CAN 1011: Data Communication

- Encoding & Modulation (Part 1)

Contents

- Encoding and Modulation (Part I)
  - ❑ Digital data into digital signals
  - ❑ Digital data into analogue signals

Four Data/Signal Combinations

		Signal	
		Analogue	**Digital**
Data	**Analogue**	- Same spectrum as data (baseband): e.g. Telephony - Different spectrum (carrier modulation): e.g. AM, FM, PM ④	Use a (converter): codec, e.g. PCM (pulse code modulation) ③
	Digital	Use a (converter): modem e.g. ASK, FSK, PSK ②	-Two signal levels: e.g. NRZ -More complex encoding: e.g. Manchester ①

Encoding Techniques

Digital data as digital signal

Digital data as analogue signal: Converter (modem)

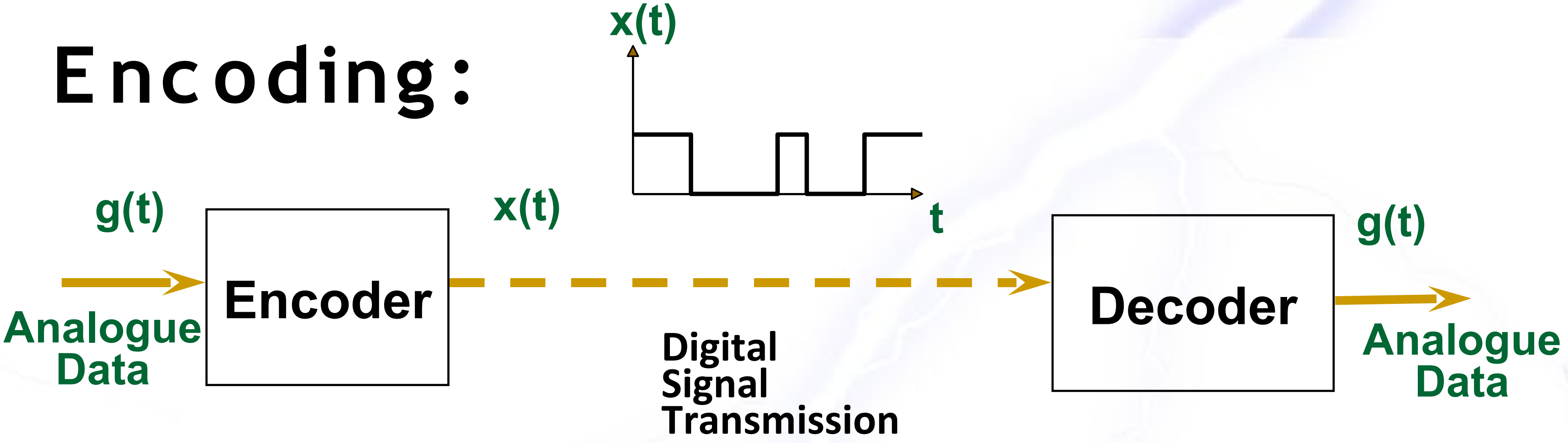
Analogue data as digital signal: Converter (codec)

Analogue data as analogue signal

In general:

- When the outcome is a <u>digital signal</u> we use an **Encoding** process
- When the outcome is an <u>analogue signal</u> we use a **Modulation** process
- The modulation of an <u>analogue signal</u> from digital data is called **shift-keying**

Encoding:



Analogue Data

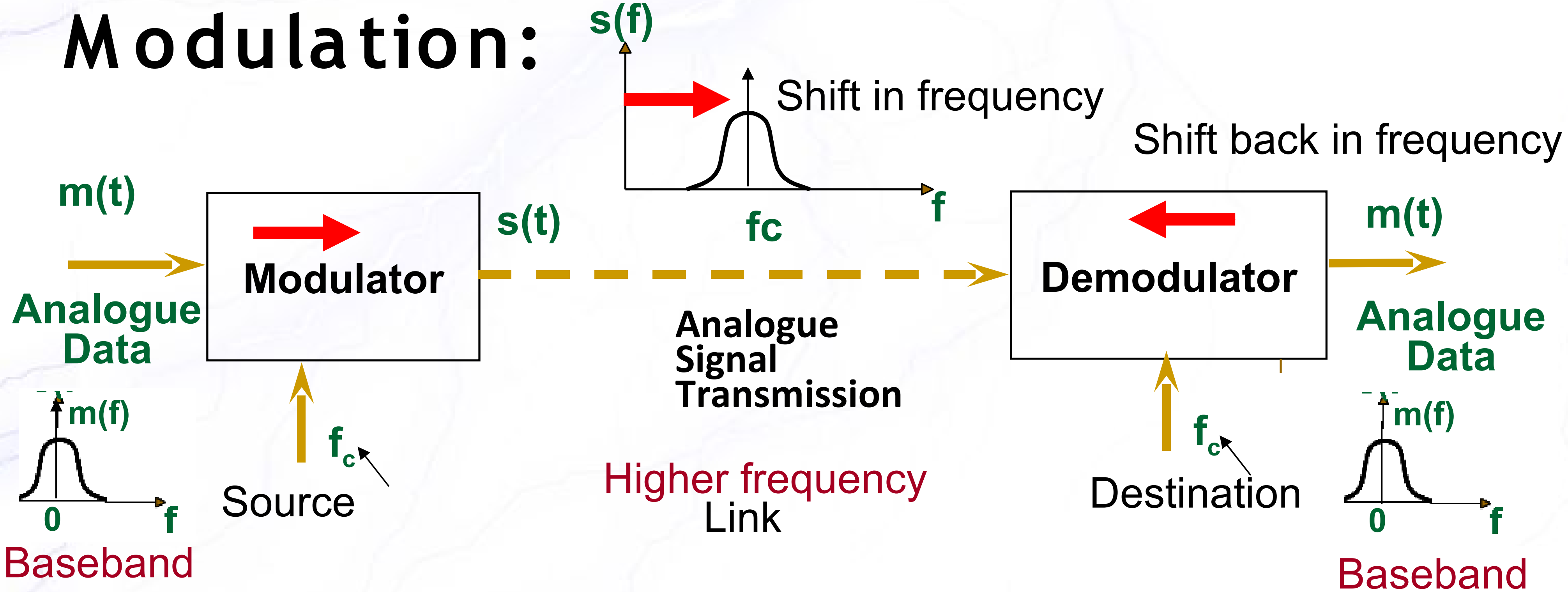
Encoder

Digital Signal Transmission

Decoder

Analogue Data

Modulation:



Shift in frequency

Shift back in frequency

Analogue Data

Modulator

Analogue Signal Transmission

Demodulator

Analogue Data

Baseband

Source

Higher frequency Link

Destination

Baseband

Encoding and Modulation: Remarks

- Encoding is simpler and less expensive than modulation
- Encoding into digital signals allows use of modern digital transmission and switching equipment
  - Basis for Time Division Multiplexing (TDM)
- Modulation shifts baseband signals to a higher region in the frequency spectrum (needs same f_cs at **both** ends)
  - Basis for Frequency Division Multiplexing (FDM)
- Optical fibers and unguided media can carry only analogue signals

Terminology

- **Unipolar Signals**
  - Binary data represented by signals of the *same* polarity, e.g. 0 -> +5 V, 1 -> +10 V ⇒ DC content
- **Bipolar (Polar) Signals**
  - Binary data represented by signals of *opposite* polarity, e.g. 0 -> +5 V, 1 -> -5 V ⇒ ideally Zero DC content
- **Mark and Space**
  - Binary 1 and Binary 0 respectively
- **Duration of a bit (T_b)**
  - Time taken for transmitter to emit a data bit
- **Data rate, R (= $1/T_b$)**
  - Rate of data transmission measured in **bits per second (bps)**
- **Duration of a Signal Element (T_s)**
  - Minimum duration of a signal pulse
- **Modulation (signaling) rate, D ($1/T_s$)**
  - Rate at which the signal level changes with time measured in **bauds = signal elements per second**

