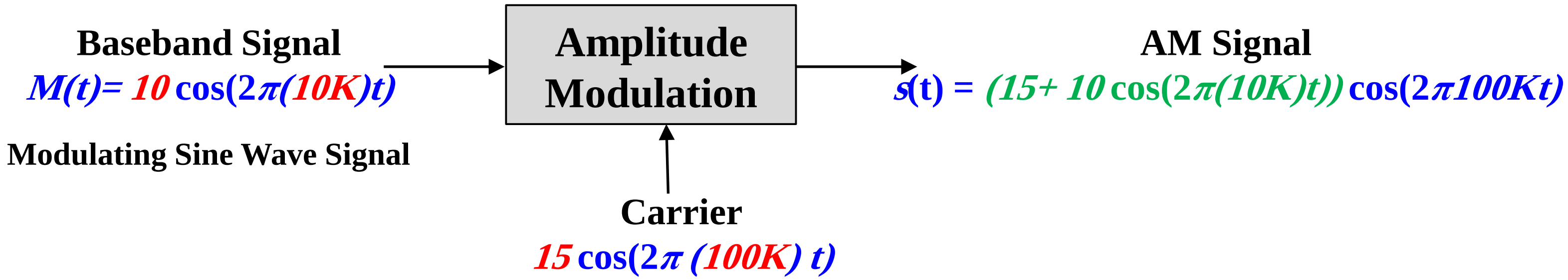
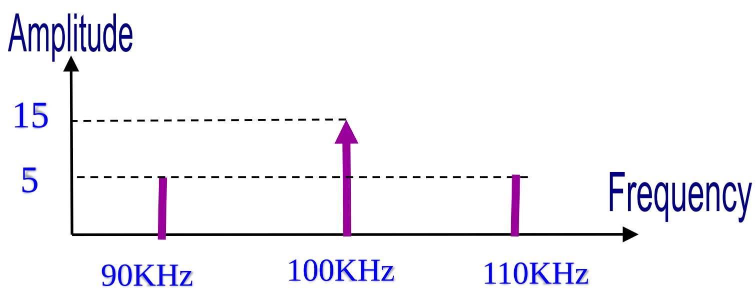


Amplitude Modulation (AM) Example 1





$$S(t) = 15\cos(2\pi\ 100K\ t) + 5\cos(2\pi\ 90K\ t) + 5\cos(2\pi\ 110K\ t)$$

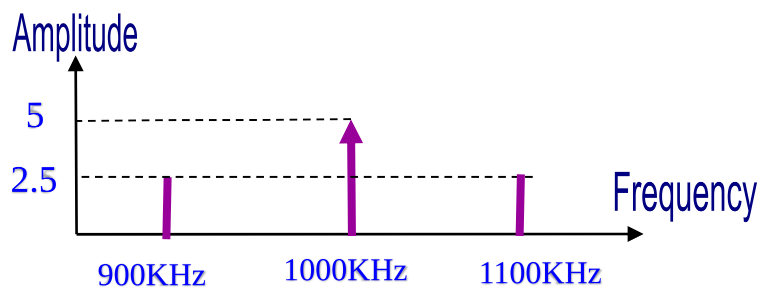
Amplitude Modulation (AM) Example 2

Baseband Signal
$M(t) = 5\cos(2\pi(100K)t)$
Modulating Sine Wave Signal

Amplitude Modulation

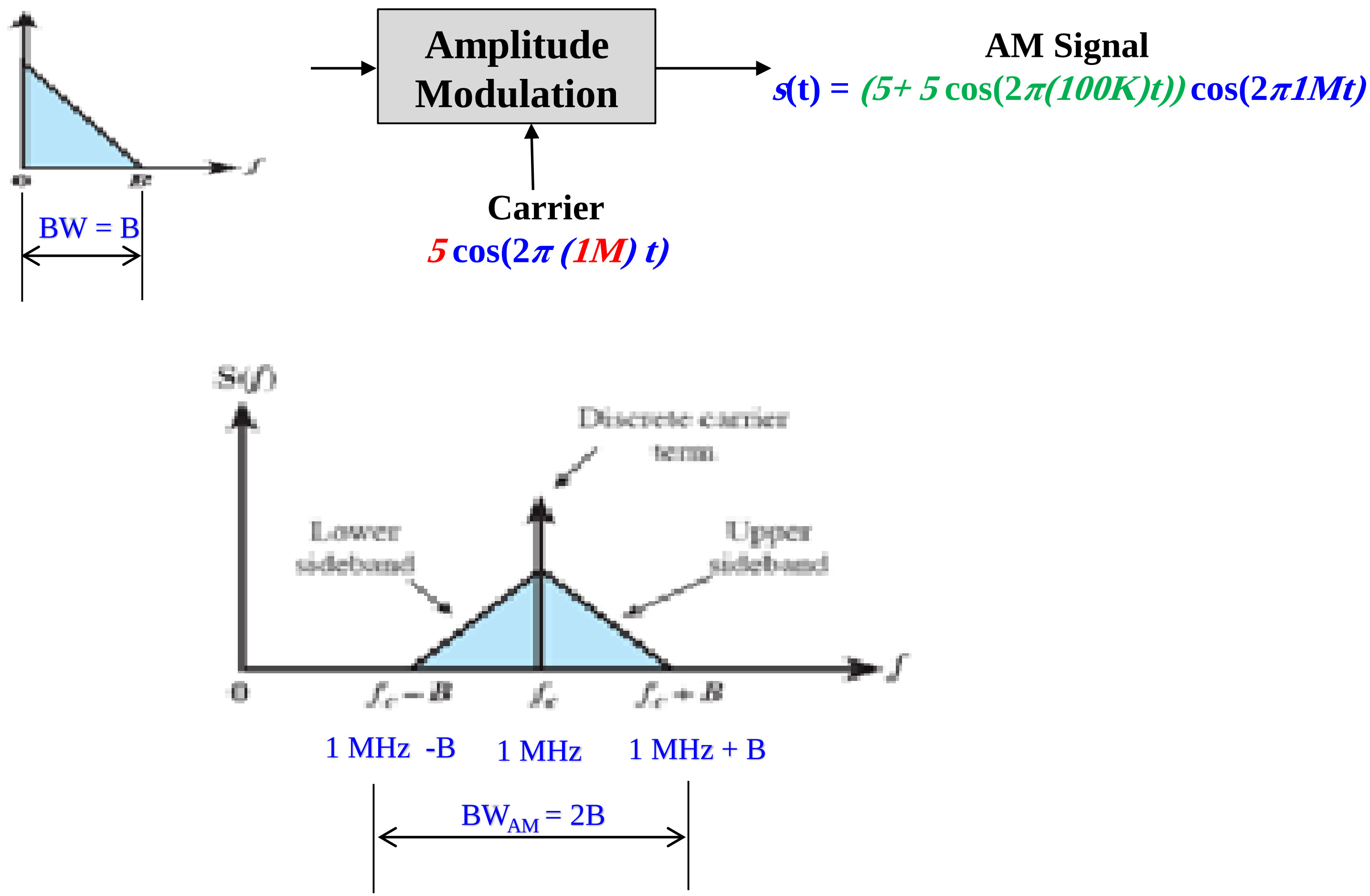
AM Signal
$s(t) = (5 + 5\cos(2\pi(100K)t))\cos(2\pi 1Mt)$

Carrier
$5\cos(2\pi(1M)t)$



$$S(t) = 5\cos(2\pi\ 1000K\ t) + 2.5\cos(2\pi\ 900K\ t) + 2.5\cos(2\pi\ 1100K\ t)$$

Amplitude Modulation (AM) Example 3



Amplitude Modulation (AM)

- **Amplitude modulation** is the simplest form of modulation.

$$s(\mathbf{t}) = [1 + n_a x(t)] \cos 2\pi f_c t$$

- $\cos(2\pi f_c t)$ = carrier signal
- $x(t)$ = normalized input signal
- $m(t)$ = input signal = $n_a x(t)$
- n_a = modulation index

Normalized to unity amplitude

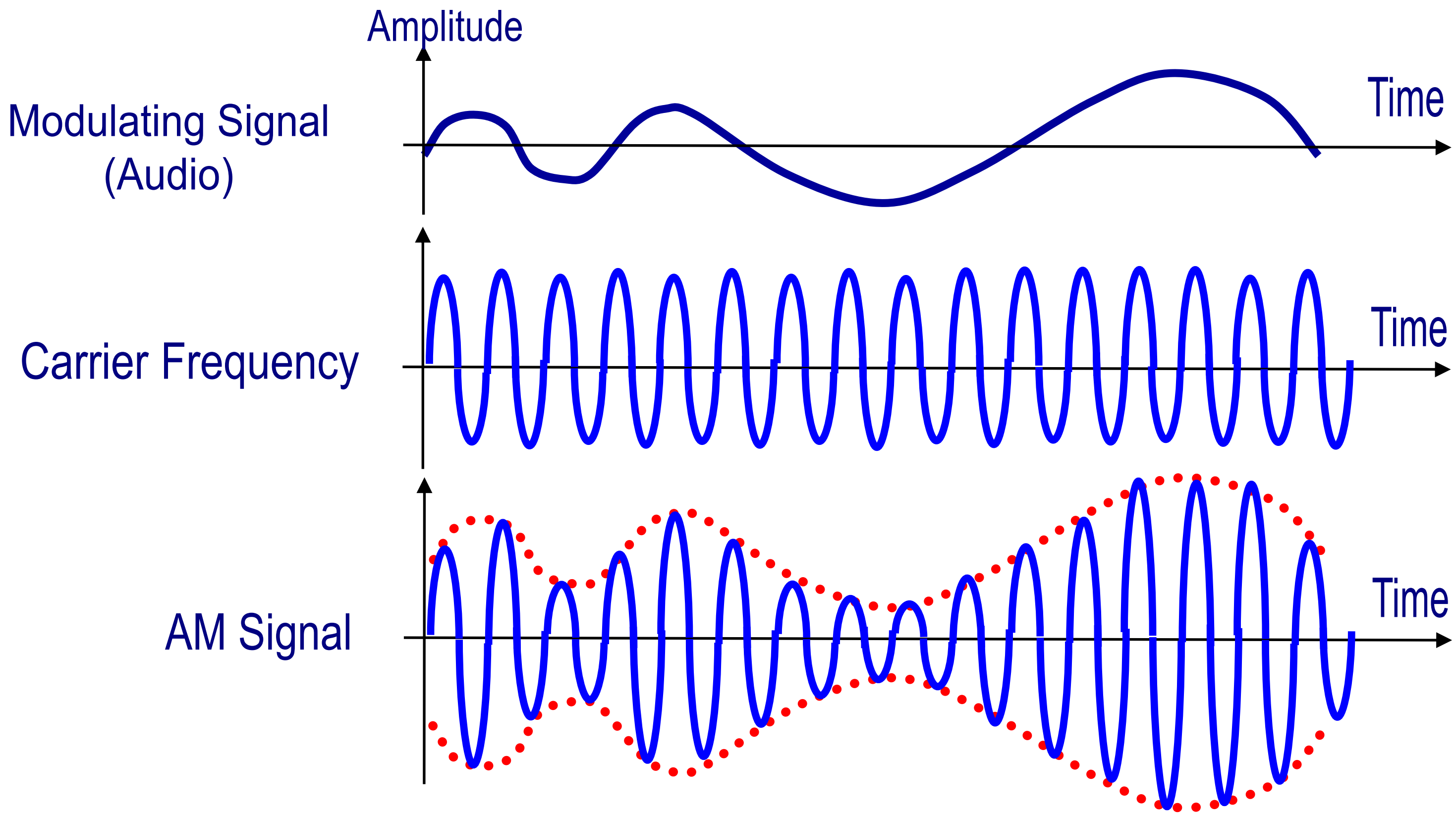
$$n_a = \frac{\text{peak amplitude of input signal } m(t)}{\text{carrier amplitude}} = \frac{M}{A}$$

- *A=1* represents the carrier amplitude which is a constant that we would choose to demonstrate the *modulation index*

  A is a dc component that prevents loss of information

- This scheme is known as **Double Sideband Transmitted Carrier (DSBTC)**

Amplitude Modulation (AM)



- The envelope of the resulting signal is **[1+$n_a x(t)$]** and, as long as **n_a<1**, the envelope is an exact reproduction of the original signal. If **n_a>1**, the envelope will cross the time axis and information is lost.

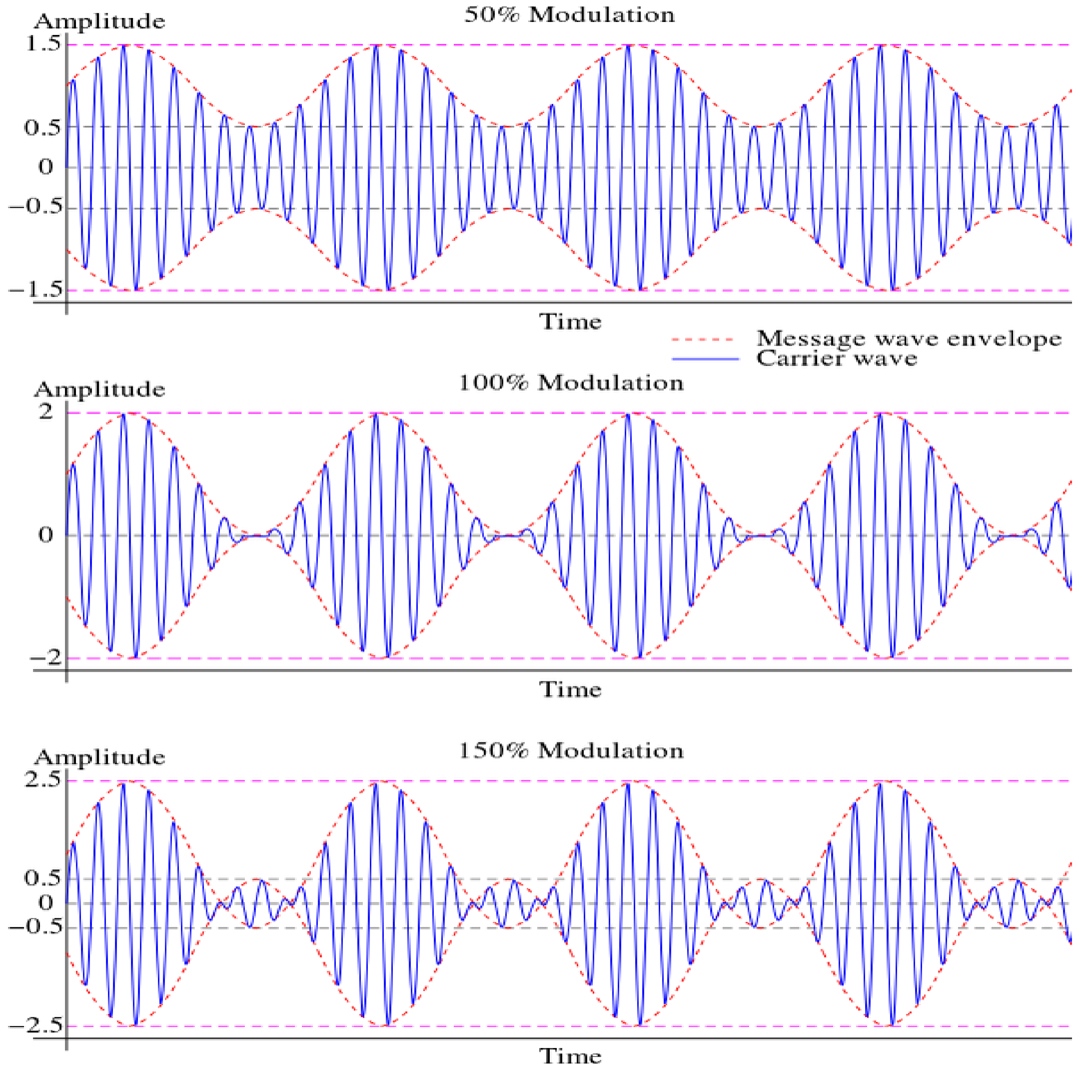
Modulation Index

A = 1 V

M = 0.5 V

M = 1 V

M = 1.5 V



Amplitude Modulation (AM)

EXAMPLE 5.4 Derive an expression for $s(t)$ if $x(t)$ is the amplitude-modulating signal $\cos 2\pi f_m t$. We have

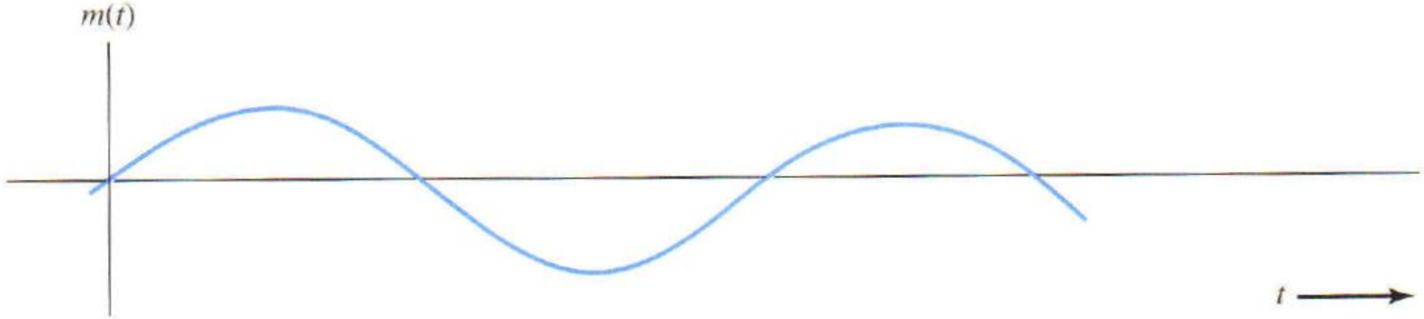
$$s(t) = [1 + n_a \cos 2\pi f_m t]\cos 2\pi f_c t$$