Not always Tb = Ts !!!
e.g. Multi-symbol transmission
(M = 4, 8, …): Tb < Ts

Example: Two different coding methods

Data rate = 1/1µs

= 1 Mbps

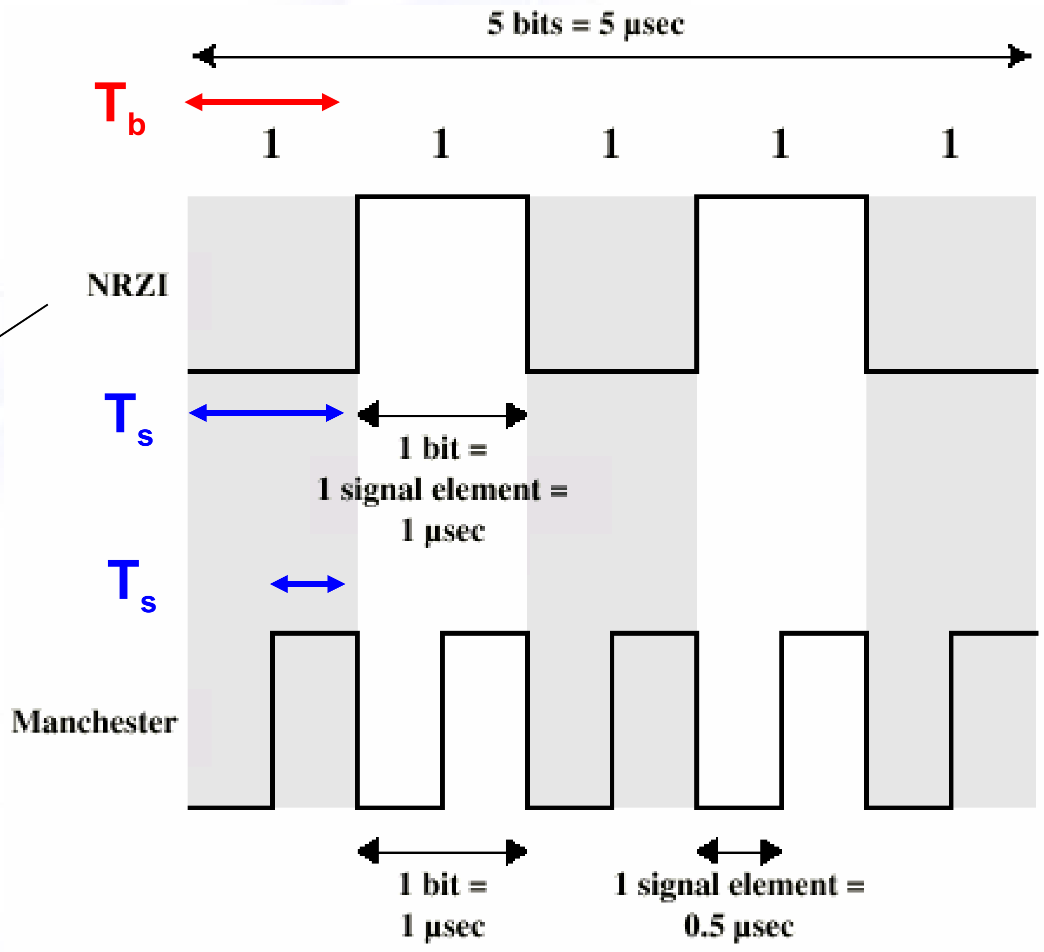
(in both cases)

Signaling Rate for NRZ-I: = 1/1µs

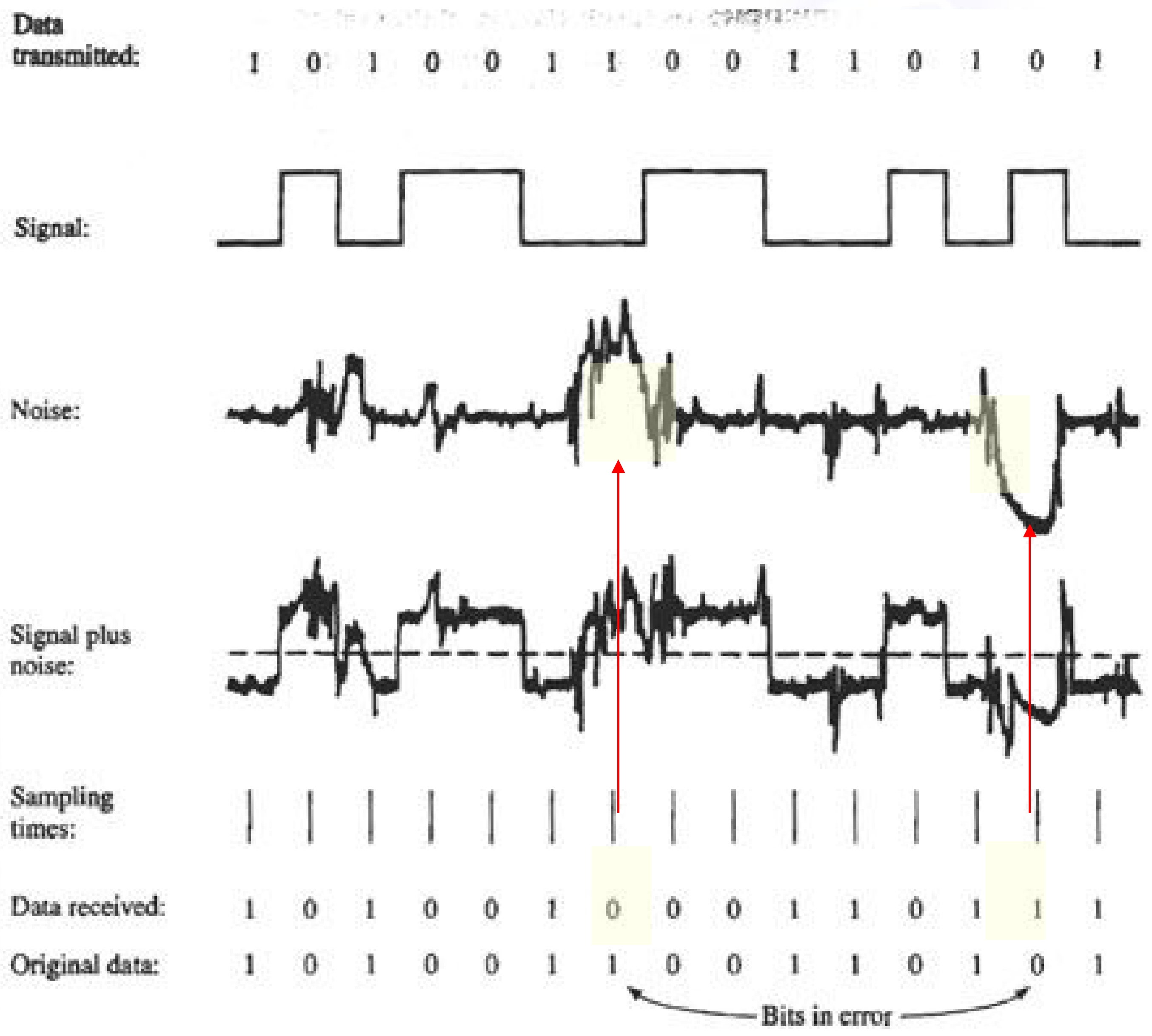
= 1 Mbauds

Signaling Rate for Manchester: = 1/0.5µs

= 2 Mbauds



Interpretation of the Received Signal



Interpreting Received Signals

- Requirements at RX:
  - Determine timing of bits – Bit start and end (When to look)

    ⇒ Need Synchronization (later)
  - Detect signal levels at mid-bit points
  - Compare signal level with a threshold level to decide on data
- Factors affecting successful signal interpretation (Affect bit error rate)
  - Bandwidth
  - Signal to noise ratio
  - Data rate
  - **Also Encoding/Modulation scheme, e.g. binary or multi-level**

1. Digital Data, Digital Signal

- Digital signal
  - Voltage/current pulses having a few discrete levels (2 levels for binary)
  - Each pulse is a signal element
  - Binary data is encoded into those signal elements
  - Encoding is the mapping of data to signal elements

Encoding Schemes

Schemes for encoding digital data as digital signals

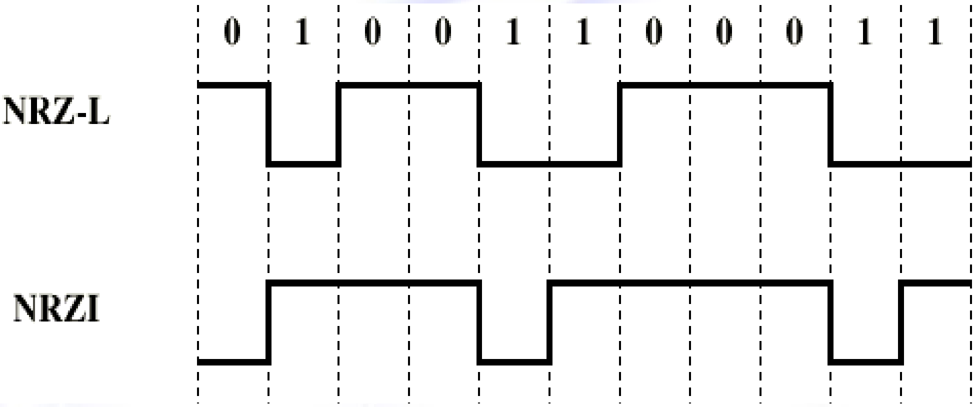
- **Non-return to Zero** (NRZ) Group:
  - Non-return to Zero-Level (NRZ-L)
  - Non-return to Zero Inverted (NRZ-I)
- **Multi-level Binary** Group:
  - Bipolar-AMI (Alternate Mark Invert)
  - Pseudoternary
- **Bi-Phase** (RZ) Group:
  - Manchester
  - Differential Manchester
- **Scrambling** Group:
  - B8ZS (Bipolar with 8-Zeros Substitution)
  - HDB3 (High Density Bipolar 3-Zeros)