By trigonometric identity, this may be expanded to

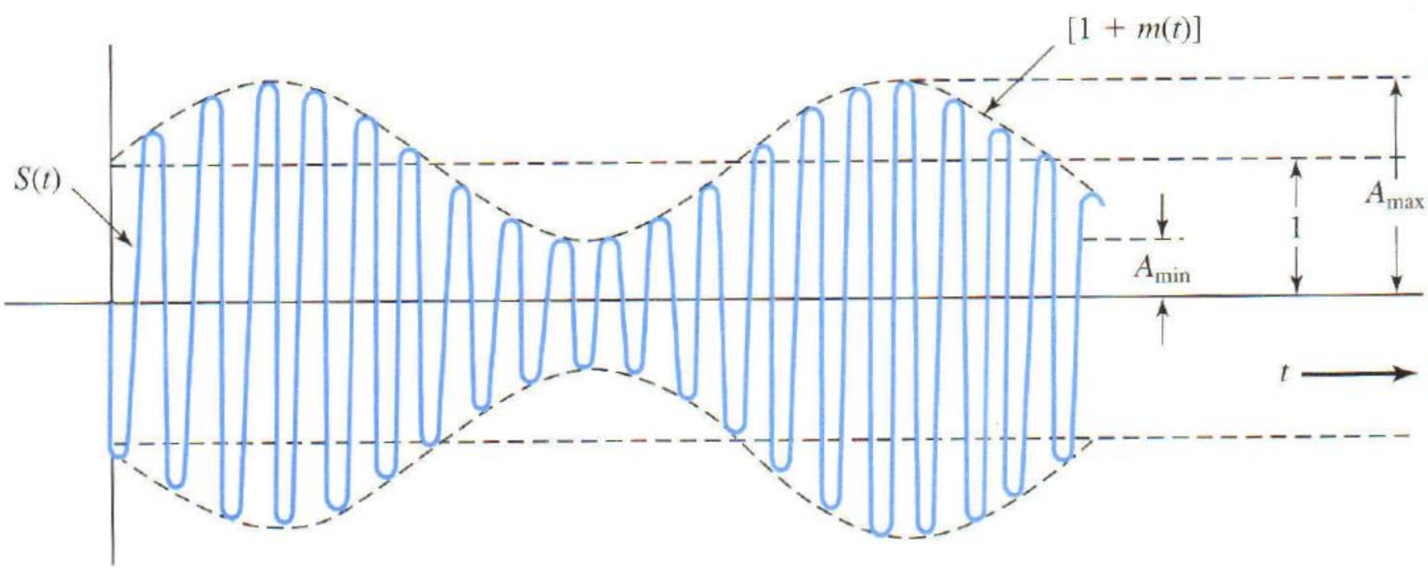
$$s(t) = \cos 2\pi f_c t + \frac{n_a}{2}\cos 2\pi(f_c - f_m)t + \frac{n_a}{2}\cos 2\pi(f_c + f_m)t$$

The resulting signal has a component at the original carrier frequency plus a pair of components each spaced f_m hertz from the carrier.

Amplitude Modulation (AM)

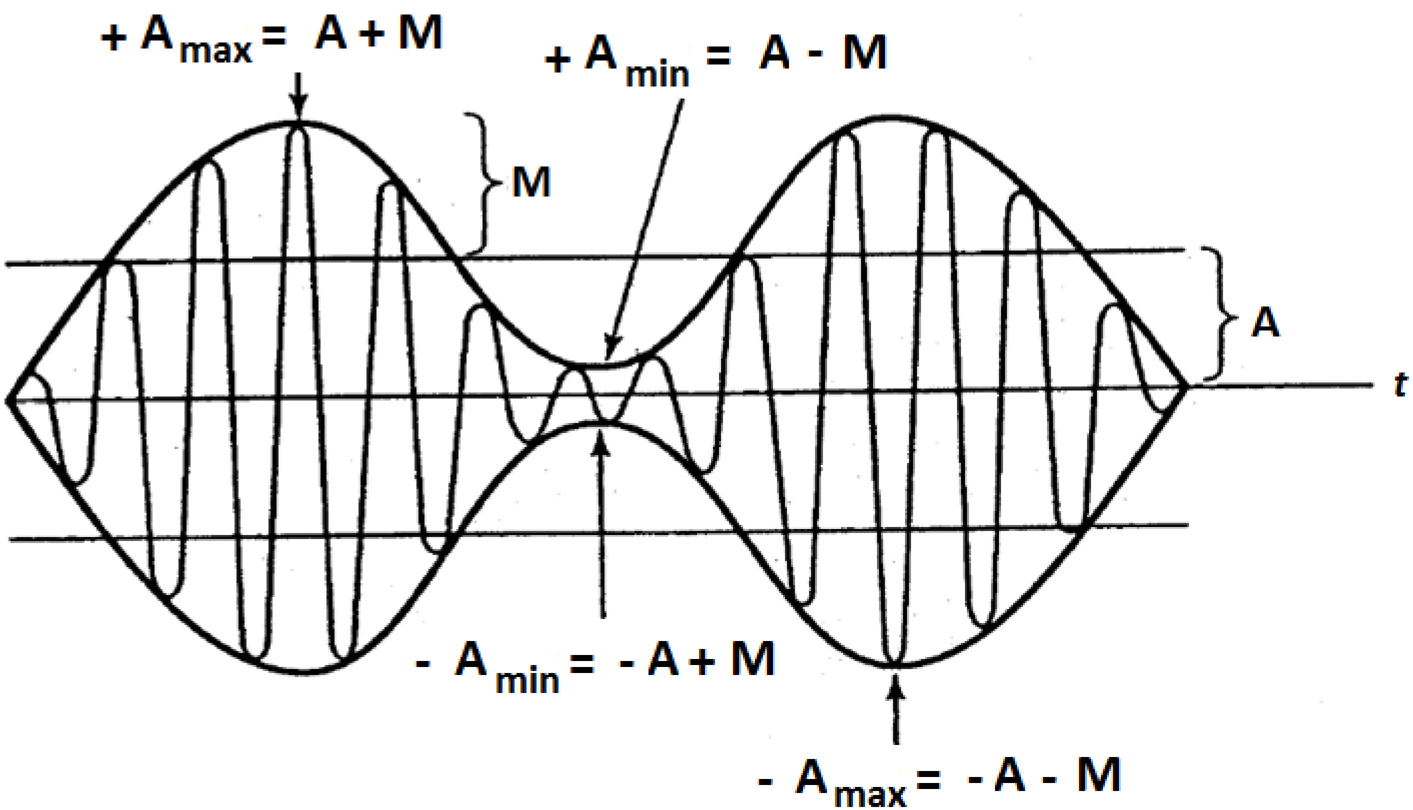


(a) Sinusoidal modulating wave

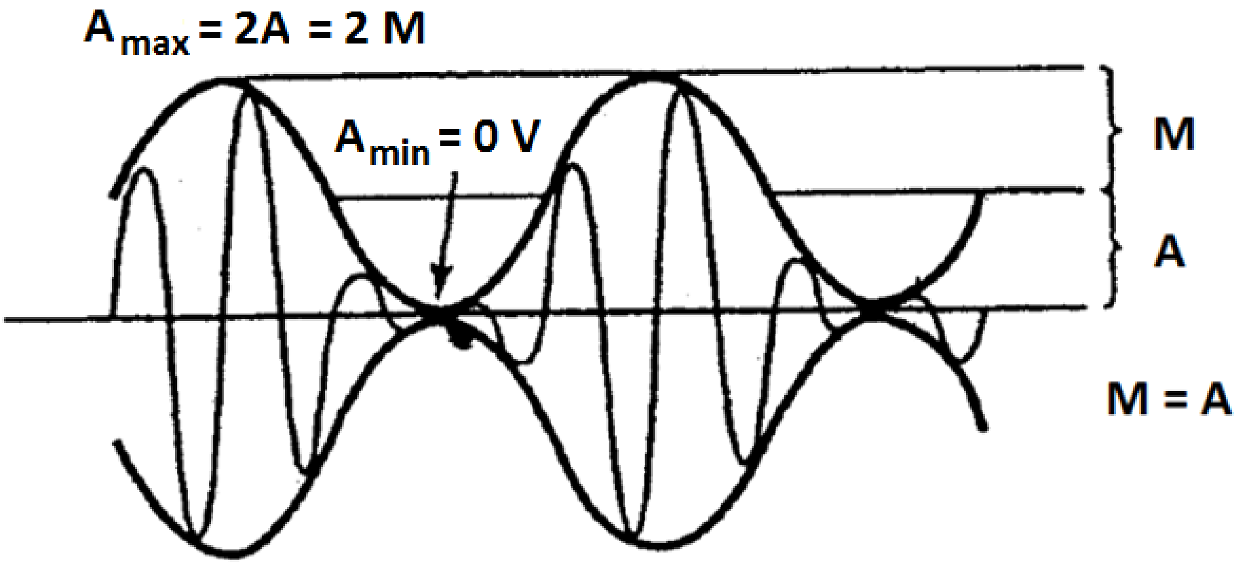


(b) Resulting AM signal

Amplitude Modulation (AM)

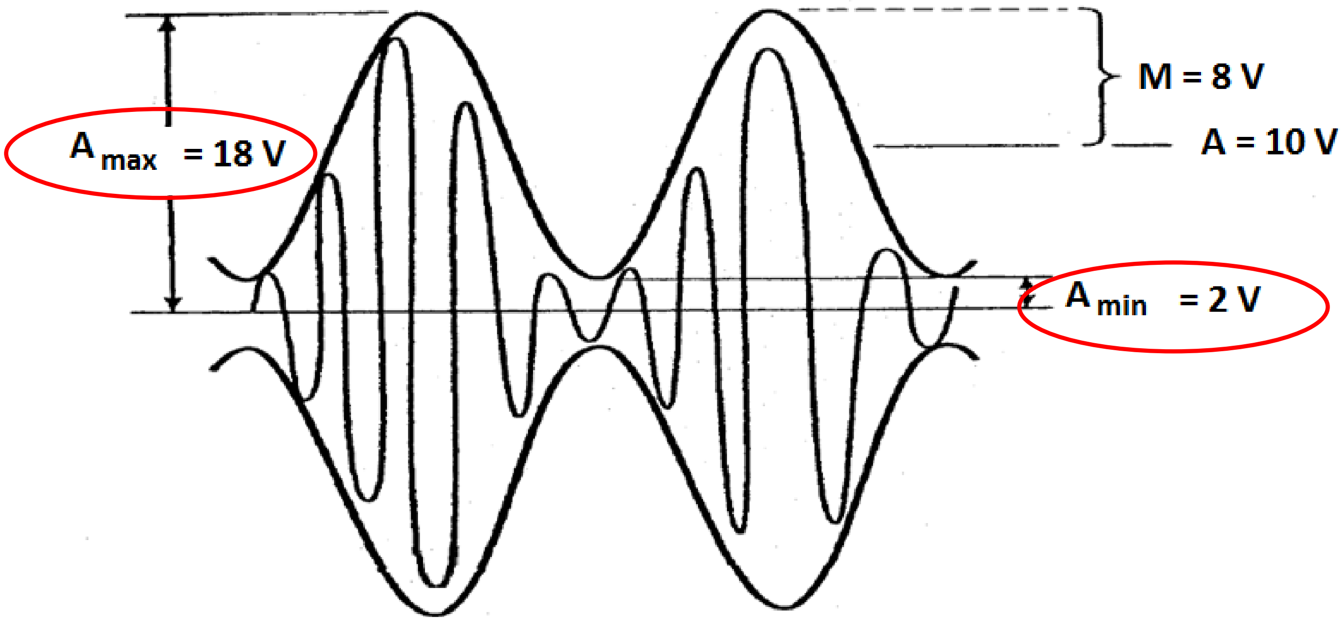


Amplitude Modulation (AM)



Modulation Index (n_a) = 1

Amplitude Modulation (AM) - Example



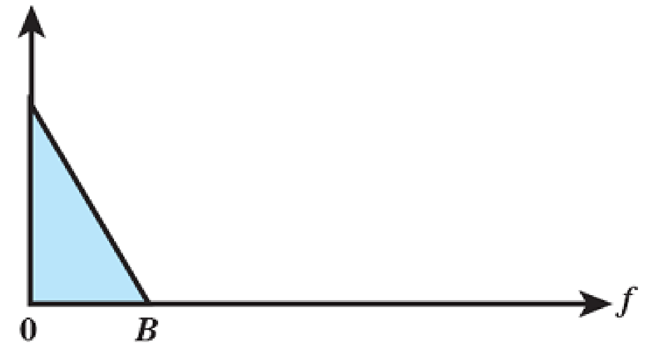
$A = ½(A_{max} + A_{min}) = ½(18 + 2) = 10\ V$

$M = ½(A_{max} - A_{min}) = ½(18 - 2) = 8\ V$

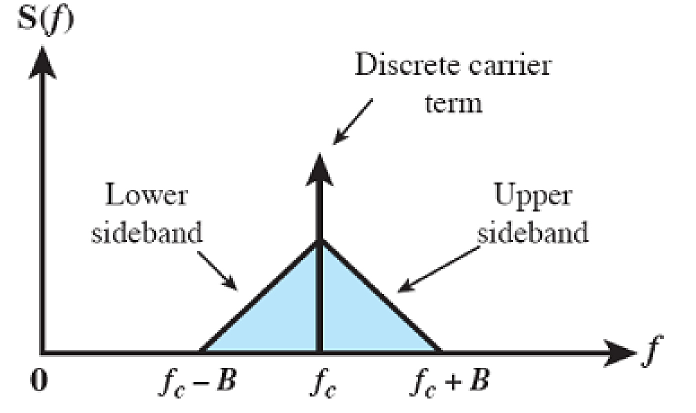
$n_a = M / A = 0.80$

Spectrum of AM Signal

- $|f|>|f_c|$ upper sideband
- $|f|<|f_c|$ lower sideband
- Both replicas of the original spectrum $M(f)$
- Lower sideband frequency reversed



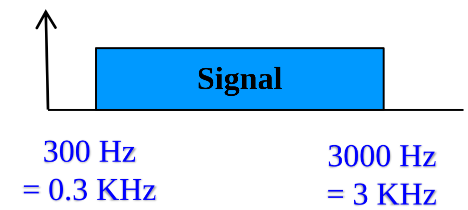
(a) Spectrum of modulating signal

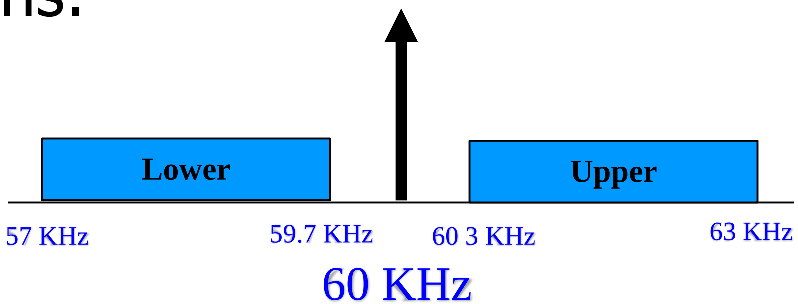


(b) Spectrum of AM signal with carrier at f_c

Spectrum of AM Signal

- Voice signal: 300-3000 Hz
- Carrier: 60 kHz
- The resulting signal s(t) contains:
  - **upper: 60.3-63 kHz**
  - **lower: 57-59.7 kHz**





- An important relationship is:

$$P_t = P_c \left(1 + \frac{n_a^2}{2}\right)$$

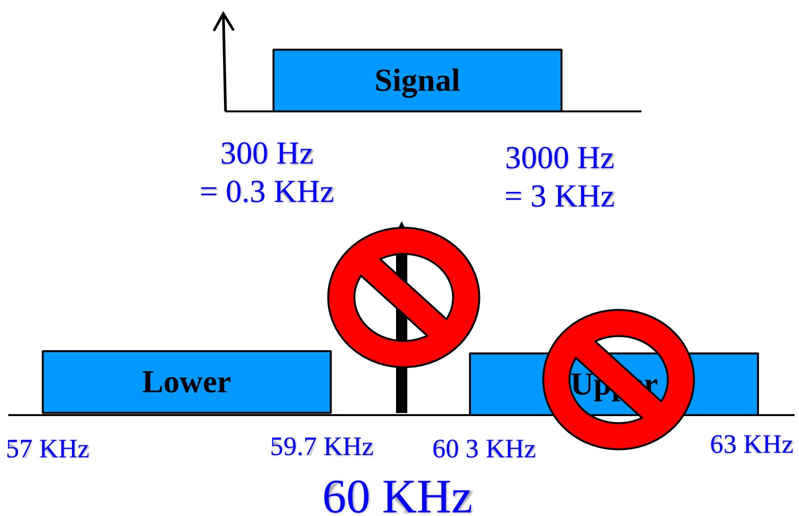
$P_c = ½ A^2$

$n_a = M / A$

  - P_t = total transmitted power in s(t)
  - P_c = transmitted power in carrier

Single Sideband (SSB)

- s(t) contains unnecessary components
- Each sideband contains spectrum of m(t)
- SSB sends only one sideband
- **Eliminate other sideband and carrier**