Aspects of comparison between schemes

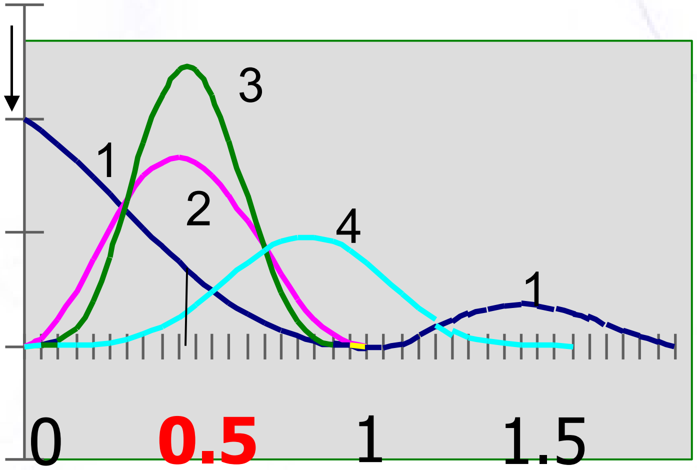
- **Clocking:** Synchronizing RX to TX can be achieved using:
  - An external clock, or better:
  - A built-in synchronizing mechanism in the **signal** itself! (so, a code with many signal transitions is better)
- **Error detection**
  - Mostly handled by higher layers, e.g. data-link control
  - But error detection capabilities built into the signal encoding scheme would help!

    Advantage: Implemented much faster (in hardware)
- **Performance with interference and noise**
  - Some encoding schemes perform better than others: e.g. with differential encoding: data is encoded as signal transition/no signal transition, and data detection at RX is **less affected by noise.**
- **Cost and complexity**
  - Some codes require signaling at a rate greater than the data rate (e.g. RZ) At higher signaling rates this requires higher bandwidth, faster circuits, etc. (larger costs)

NRZ Group
Pros and Cons:



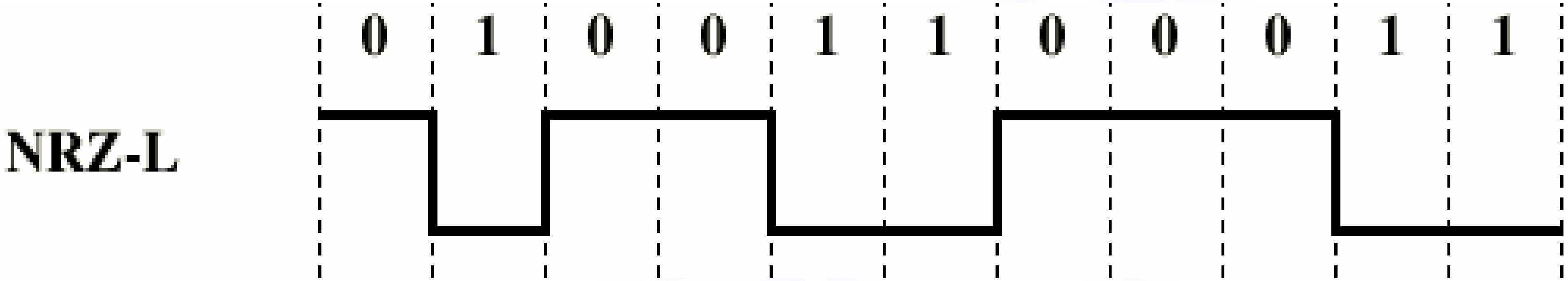
- Pros
  - Easy to implement
  - Modest bandwidth requirements
- Cons
  - Large DC component
  - Poor TX-RX synchronization:



e.g. **No signal transitions for long strings of 0’s or 1's**
(so few edges are available for synchronization)