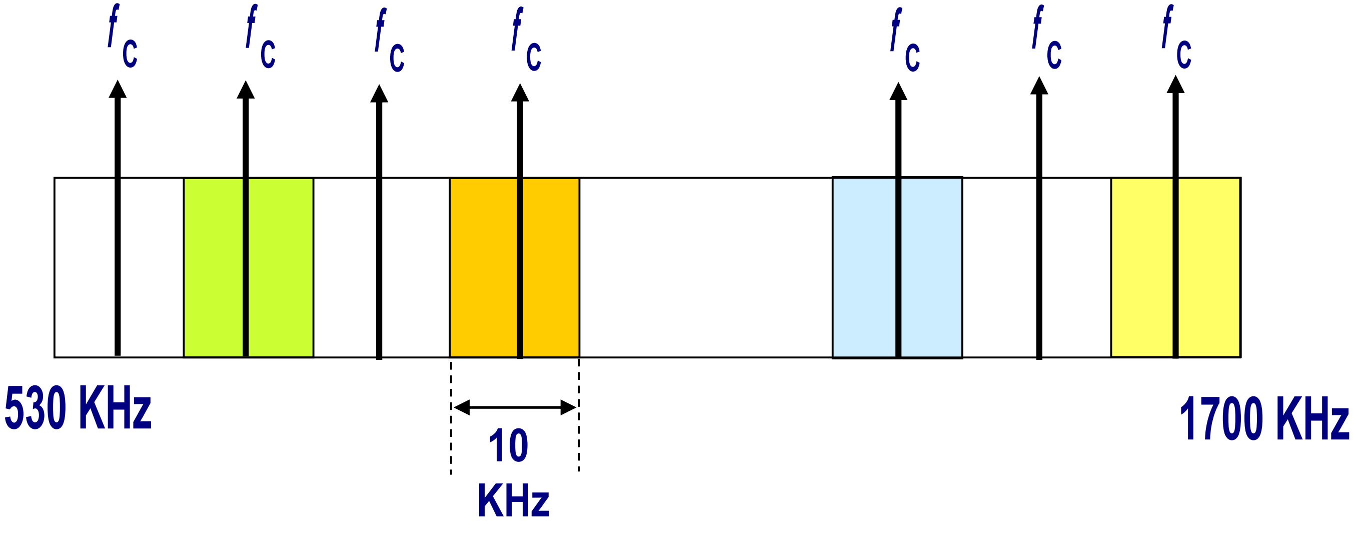


Single Sideband (SSB)

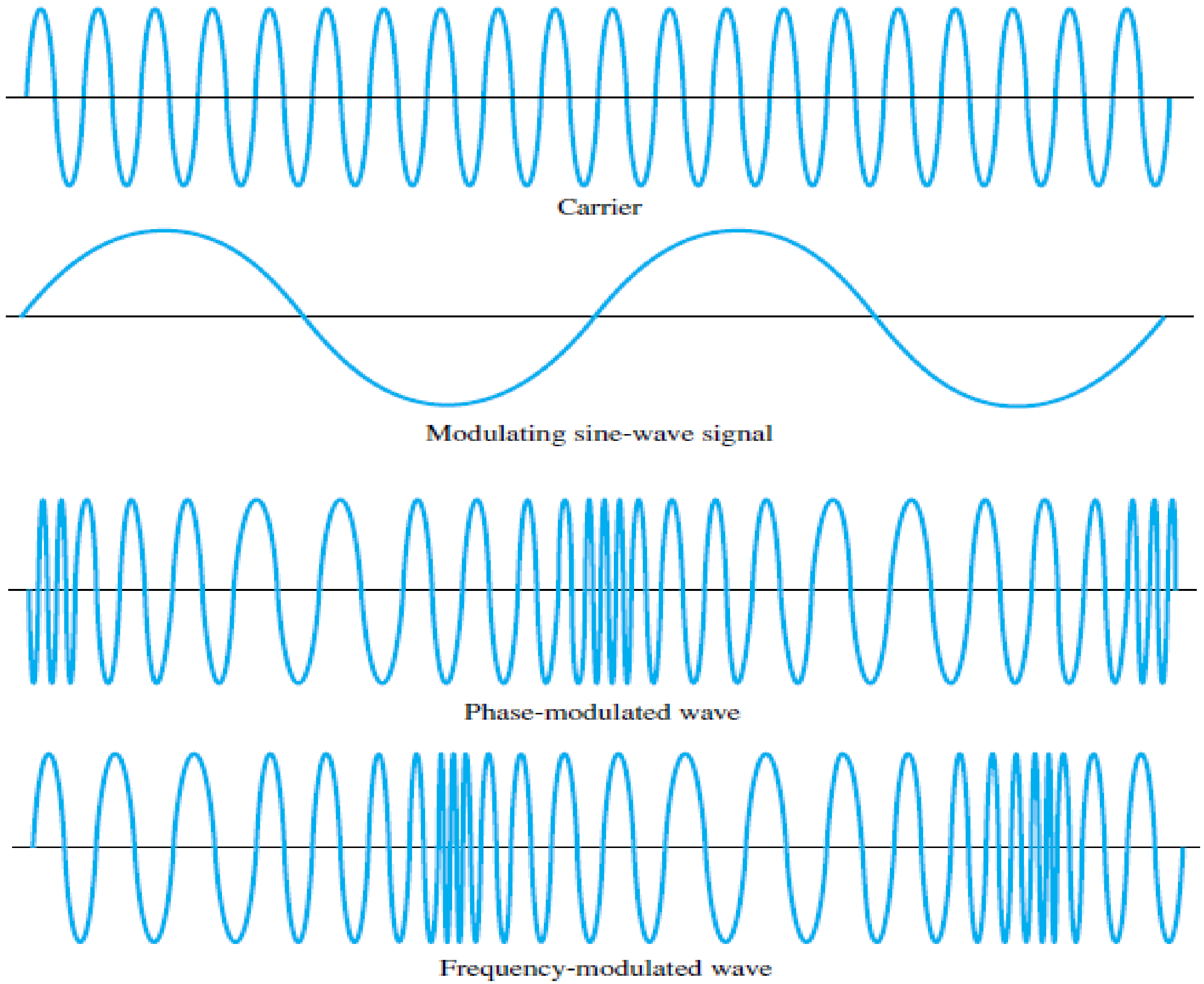
- **Advantages**
  - **only half bandwidth required ($B_T = B$)**
    - **for DSBTC $B_T = 2B$ (B of original signal)**
  - **Less power required**
    - **no power of other sideband or carrier**
- **Disadvantages of suppressing the carrier**
  - carrier used for **synchronization**
  - For example, suppose that the original analog signal is an ASK waveform encoding digital data. The receiver needs to know the starting point of each bit time to interpret the data correctly. A constant carrier provides a clocking mechanism by which to time the arrival of bits.
- **Vestigial sideband (VSB)** - **compromise**
  - single sideband, reduced power carrier

Amplitude Modulation (AM)

AM Band Allocation:

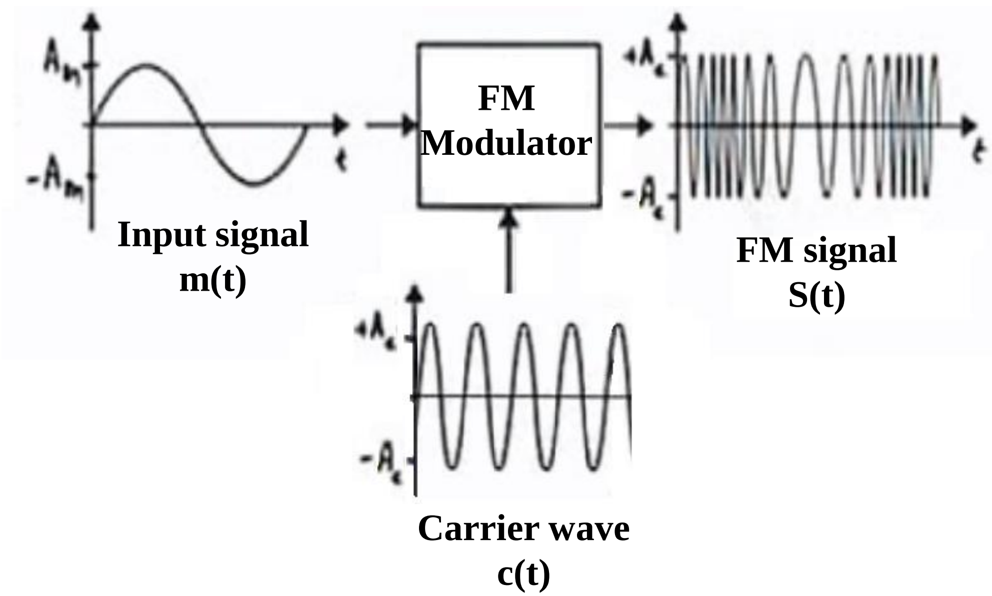


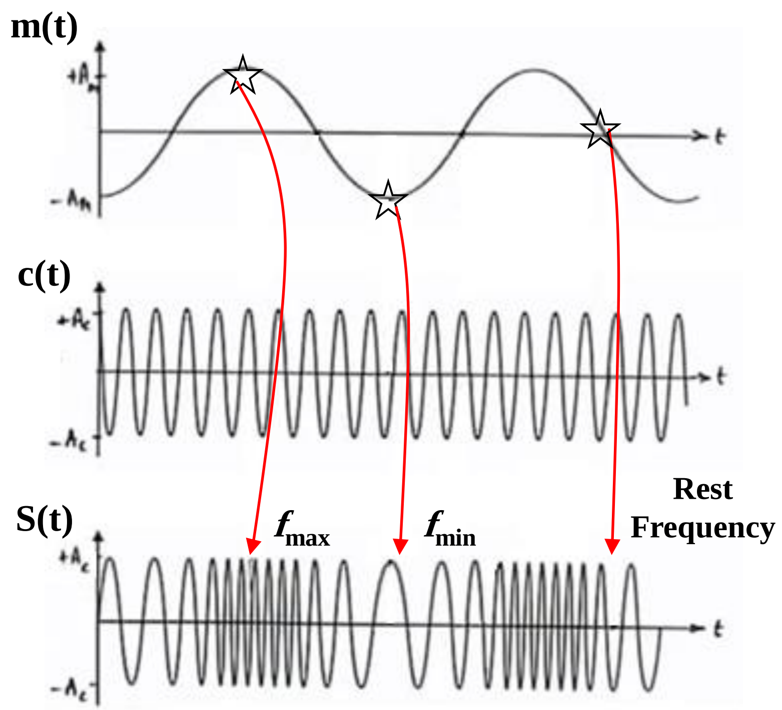
Angle Modulation



Frequency Modulation (FM)

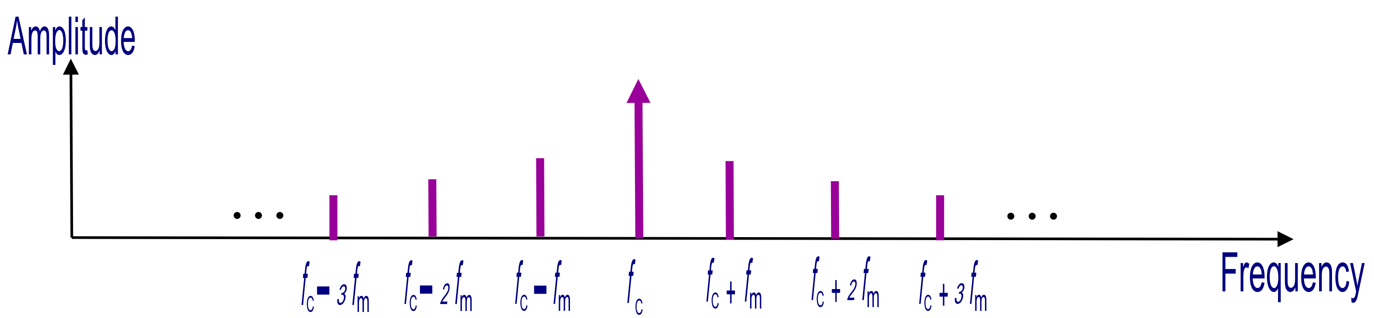
- In FM, the **frequency of the carrier is varied according to the amplitude of input analog signal**.





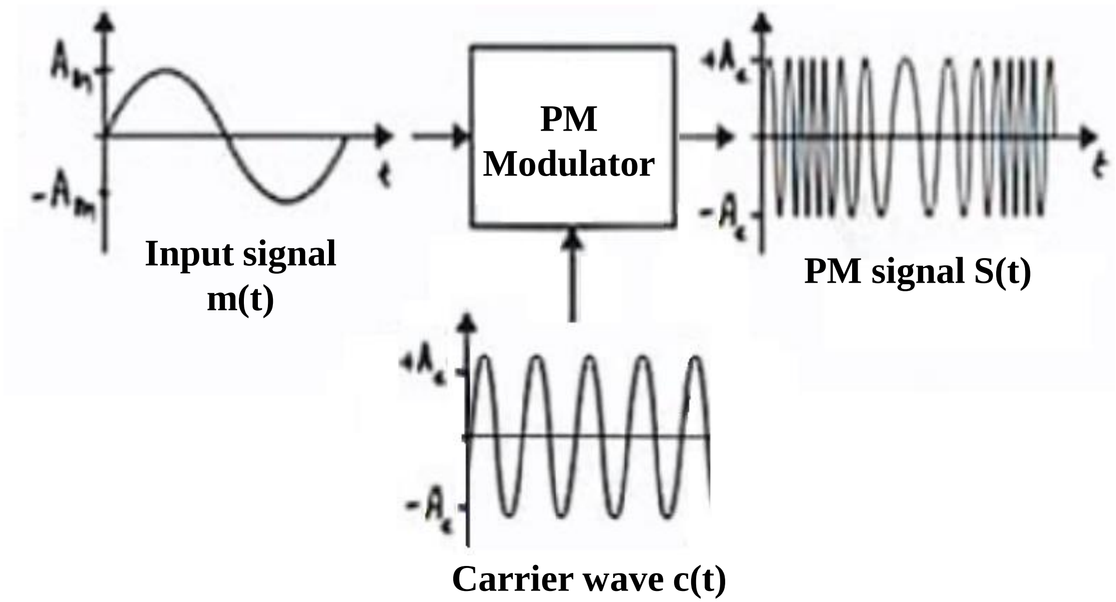
Frequency Modulation (FM)

- Input analog signal m(t) = $M \cos(2\pi f_m t)$
- Carrier wave c(t) = $A \cos(2\pi f_c t)$
- FM signal is s(t) = $A \cos(2\pi(f_c + n_f m(t))\, t)$
- FM signal is s(t) = $A \cos(2\pi(f_c + n_f M \cos(2\pi f_m t))\, t)$



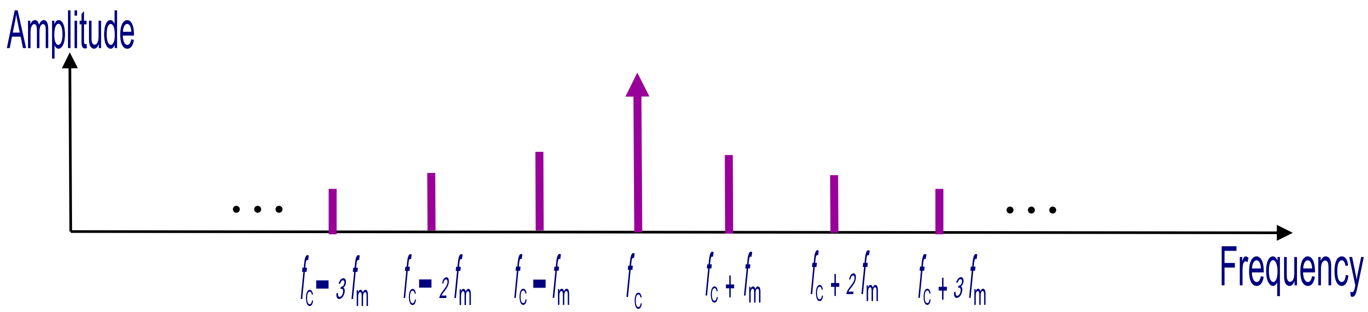
Phase Modulation (PM)

⌘ In PM, the **phase of the carrier is varied according to the amplitude of input analog signal**.



Phase Modulation (PM)

- Input analog signal m(t) = $M\cos(2\pi f_m t)$
- Carrier wave c(t) = $A\cos(2\pi f_c t)$
- PM signal is s(t) = $A\cos(2\pi f_c t + n_p m(t))$
- PM signal is s(t) = $A\cos(2\pi f_c t + n_p M\cos(2\pi f_m t))$



Angle Modulation

- ⌘ **Angle Modulation** includes FM and PM

$$s(t) = A_c \cos[2\pi f_c t + \phi(t)]$$

- ⌘ For **phase modulation**, the phase is proportional to the modulating signal:

  PM: $\phi(t) = n_p m(t)$, , where n_p = PM index

- ⌘ For **frequency modulation**, the derivative of the phase is proportional to the modulating signal:

  FM: $\phi`(t) = n_f m(t)$, , where n_f = FM index

  $\phi`(t)$ = derivative of $\varphi(t)$

Angle Modulation

$$s(t) = A_c \cos[2\pi f_c t + \emptyset(t)]$$

PM

Case 1: Given m(t), Find s(t)

Step 1: $\emptyset(t) = n_p m(t)$

Step 2: $s(t) = A_c cos[2\pi f_c t + \emptyset(t)]$

Case 2: Given s(t), Find m(t)

$\emptyset(t) = n_p m(t)$

Step 1: $m(t) = \frac{\emptyset(t)}{n_p}$

FM

Case 1: Given m(t), Find s(t)

Step 1: $\emptyset'(t) = n_f m(t)$

Step 2: $\emptyset(t) = \int n_f m(t)\, dt$

Step 3: $s(t) = A_c cos[2\pi f_c t + \emptyset(t)]$

Case 2: Given s(t), Find m(t)

Step 1: Find $\emptyset'(t)$

Step 2: $\emptyset'(t) = n_f m(t)$

$\rightarrow m(t) = \frac{\emptyset\prime(t)}{n_f}$

Angle Modulation

- The phase of *s(t) at any instant is just* **$2\pi f_c t + \phi(t)$**.
- In PM, the instantaneous phase deviation is proportional to *m(t).*
- Because **frequency can be defined as the rate of change of phase of a signal**, the **instantaneous frequency of s(t)** is:

$$\boxed{2\pi f_i(t) = \frac{d}{dt}[2\pi f_c t + \phi(t)]}$$

$$\rightarrow \boxed{f_i(t) = f_c + \frac{1}{2\pi}\phi^{'}(t)}$$

Frequency Modulation (FM)

- FM Peak deviation (ΔF):

$$\Delta F = \frac{1}{2\pi} n_f A_m \text{ Hz}$$

  - A_m = maximum value of m(t)
  - n_f = FM index
  - ΔF = maximum shift away from f_c in one direction

- **FM: A_m is high → high ΔF → high B_T**
- **FM**: average power level of FM signal is constant = $\frac{1}{2}A_c^2$
- **AM**: modulation affects power not bandwidth (**B_{AM} = 2B**)

$$P_t = P_c\left(1 + \frac{n_a^2}{2}\right)$$

Phase Modulation - Example

EXAMPLE 5.5 Derive an expression for $s(t)$ if $\phi(t)$ is the phase-modulating signal $n_p \cos 2\pi f_m t$. Assume that $A_c = 1$. This can be seen directly to be

$$s(t) = \cos[2\pi f_c t + n_p \cos 2\pi f_m t]$$

The instantaneous phase deviation from the carrier signal is $n_p \cos 2\pi f_m t$. The phase angle of the signal varies from its unmodulated value in a simple sinusoidal fashion, with the peak phase deviation equal to n_p.