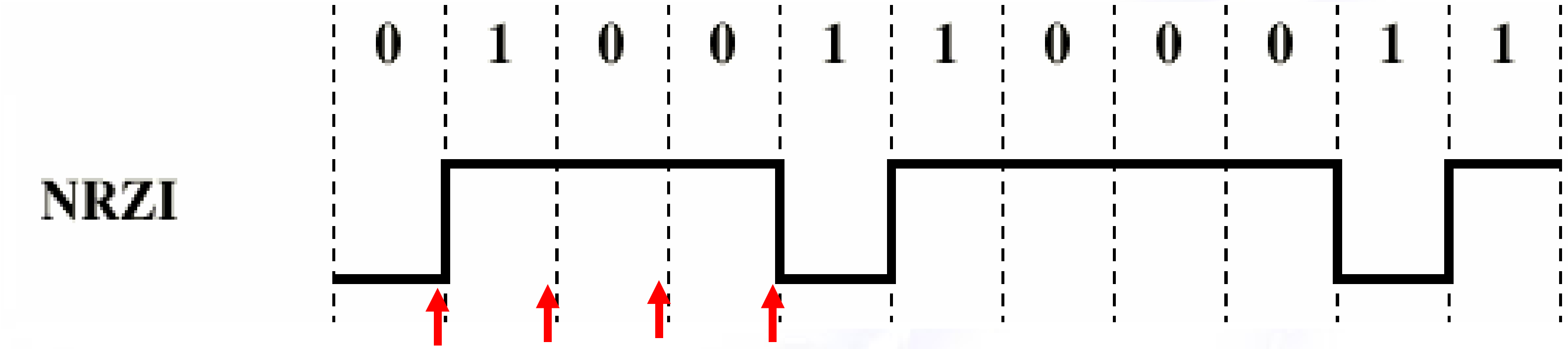
- Used for magnetic recording
- Not used much for signal transmission

NRZ-L: Non-return to Zero Level



- Two different signal voltages for the 0 and 1 data bits
- Voltage level is constant (no return to zero, so no signal transition) for the full duration of the data bit interval
- e.g. positive voltage for space and 0V for mark
- More often, negative voltage for one data value and positive for the other (bipolar signal) (Why?)
- An example of absolute encoding: Mapping data **directly** to signal **levels**

NRZ-I: Non-return to Zero Invert

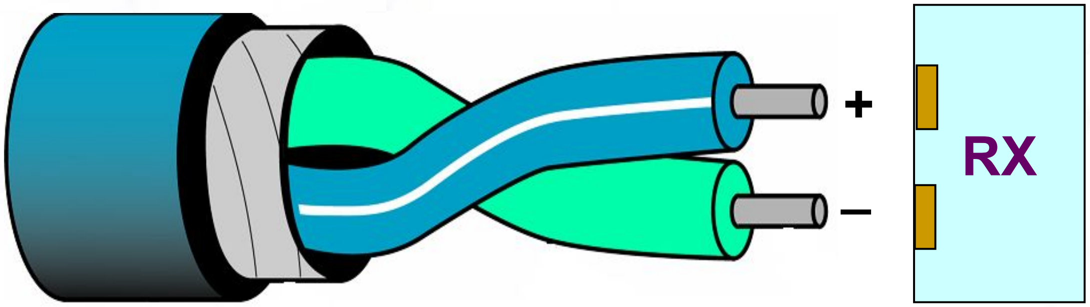


- Still constant voltage level for bit duration of (hence NRZ)
- But data is encoded as presence or absence of signal transition at the beginning of bit time:
  - Transition (low to high or high to low): Denotes binary 1
  - No transition: Denotes binary 0
- This is an example of differential encoding:Encoding data as a change/no change in signal level.