The preceding expression can be expanded using Bessel's trigonometric identities:

$$s(t) = \sum_{n=-\infty}^{\infty} J_n(n_p) \cos\left(2\pi f_c t + 2\pi n f_m t + \frac{n\pi}{2}\right)$$

where $J_n(n_p)$ is the nth-order Bessel function of the first kind. Using the property

$$J_{-n}(x) = (-1)^n J_n(x)$$

this can be rewritten as

$$s(t) = J_0(n_p) \cos 2\pi f_c t + \sum_{n=1}^{\infty} J_n(n_p)\left[\cos\left(2\pi(f_c + n f_m)t + \frac{n\pi}{2}\right) + \cos\left(2\pi(f_c - n f_m)t + \frac{(n+2)\pi}{2}\right)\right]$$

The resulting signal has a component at the original carrier frequency plus a set of sidebands displaced from f_c by all possible multiples of f_m. For $n_p \ll 1$, the higher-order terms fall off rapidly.

Frequency Modulation - Example

EXAMPLE 5.6 Derive an expression for $s(t)$ if $\phi'(t)$ is the frequency modulating signal $-n_f \sin 2\pi f_m t$. The form of $\phi'(t)$ was chosen for convenience. We have

$$\phi(t) = -\int n_f \sin 2\pi f_m t \, dt = \frac{n_f}{2\pi f_m} \cos 2\pi f_m t$$

Thus

$$\begin{aligned} s(t) &= \cos\left[2\pi f_c t + \frac{n_f}{2\pi f_m} \cos 2\pi f_m t\right] \\ &= \cos\left[2\pi f_c t + \frac{\Delta F}{f_m} \cos 2\pi f_m t\right] \end{aligned}$$

The instantaneous frequency deviation from the carrier signal is $-n_f \sin 2\pi f_m t$. The frequency of the signal varies from its unmodulated value in a simple sinusoidal fashion, with the peak frequency deviation equal to n_f radians/second.

The equation for the FM signal has the identical form as for the PM signal, with $\Delta F / f_m$ substituted for n_p. Thus the Bessel expansion is the same.

Angle Modulation

- AM
  - linear, produce frequencies = $f_m \pm f_c$
  - $B_T = 2B$
    - B_T = transmitted AM signal bandwidth
    - B = input signal bandwidth
- FM/PM
  - include term of form cos φ(t)
  - **nonlinear, produce wide range of frequencies**
  - both require more bandwidth than AM

Angle Modulation

- FM/PM

Carson's rule

$$B_T = 2(\beta + 1)B$$

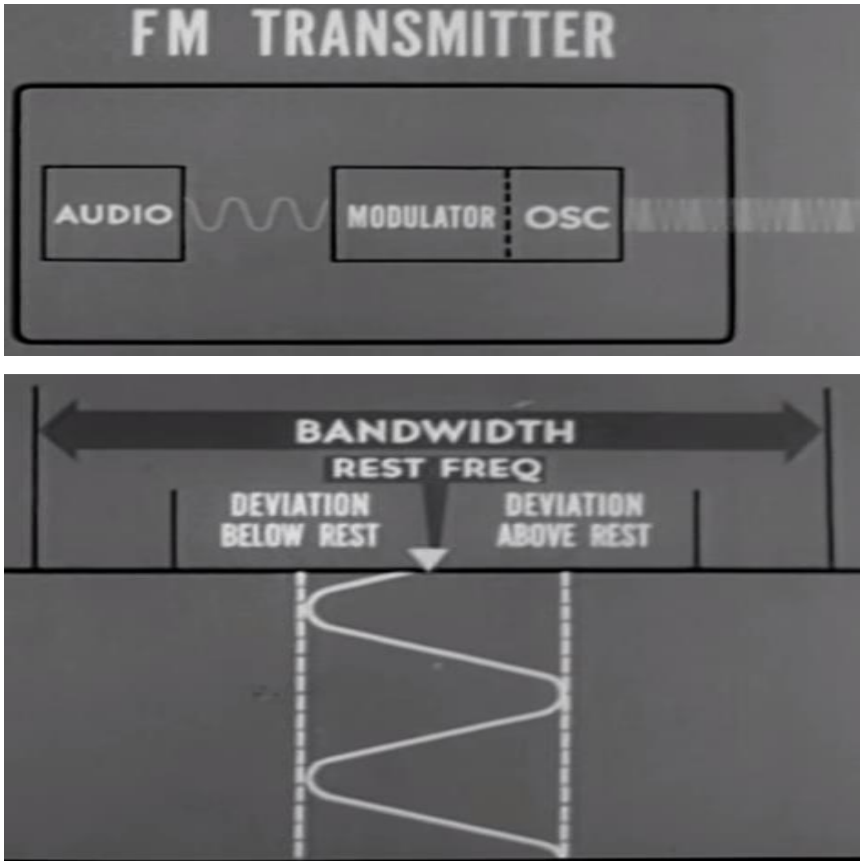
where

$$\beta = \begin{cases} n_p A_m & \text{for PM} \\ \dfrac{\Delta F}{B} = \dfrac{n_f A_m}{2\pi B} & \text{for FM} \end{cases}$$

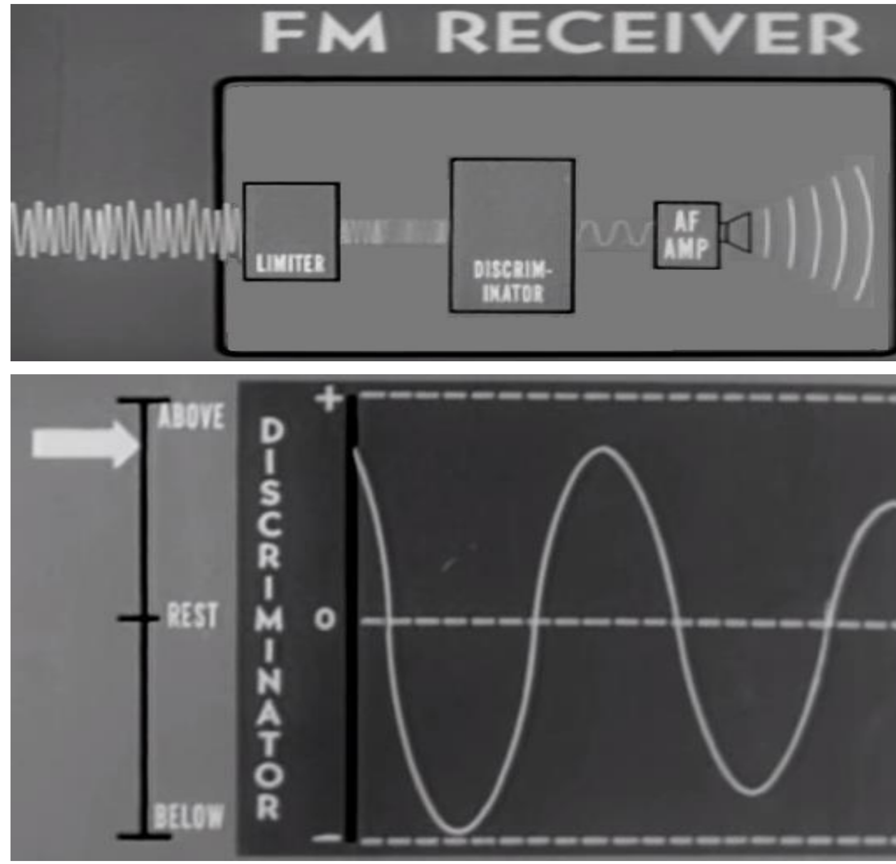
We can rewrite the formula for FM as

$$B_T = 2\Delta F + 2B$$

Frequency Modulation (FM)



FM Transmitter

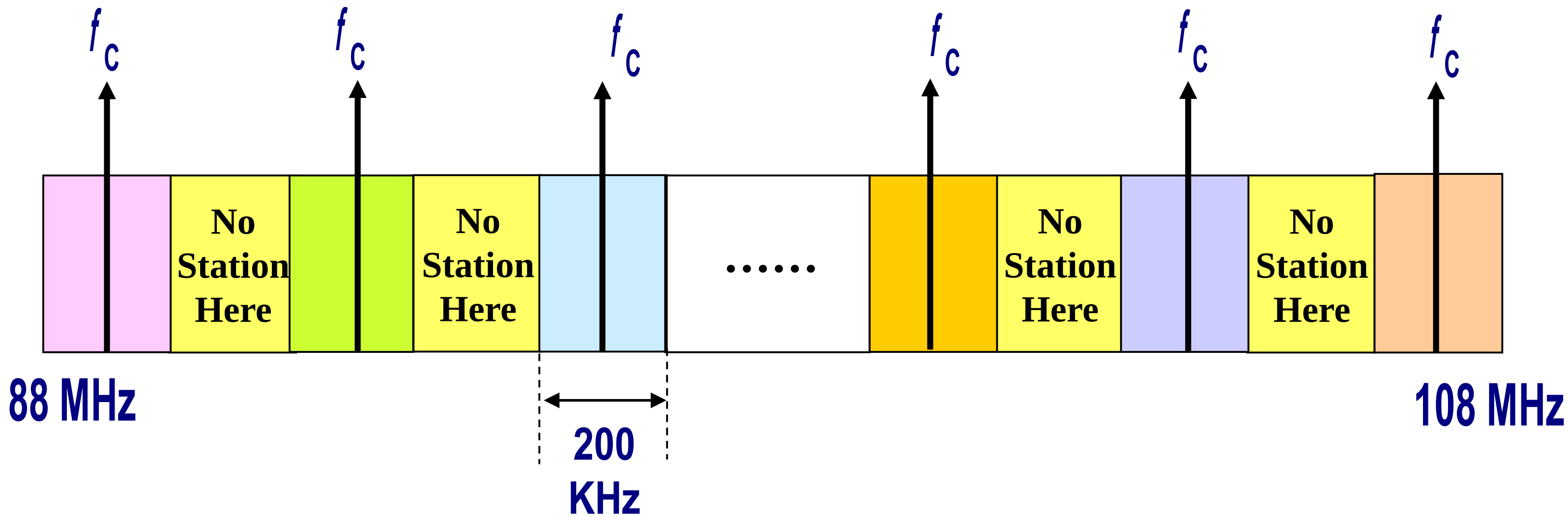


FM Receiver

https://www.youtube.com/watch?v=gfz1FbIOMbs

Frequency Modulation (FM)

FM Band Allocation:



Example

- **Angle modulated** signal

$$s(t) = 20\cos\left[10^6 \pi t + \overbrace{4\sin 2\pi(1000)t}^{\phi(t)}\right]$$

- Find **max phase** and **frequency deviation.**
- **Answer:**

$$\phi(t) = n_p m(t) = 4\sin 2\pi(1000)t$$

Max phase deviation = 4 radians

$$\phi'(t) = n_f m(t) = 4(2000\pi)\cos 2\pi(1000)t$$

$$n_f A_m = 4(2000\pi)$$

$$\Delta F = \frac{1}{2\pi} n_f A_m$$

$$\Rightarrow \Delta F = \frac{1}{2\pi} 4(2000\pi)$$

$$\Rightarrow \Delta F = 4000\,\text{Hz}$$

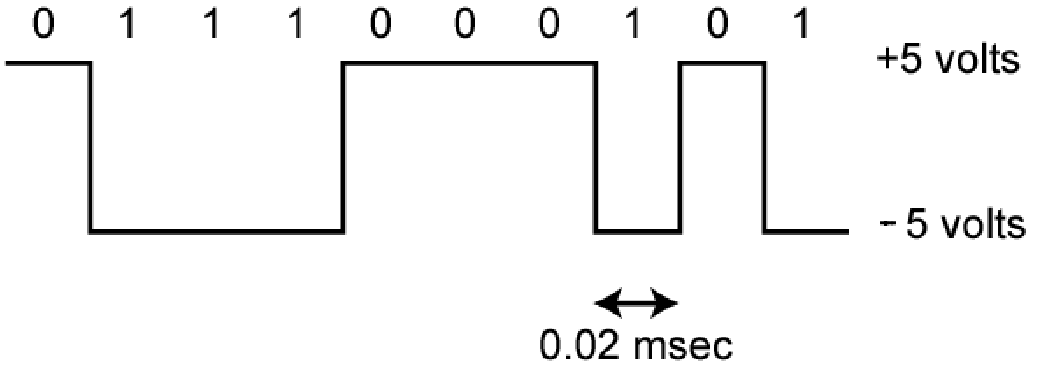
Max frequency deviation = 4000 Hz

Encoding Techniques

Digital Data, Digital Signal

Digital Data, Digital Signal

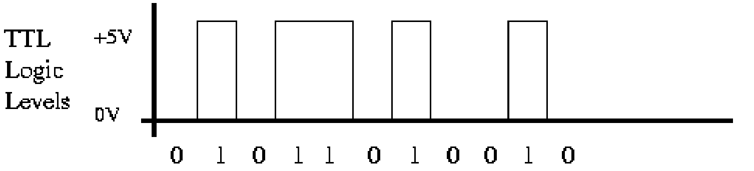
- Digital signal
  - Discrete, discontinuous voltage pulses
  - Each pulse is a signal element
  - **Binary data encoded into signal elements**



Terms (1)

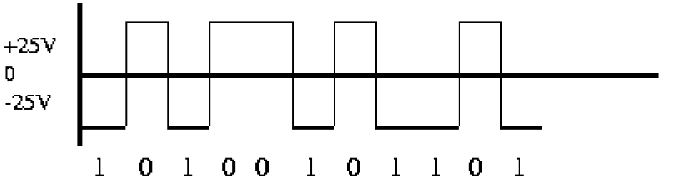
⌘ Unipolar

- A positive voltage represents a binary 1, and zero volts indicates a binary 0
- It is called **Return to Zero (RZ)**



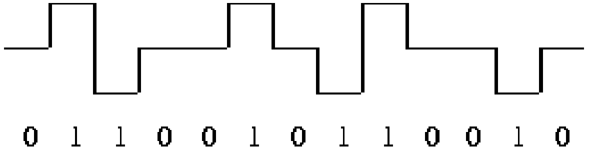
⌘ Polar

- One logic state represented by positive voltage the other by negative voltage
- It is called **None Return To Zero (NRZ)**
- Example: RS-232



⌘ Bipolar

- Bipolar line encoding has 3 voltage levels, a low or 0 is represented by a 0 Volt level and a 1 is represented by alternating polarity pulses.



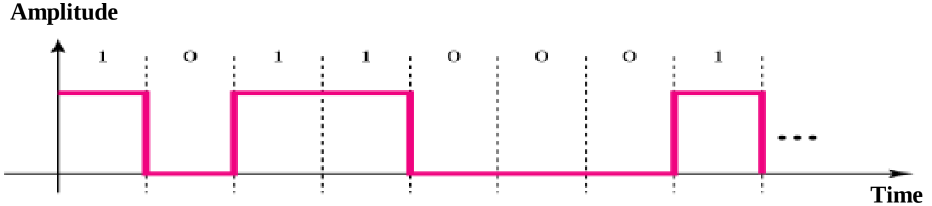
Terms (2)

- **Data rate (*R*)**
  - Rate of data transmission in **bits per second**
- **Duration or length of a bit (T_b)**
  - Time taken for transmitter to emit the bit
- **Modulation rate (R_s)**
  - Rate at which the signal level changes
  - Measured in **baud = signal elements per second**

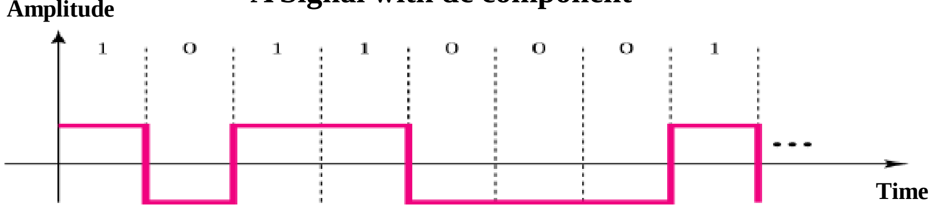
Terms (3)

⌘ DC component

- Some line coding schemes leave a residual direct –current (dc) component (**component at frequency 0**)
- Dc components is **undesirable**
  - The signal is distorted if it passed through a system (such as transformer) that does not allow the passage of dc
  - **Dc is extra energy residing on the line and is useless**



A Signal with dc component



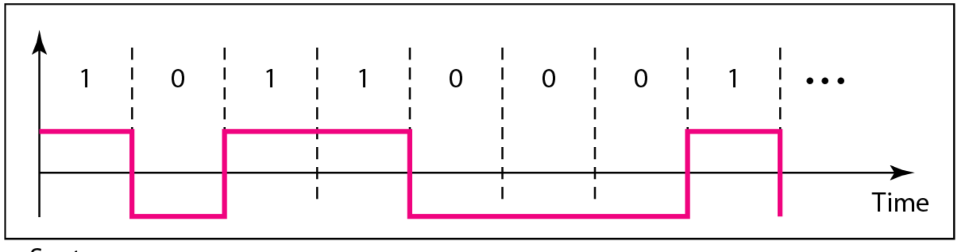
A Signal without dc component

Terms (4)

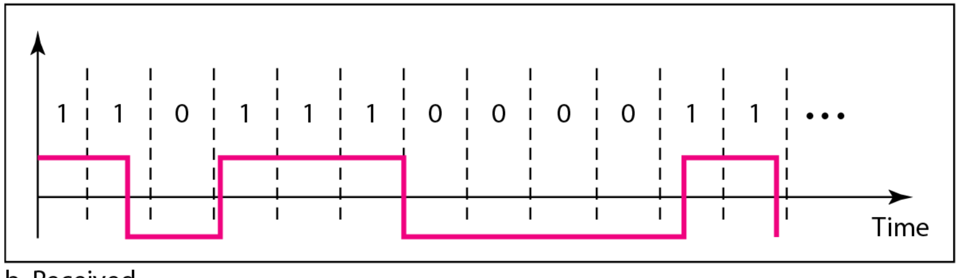
⌘ Synchronization

- To correctly interpret the signals received , the receiver's bit intervals must correspond exactly to the sender's bit intervals (the same clock rate).

- Example: Faster receiver clock



a. Sent



b. Received

Definitions

Term	Units	Definition
Data element	Bits	A single binary one or zero
Data rate	Bits per second (bps)	The rate at which data elements are transmitted
Signal element	Digital: a voltage pulse of constant amplitude Analog: a pulse of constant frequency, phase, and amplitude	That part of a signal that occupies the shortest interval of a signaling code
Signaling rate or modulation rate	Signal elements per second (baud)	The rate at which signal elements are transmitted

Interpreting Signals

- Need to know
  - **Timing of bits** - *when they start and end*
  - **Signal levels**

- Factors affecting successful interpreting of signals
  - **Signal to noise ratio (SNR)**
  - **Data rate**
  - **Bandwidth**
- **An increase in data rate increases bit error rate (BER).**
- **An increase in SNR decreases bit error rate.**
- **An increase in bandwidth allows an increase in data rate.**

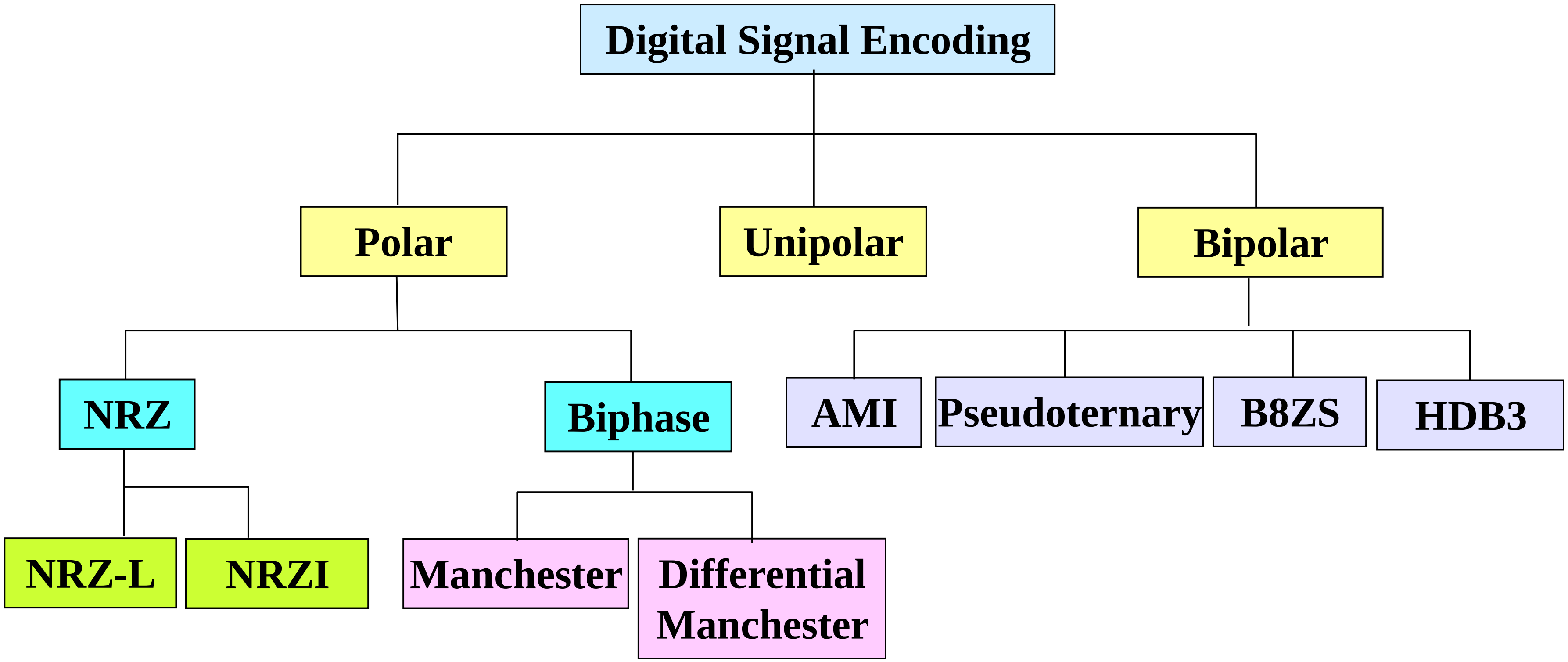
Comparison of Encoding Schemes

- **Signal Spectrum**
  - **Lack of high frequencies components means less bandwidth** is required for transmission
  - **Lack of dc component** is also desirable
  - Concentrate power in the middle of the bandwidth
- **Clocking**
  - Synchronizing transmitter and receiver
  - Separate clock to synchronize the transmitter and the receiver
  - Alternatively, suitable encoding (i.e., Manchester Encoding) provides synchronization

Comparison of Encoding Schemes

- **Error detection**
  - Can be built in to signal encoding
- **Signal interference and noise immunity**
  - Some codes are better than others
- **Cost and complexity**
  - Higher signal rate (& thus data rate) lead to higher costs
  - Some codes require signal rate greater than data rate

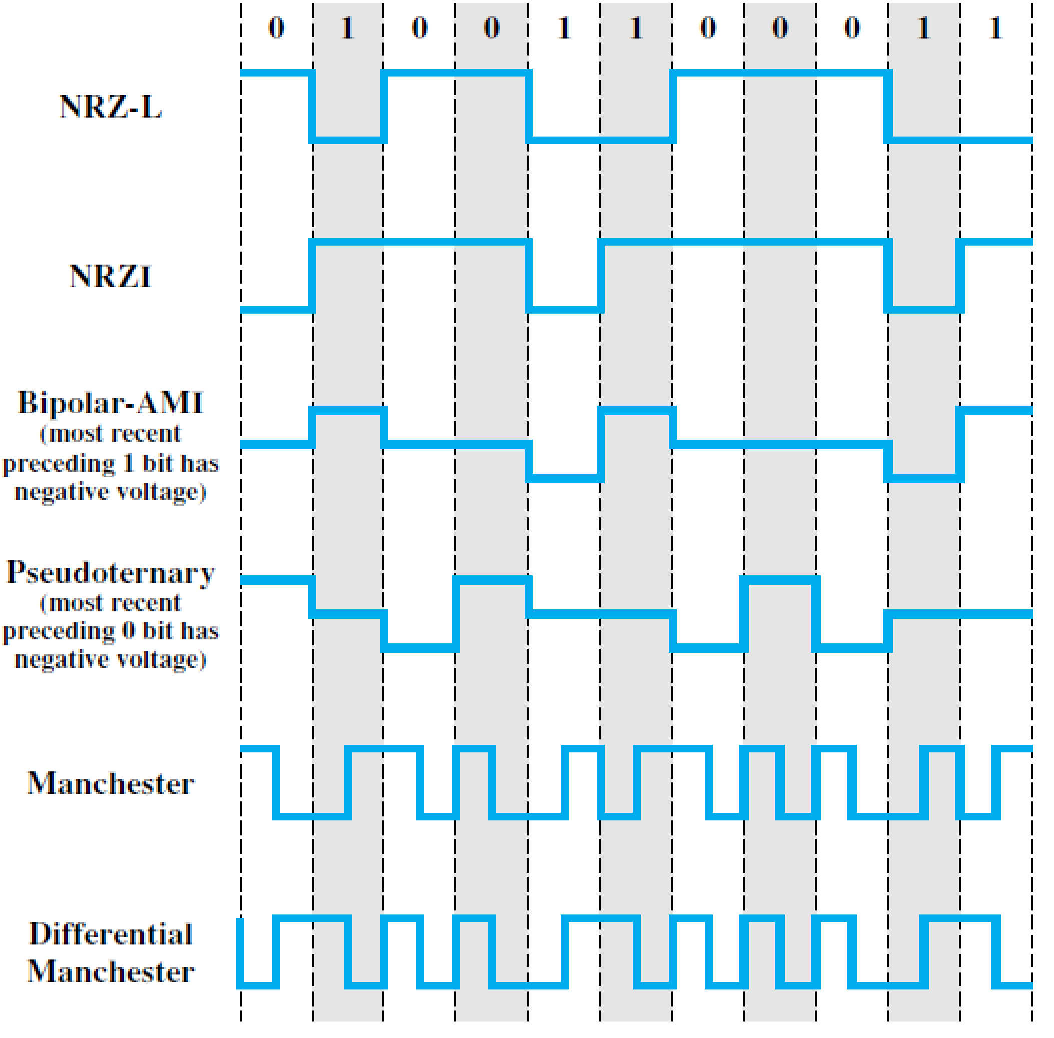
Encoding Schemes



Encoding Schemes

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

Encoding Schemes



Encoding Schemes

Nonreturn to Zero-Level (NRZ-L)
0 = high level
1 = low level
Nonreturn to Zero Inverted (NRZI)
0 = no transition at beginning of interval (one bit time)
1 = transition at beginning of interval
Bipolar-AMI
0 = no line signal
1 = positive or negative level, alternating for successive ones
Pseudoternary
0 = positive or negative level, alternating for successive zeros
1 = no line signal
Manchester
0 = transition from high to low in middle of interval
1 = transition from low to high in middle of interval
Differential Manchester
Always a transition in middle of interval
0 = transition at beginning of interval
1 = no transition at beginning of interval
B8ZS
Same as bipolar AMI, except that any string of eight zeros is replaced by a string with two code violations
HDB3
Same as bipolar AMI, except that any string of four zeros is replaced by a string with one code violation

Encoding Techniques

- **Nonreturn to Zero-Level (NRZ-L)**
  - 0 = high level
  - 1 = low level
- **Nonreturn to Zero Inverted (NRZI)**
  - 0 = no transition at beginning of interval (one bit time)
  - 1 = transition at beginning of interval
- **Bipolar-AMI**
  - 0 = no line signal
  - 1 = positive or negative level, alternating for successive ones

Encoding Techniques

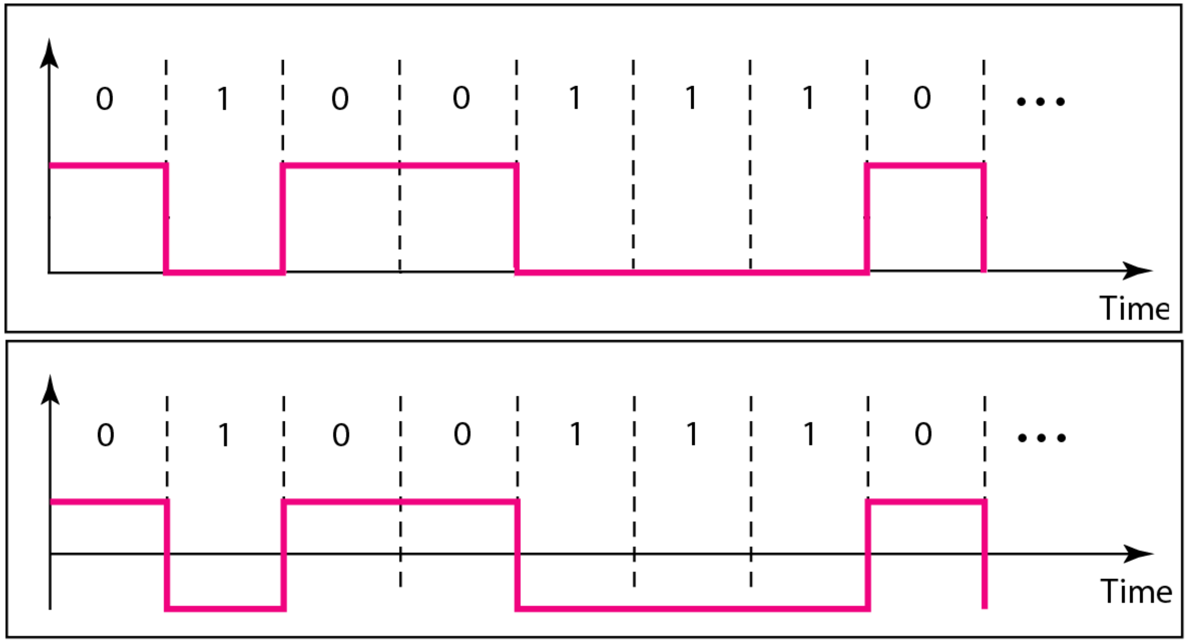
- **Pseudoternary**
  - 0 = positive or negative level, alternating for successive zeros
  - 1 = no line signal
- **Manchester**
  - 0 = transition from high to low in middle of interval
  - 1 = transition from low to high in middle of interval
- **Differential Manchester**
  - Always a transition in middle of interval
  - 0 = transition at beginning of interval
  - 1 = no transition at beginning of interval

Encoding Techniques

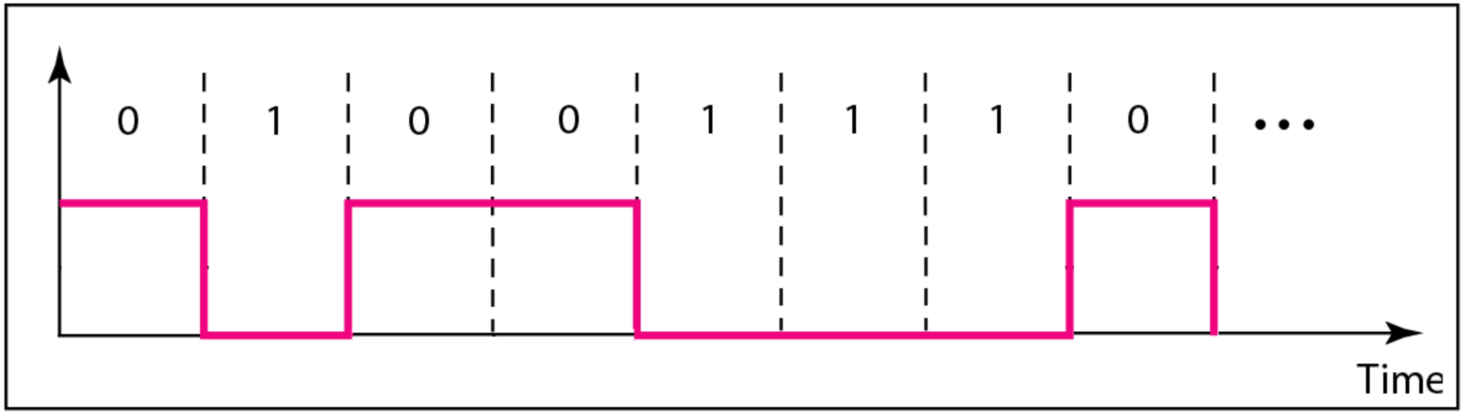
- **B8ZS**
  - based on bipolar AMI
  - string of 8 zeros is replaced by a string with two code violations
- **HDB3**
  - string of 4 zeros is replaced by a string with one code violation

Nonreturn to Zero-Level (NRZ-L)

- Two different voltages for 0 and 1 bits
- Voltage constant during bit interval
- More often, **negative voltage for bit one and positive for bit zero.**



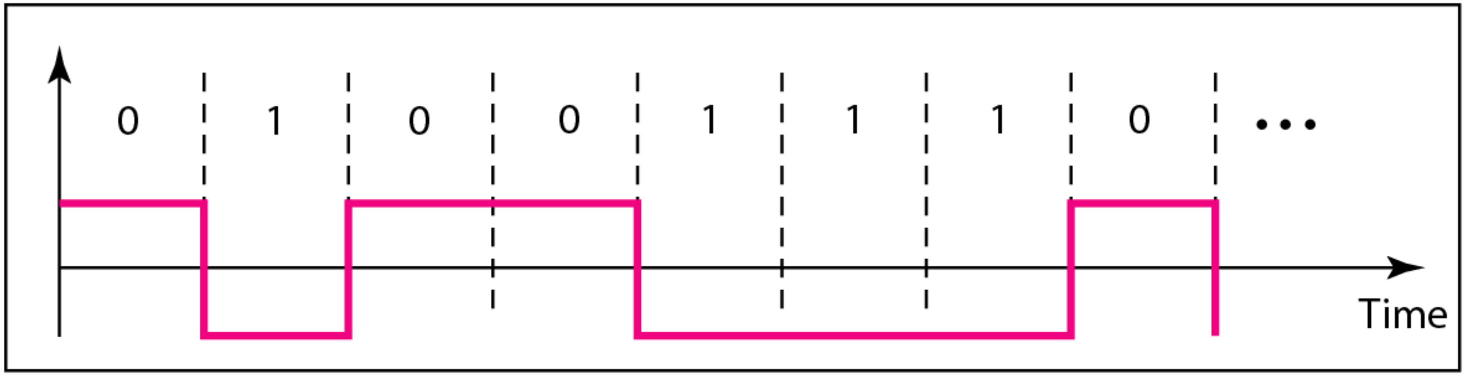
Nonreturn to Zero-Level (NRZ-L)



Unipolar NRZ-L

- **Unipolar NRZ-L** has two major shortcomings
  - It has a DC component, meaning that its average voltage is not 0 but some positive constant.
  - Lack of synchronization. If we have a long sequence of 0s or 1s, we won't be able to know how many we got.

Nonreturn to Zero-Level (NRZ-L)

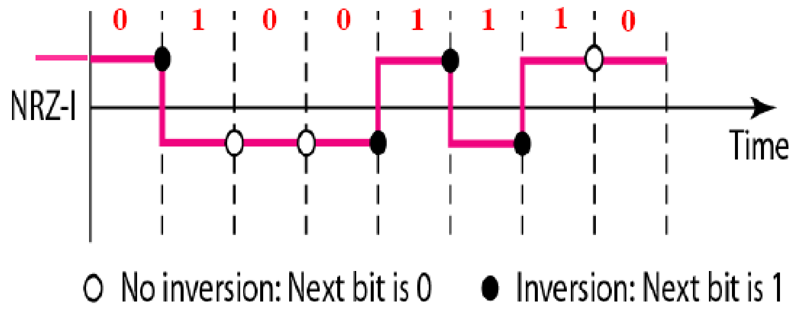


Polar NRZ-L

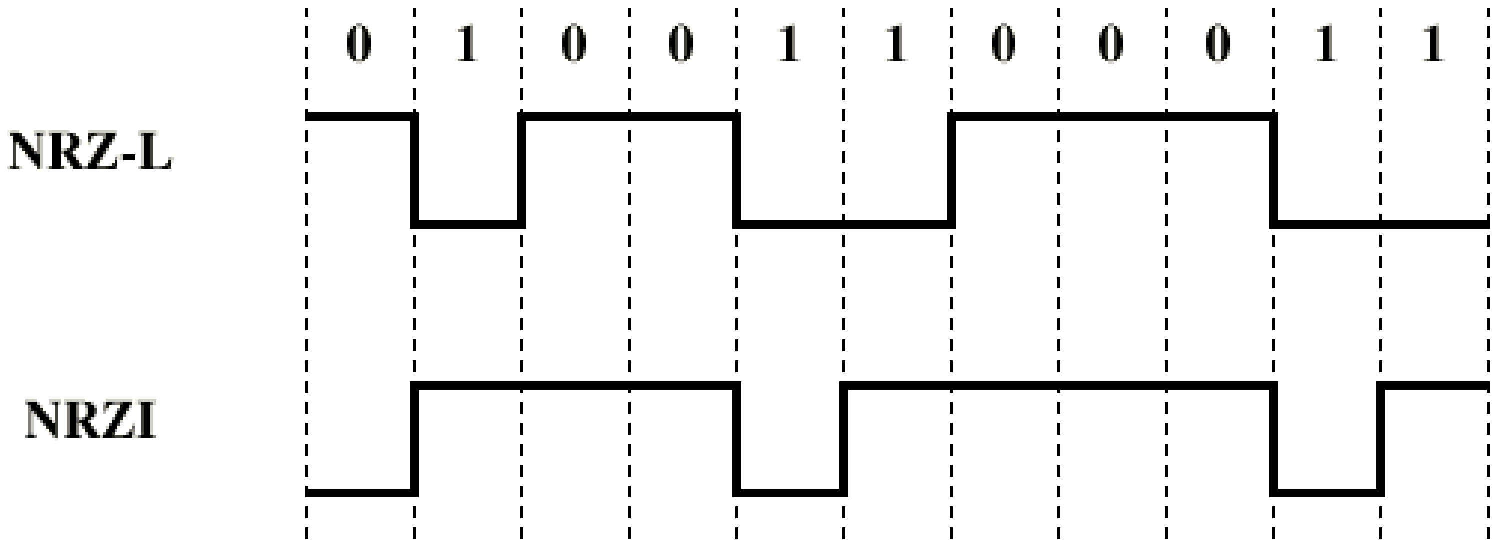
- **Polar NRZ-L** handles the DC component issue, meaning the average voltage level is 0.
- However, **long sequence of 0s or 1s leads to constant voltage level → Suffers from presence of dc component**
- It still has the **synchronization problem**.

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



NRZ



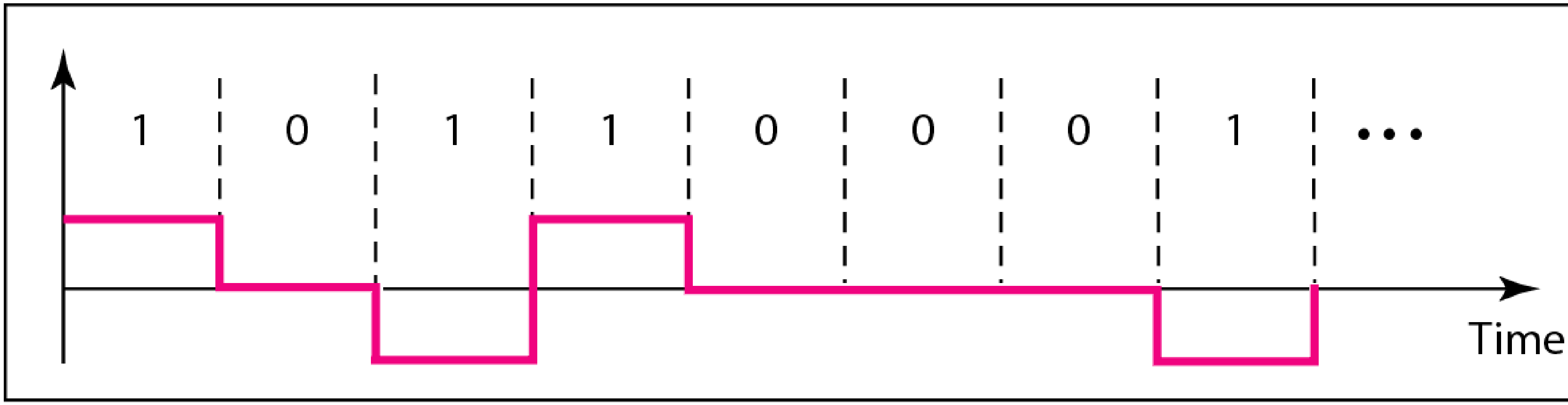
NRZ Pros & Cons

- **Pros**
  - **Easy** to engineer
  - Make **good use of bandwidth**
- **Cons**
  - Suffers from presence of **dc component**
    - long sequence of 0s or 1s → constant voltage level
  - **No synchronization** capability
    - long sequence of 0s or 1s → out of sync

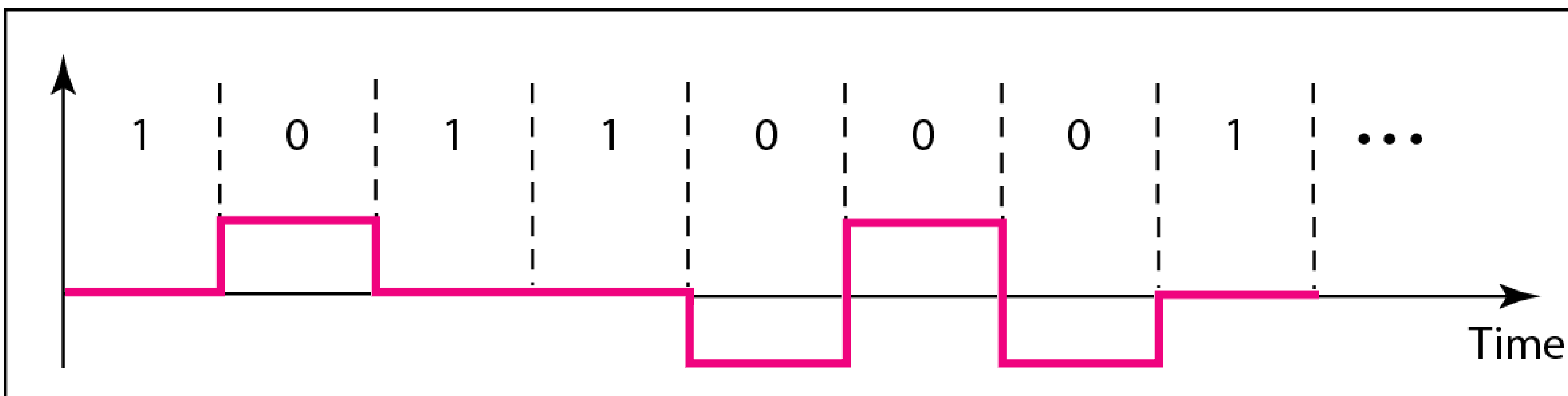
Multilevel Binary Bipolar-AMI

- 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**
  - **No net dc component**
  - **Lower bandwidth**
  - **Easy error detection**
  - **Long runs of zeros still a problem**

Multilevel Binary



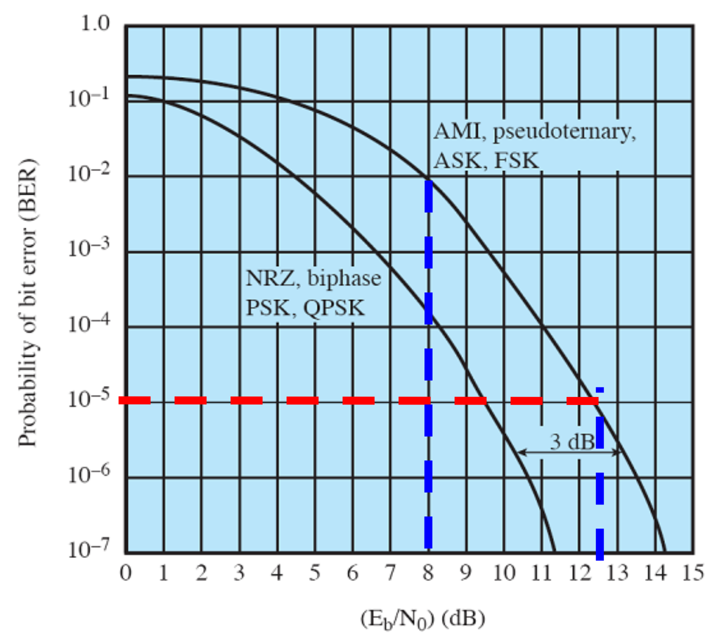
Bipolar-AMI



Pseudoternary

Multilevel Binary Issues

- Synchronization with long runs of 0's (AMI) or 1's (Pseudoternary)
  - can insert additional bits (ISDN)
  - scramble data (later)
- **Not as efficient as NRZ**
  - **Each signal element only represents one bit**
    - Receiver needs to distinguish between three levels: +A, -A, 0
  - **Requires approx. 3dB more signal power for same probability of bit error**



Biphase

- **Manchester** and **differential Manchester**
- Transition at the middle of each bit period
- **Manchester**
  - Mid-bit transition: data & clocking
- **Differential Manchester**
  - Mid-bit transition: clocking only
- Popular in data transmission
  - Used in Ethernet, coax and TP bus LANs

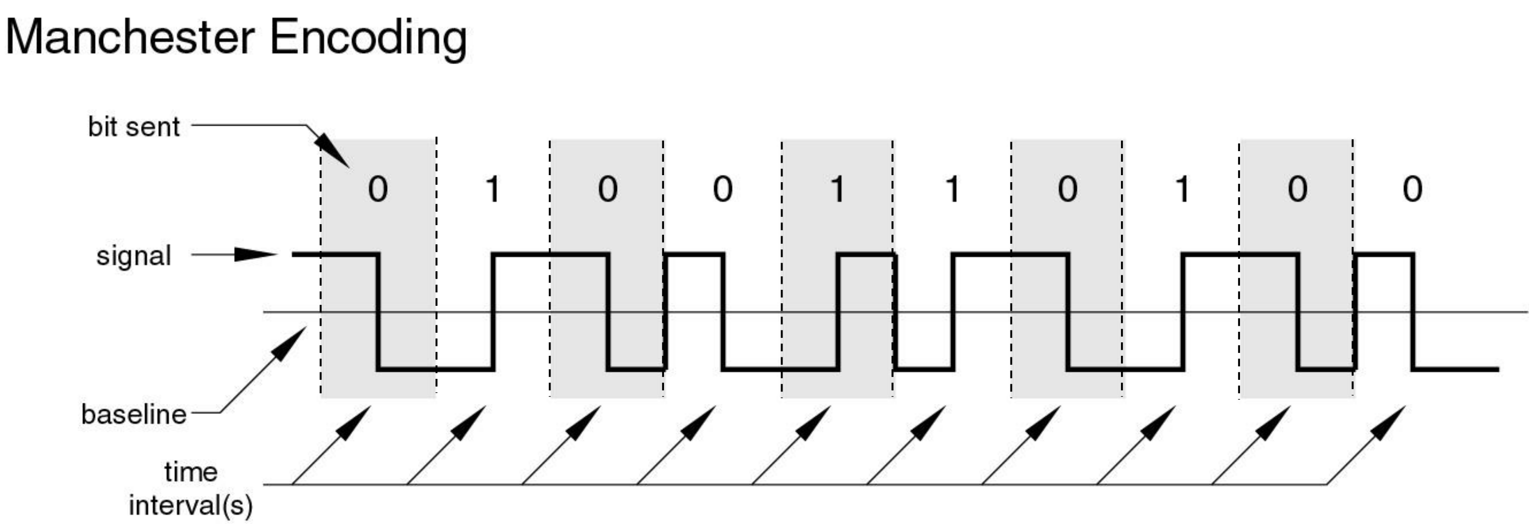
Biphase Features

- **Synchronization**
  - receiver can synchronize at transition
- **Clocking**
  - self-clocking code
- **Error detection**
  - absence of transition indicates error
  - noise invert two transition sides undetected
- **No dc component**

- **Disadvantage: more bandwidth**

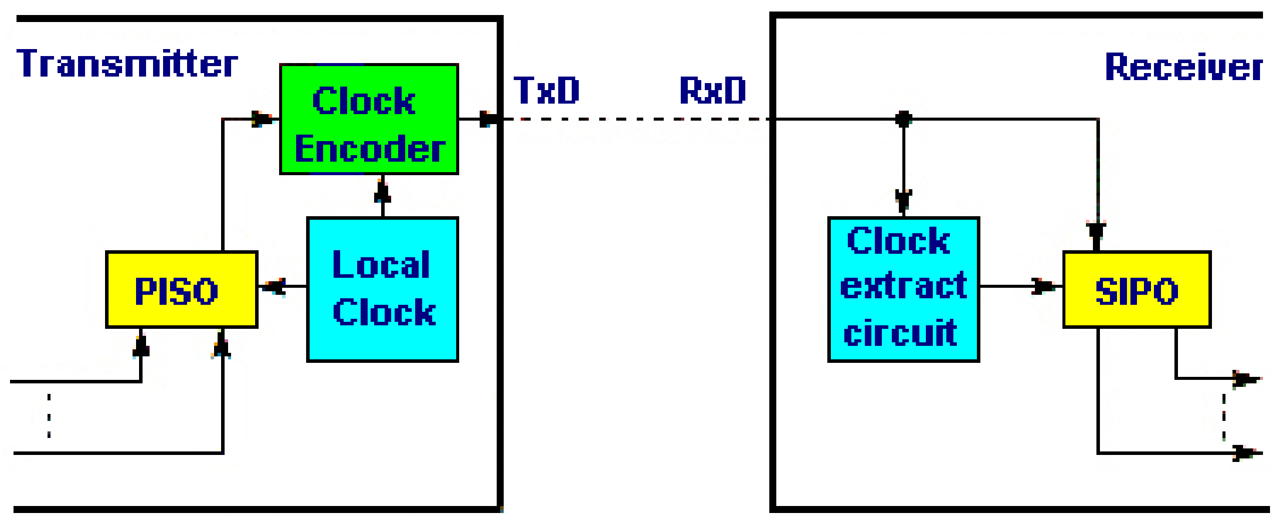
Manchester Encoding

- 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.



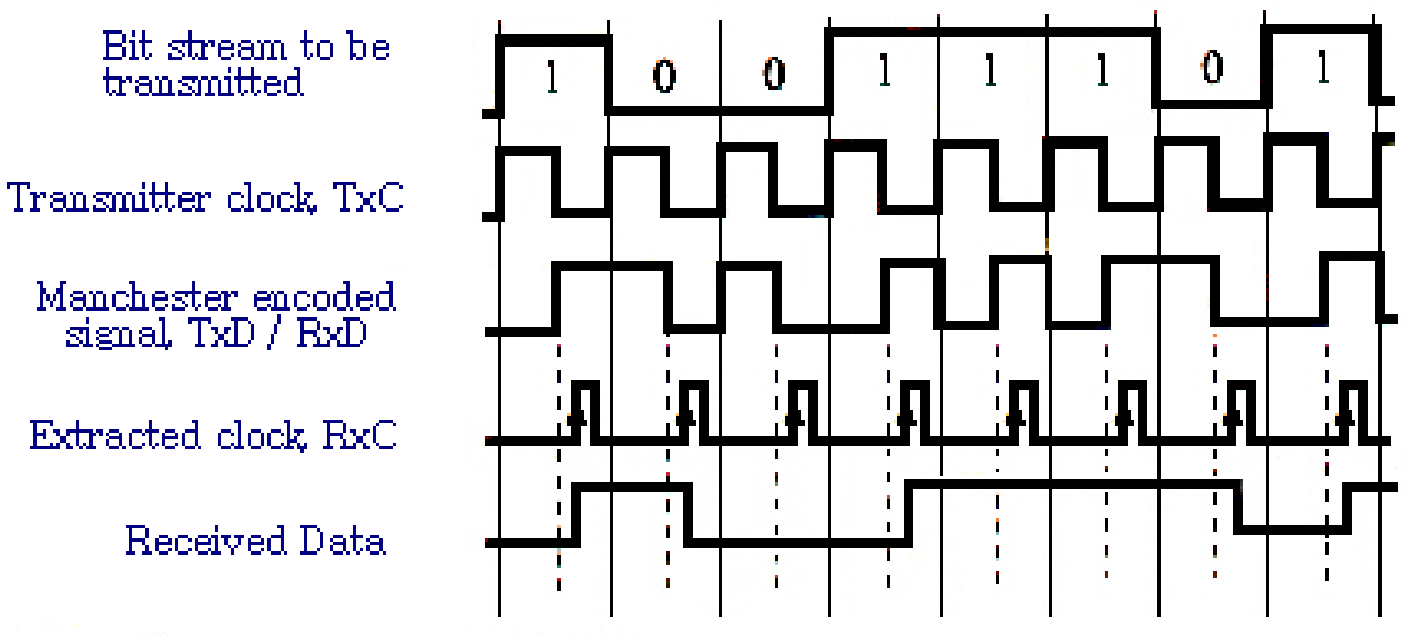
Manchester Encoding

Clock Encoding and Extraction:



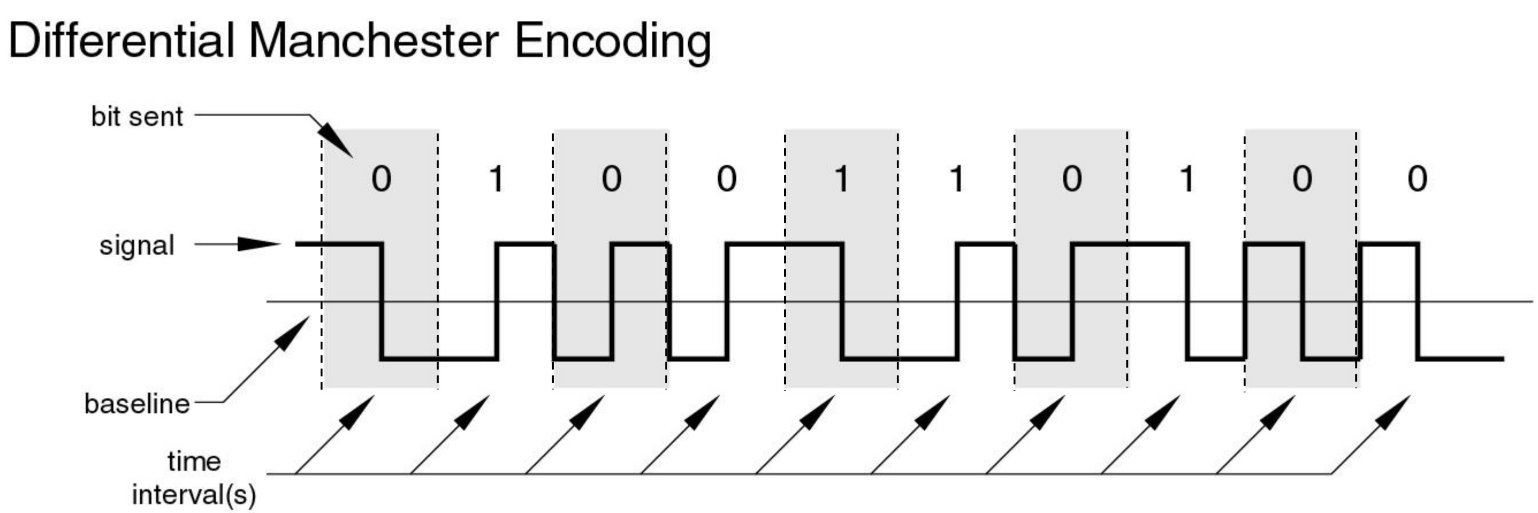
Manchester Encoding

Clock Encoding and Extraction:



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



Biphase Pros and Cons

- **Pros**
  - **Synchronization** on mid bit transition (self clocking)
  - Has **no dc component**
  - Has **error detection**
    - Absence of expected transition
- **Con**
  - At least one transition per bit time and possibly two
  - **Maximum modulation rate is twice NRZ**
  - Requires **more bandwidth**

Modulation Rate

- Because of encoding, data rate (bps) is different from modulation rate (baud)
- Modulation rate:

$$R_s = R/m = R / \log_2 M$$

  - R = data rate (bps)
  - m = bits per signal element = $\text{Log}_2 M$
  - M = number of different signal elements = 2^m

- **Number of transitions occur in bit time**
- **Depends on encoding and bit sequence**

Modulation Rate - Example

A signal has two data levels with a signal element duration of 1 ms. Calculate the modulation rate and data rate.

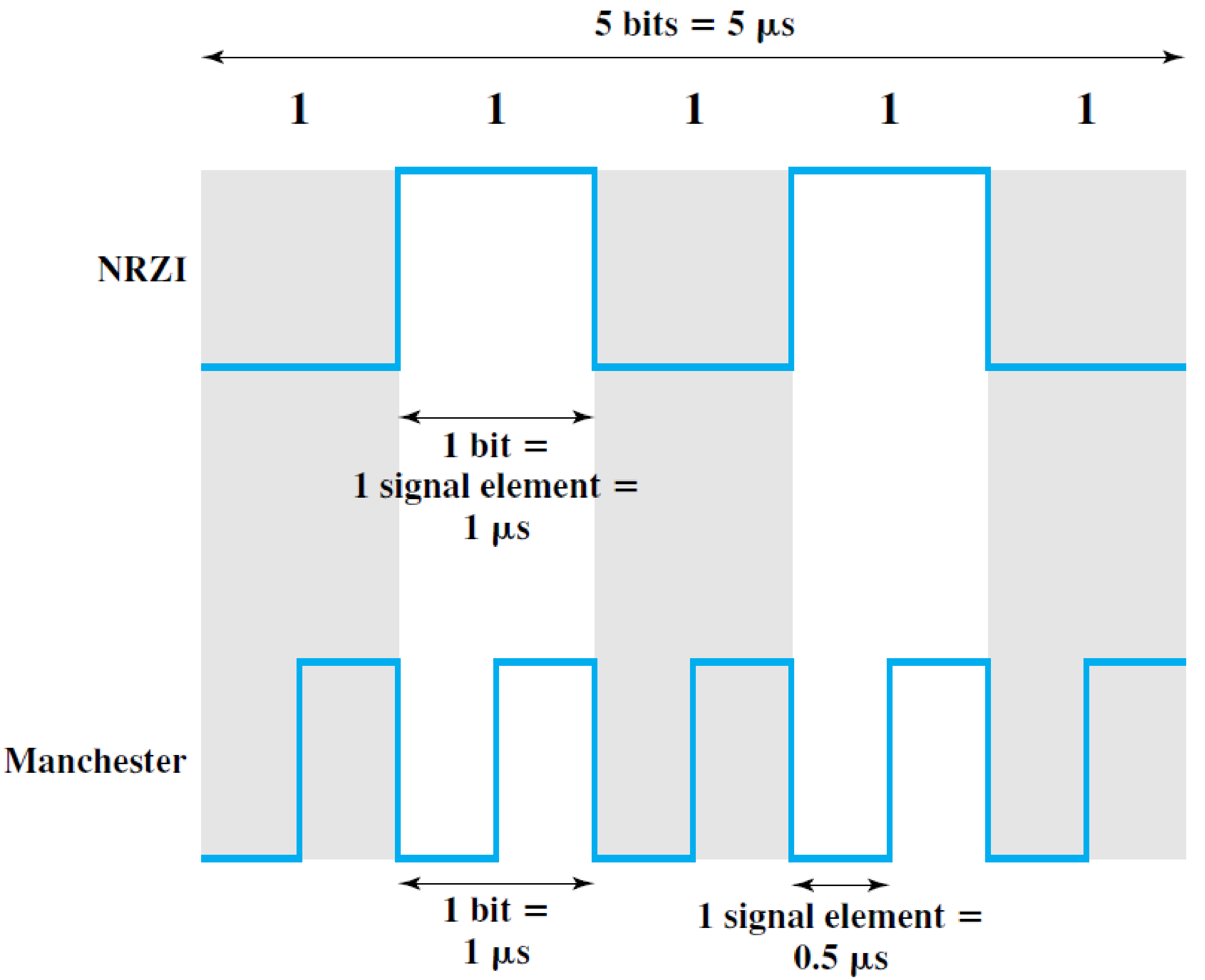
Answer:

Modulation rate = 1/ 1×10^{-3}= 1000 signal elements/ sec (baud)

$$\boxed{\mathbf{R = R_s \times \log_2 M = R_s \times m}}$$

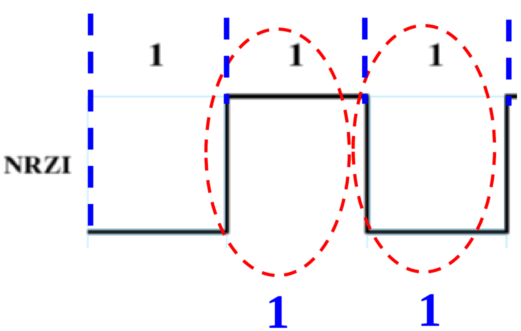
Data Rate = Modulation rate x $\log_2 2$ = 1000 bps

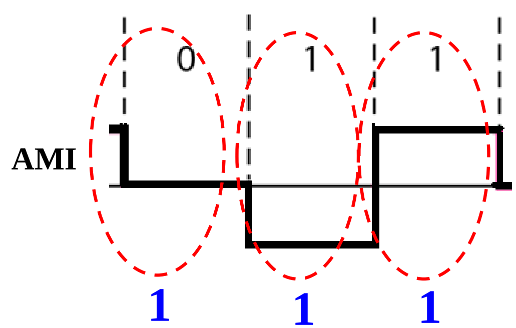
Modulation Rate

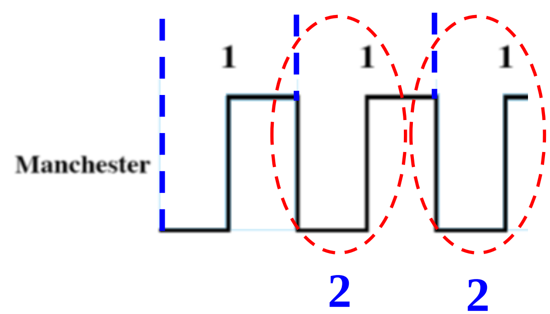


Number of Transitions

	Minimum	101010. . .	Maximum
NRZ-L	0 (all 0s or 1s)	1.0	1.0
NRZI	0 (all 0s)	0.5	1.0 (all 1s)
Bipolar-AMI	0 (all 0s)	1.0	1.0
Pseudoternary	0 (all 1s)	1.0	1.0
Manchester	1.0 (1010 . . .)	1.0	2.0 (all 0s or 1s)
Differential Manchester	1.0 (all 1s)	1.5	2.0 (all 0s)



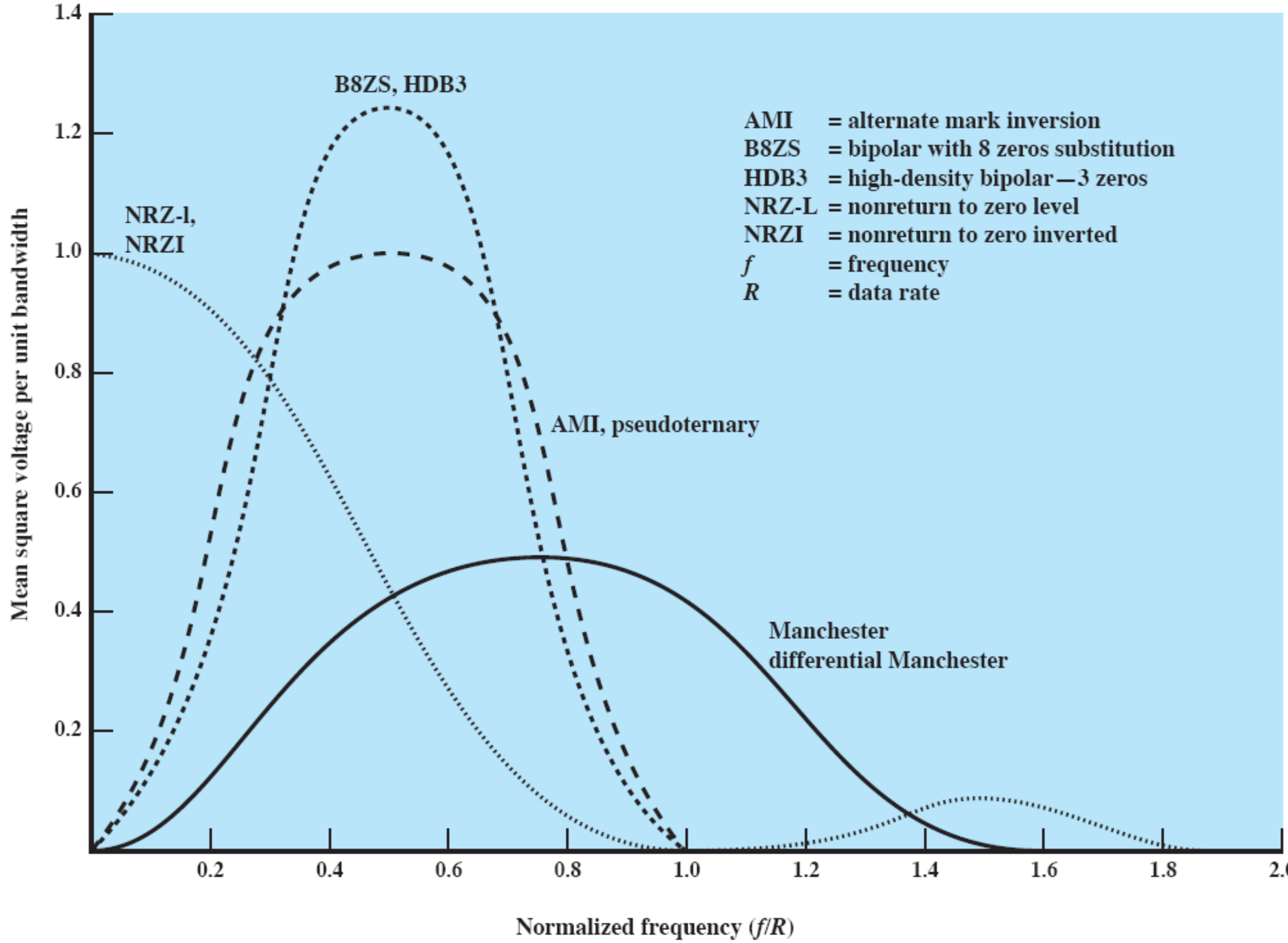




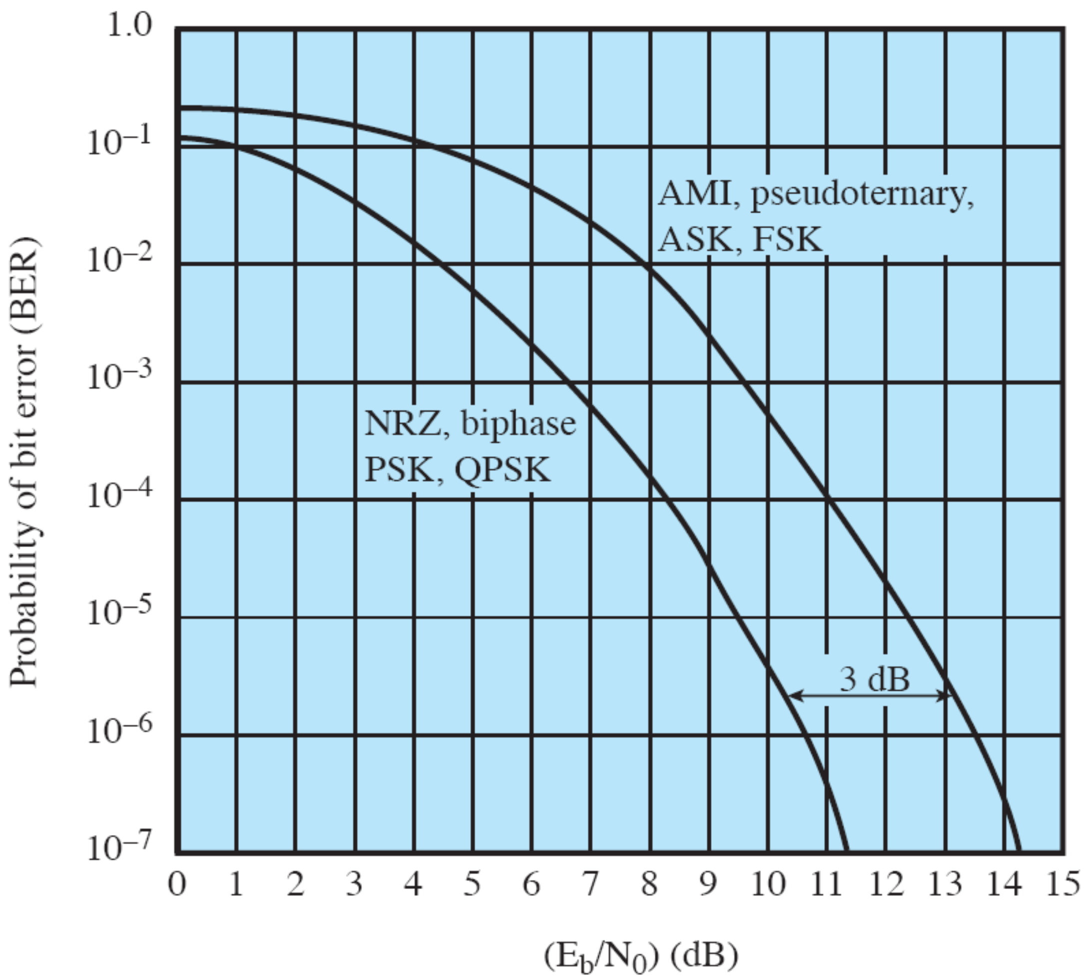
Number of Transitions

- For the 11-bit binary string **01001100011**, the number of transitions for the encoding schemes is:
  - **NRZ-L → 5**
  - **NRZI → 5**
  - **Bipolar – AMI → 7**
  - **Pseudoternary → 8**
  - **Manchester → 16**
  - **Differential Manchester → 16**

Encoding VS Spectral Density



Encoding VS Bit Error Rate



Comparison of Encoding Schemes

Encoding Scheme	DC Component	Synchronization	Error Detection	Noise Immunity	Clocking	Cost (Higher signal rate)
NRZ-L	Long sequence of 0s or 1s	Long sequence of 0s or 1s	No	Yes	No	No
NRZI	Long sequence of 0s	Long sequence of 0s	No	Yes	No	No
AMI	None	Long sequence of 0s	Yes (Pulses must alternate in polarity)	No (Requires approx. 3dB more signal power for same BER)	No	No
Pseudoternary	None	Long sequence of 1s	Yes (Pulses must alternate in polarity)	No (Requires approx. 3dB more signal power for same BER)	No	No
Manchester	None	Yes	Yes (Absence of transition)	Yes	Yes	Yes (2 transitions/bit for 0s or 1s)
Differential Manchester	None	Yes	Yes (Absence of transition)	Yes	Yes	Yes (2 transitions/bit for 0s)

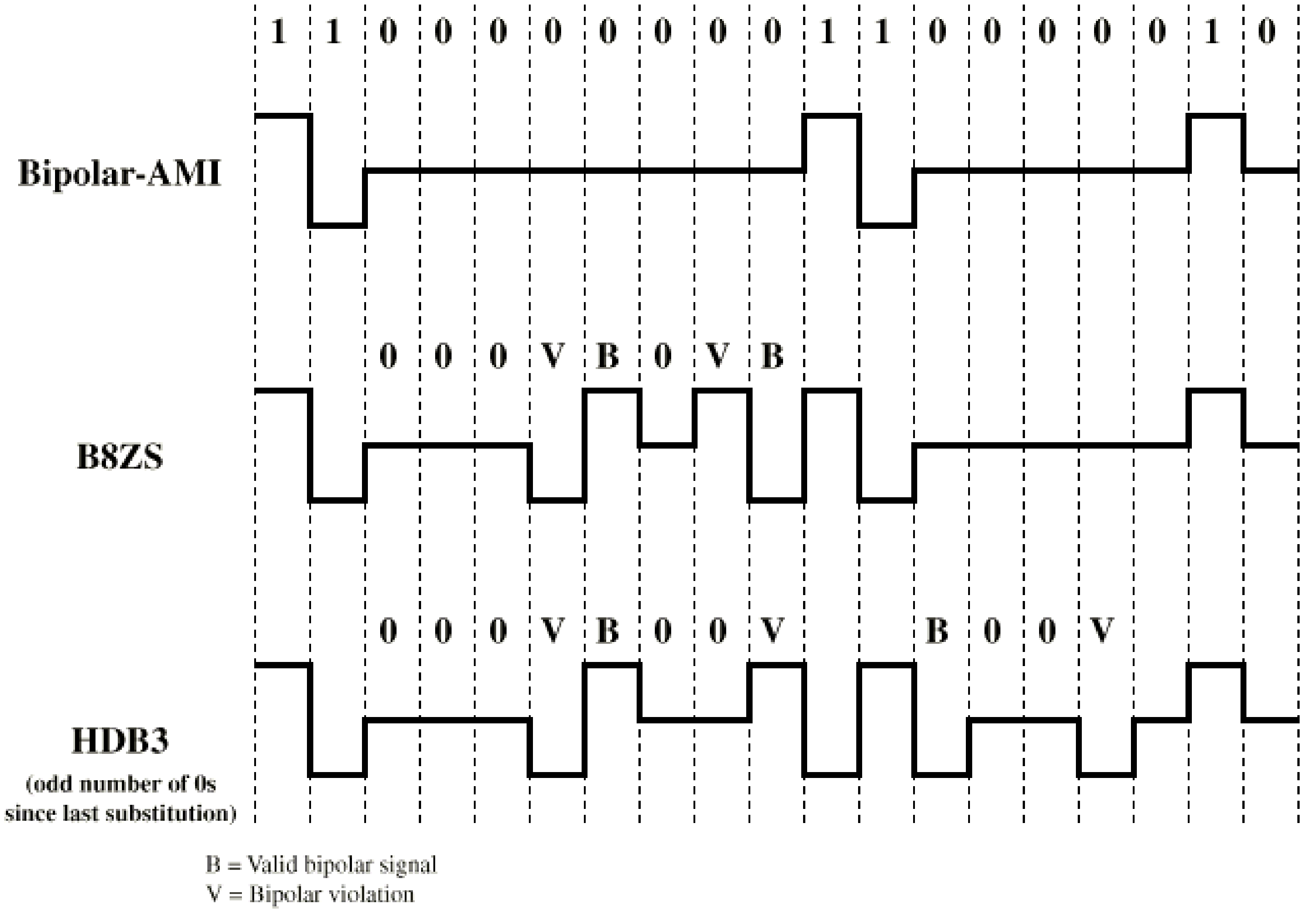
Scrambling

- use scrambling to replace sequences that would produce constant voltage
- Long series of 0s or 1s replaced with filling sequence provide sufficient transitions
- 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
- Receiver replace with original sequence

Scrambling Techniques

- Two main techniques:
  - **Bipolar with 8 zeros substitution (B8ZS)**
  - **High-density bipolar-3 zeros (HDB3)**

B8ZS and HDB3



Bipolar with 8-zeros substitution (B8ZS)

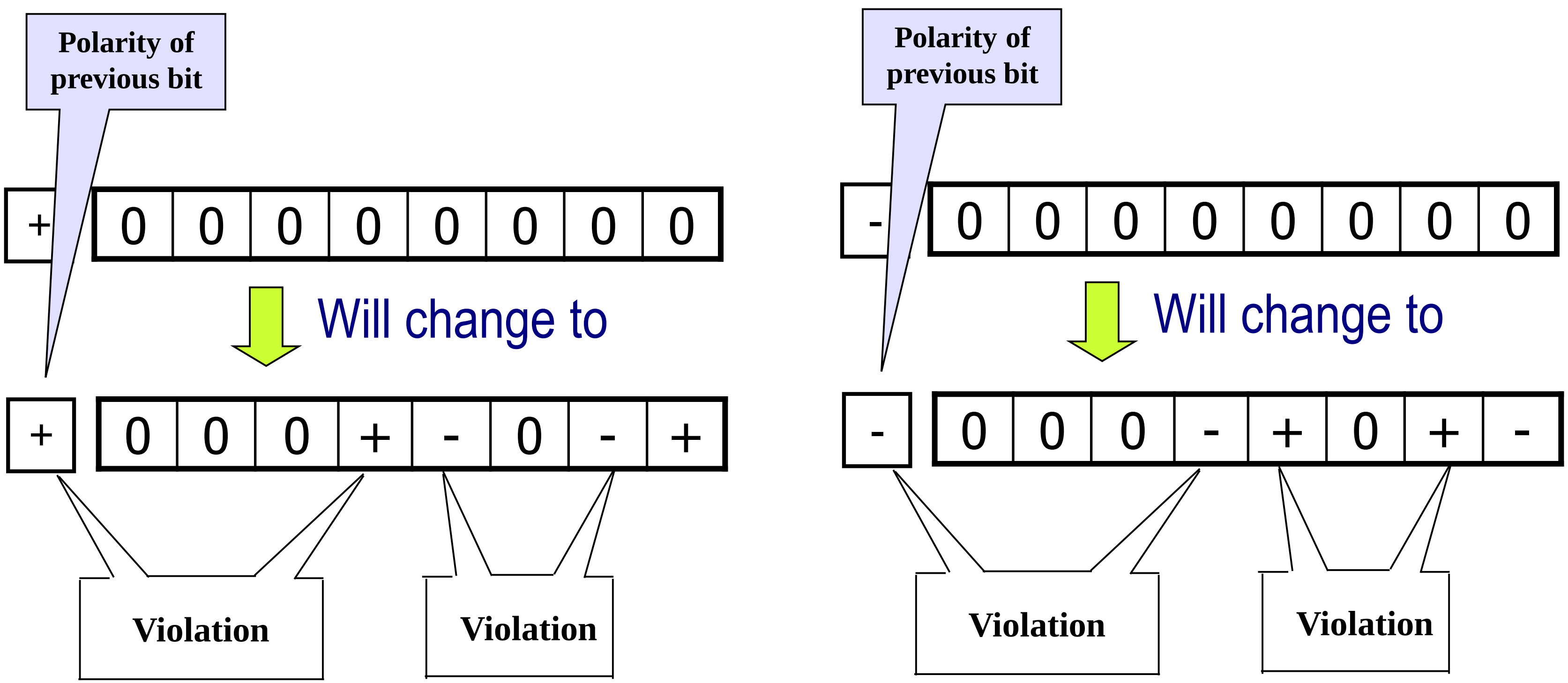
- ⌘ Bipolar With 8 Zeros Substitution
- ⌘ Based on bipolar-AMI
- ⌘ If octet of all zeros and last voltage pulse preceding was positive encode as 000+-0-+
- ⌘ If octet of all zeros and last voltage pulse preceding was negative encode as 000-+0+-
- ⌘ Causes **two violations** of AMI code
- ⌘ Unlikely to occur as a result of noise
- ⌘ Receiver detects and interprets as octet of all zeros

Bipolar with 8-zeros substitution (B8ZS)

Two code violations, not allowed by AMI

- 8 zero bits, preceding voltage positive
  - encode as 000+−0−+
- 8 zero bits, preceding voltage negative
  - encode as 000−+0+−

Bipolar with 8-zeros substitution (B8ZS)



High Density Bipolar 3 Zeros (HDB3)

- Based on bipolar-AMI
- String of four zeros replaced with one or two pulses
- 4 zeros, preceding +, odd number of pulses
  - encode as 000+
- 4 zeros, preceding +, even number of pulses
  - encode as −00−
- 4 zeros, preceding −, odd number of pulses
  - encode as 000−
- 4 zeros, preceding −, even number of pulses
  - encode as +00+

High Density Bipolar 3 Zeros (HDB3)

4 zeros → string with 1 or 2 code violations

⌘ Ensure successive violations of opposite polarity

	Number of Bipolar Pulses (ones) since Last Substitution	
Polarity of Preceding Pulse	**Odd**	**Even**
–	000–	+00+
+	000+	–00–

High Density Bipolar 3 Zeros (HDB3)

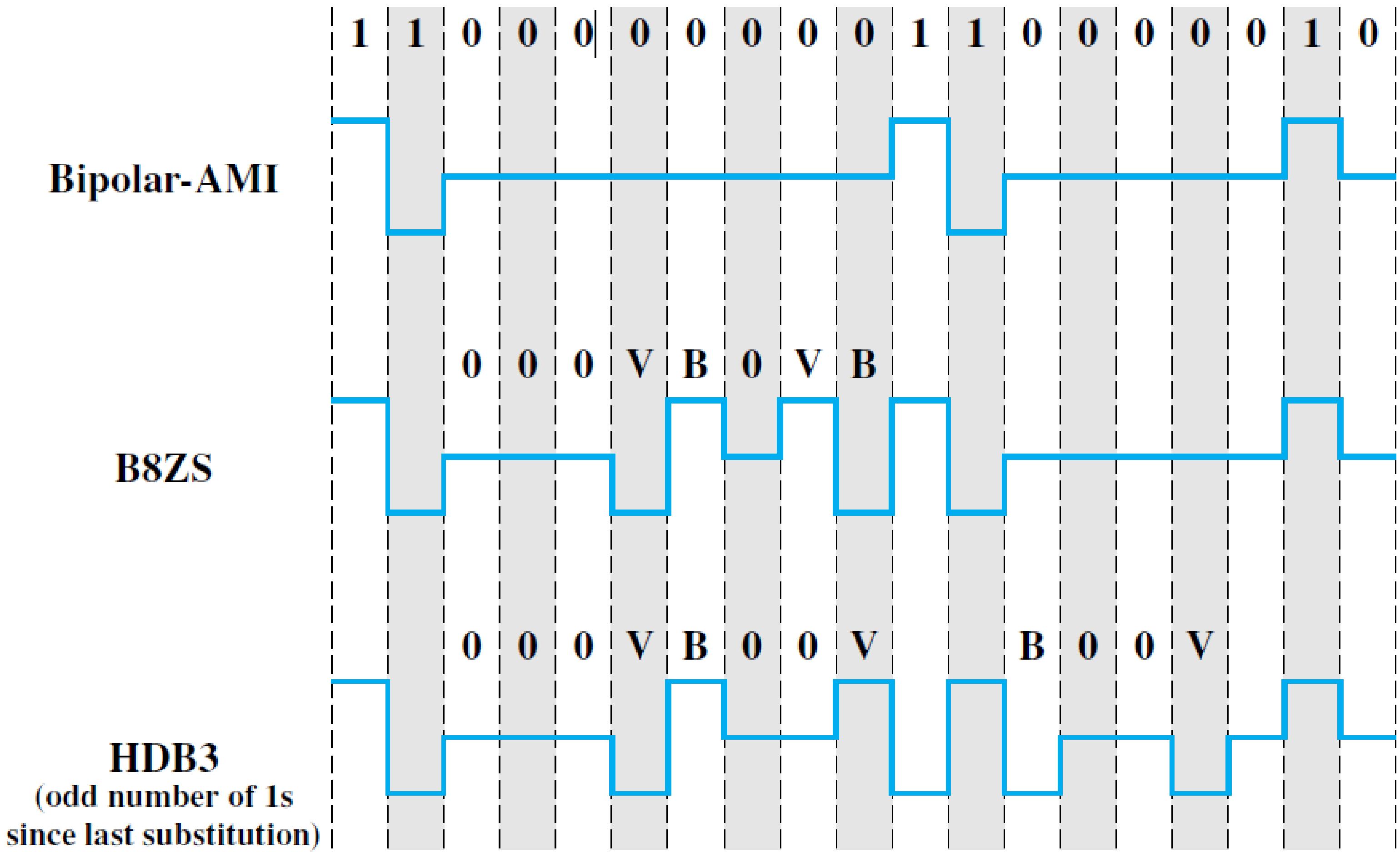
+	0	0	0	0		-	0	0	0	0
+	0	0	0	+		-	0	0	0	-

If the number of 1s since the last substitution is odd

+	0	0	0	0		-	0	0	0	0
+	-	0	0	-		-	+	0	0	+

If the number of 1a since the last substitution is even

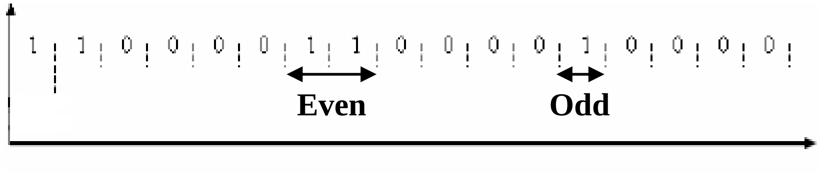
B8ZS and HDB3

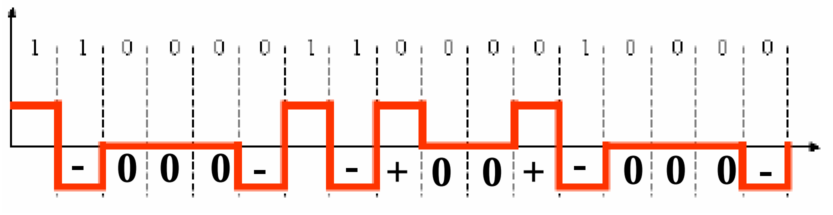


B = Valid bipolar signal
V = Bipolar violation

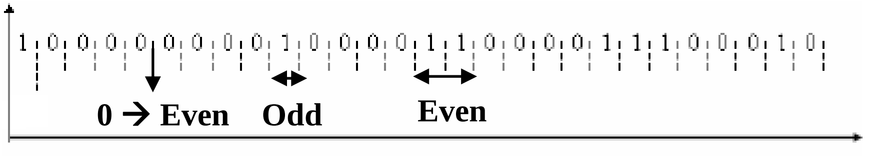
HDB3 - Examples

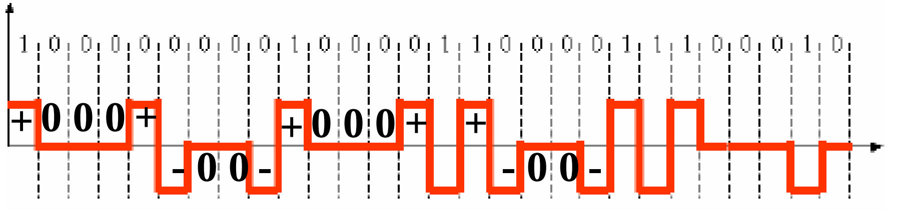
Example 1:





Example 2:





Summary

- looked at signal encoding techniques
  - digital data, digital signal
  - analog data, digital signal
  - digital data, analog signal
  - analog data, analog signal