Differential Encoding

- Data is represented by signal transitions rather than signal levels
- Advantages;
  - With noise, signal transitions (or lack of them) are detected more easily than signal levels ⇒ Better noise immunity
  - In complex transmission layouts, it is easy to accidentally lose sense of polarity

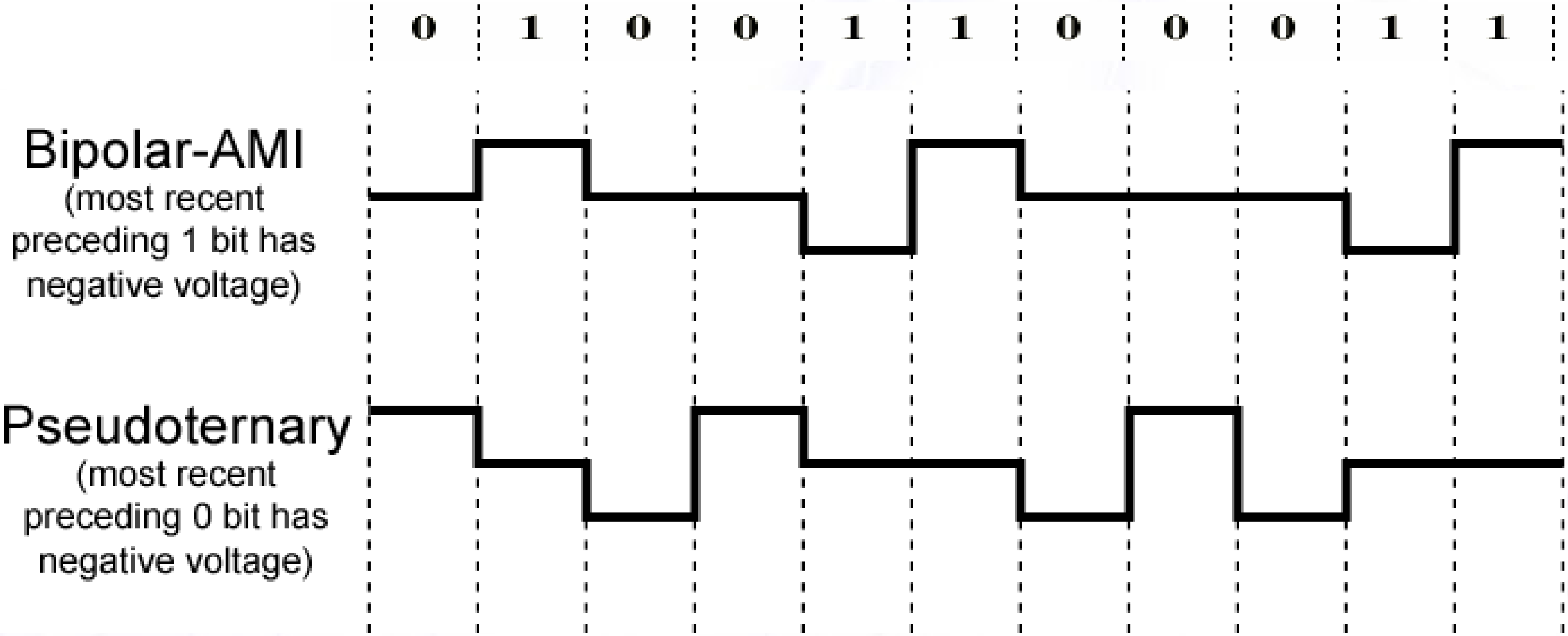
Effect of swapping terminals on:
- NRZ-L
- NRZI



The Multilevel Binary Group

- Uses more than two signal levels (3 in this case)
- Signal is multi-level but data is still binary!
- Bipolar-AMI (Alternate Mark (1) Inversion)
  - 0 data is represented by no line signal
  - 1 data represented by positive or negative pulse
  - The “1” pulses alternate in polarity (why? 2 reasons!)
  - Advantages:
    - No net DC component (for any data sequence!)
    - Lower bandwidth than NRZ
    - No loss of sync with a long string of 1’z
      (but zeros still a problem- Will try to solve it later)
    - Alteration of pulse polarity also useful for error detection

Bipolar-AMI and Pseudoternary



Pseudoternary

- Opposite of Bipolar-AMI:
  - 1 represented by no line signal
  - 0 represented by alternating positive and negative pulses
- Could be called Bipolar-ASI: (Why?)
- No advantage or disadvantage over bipolar-AMI

The Multilevel Binary Group: Advantages

- No net DC component
- Spectrum centered at the middle of the BW
- Lower bandwidth than NRZ
- No loss of sync with a long string of 1'z
  (but zeros still a problem- Will try to solve it later)
- Alteration of pulse polarity also useful for error detection: Next slide

Disadvantages of Multilevel Binary

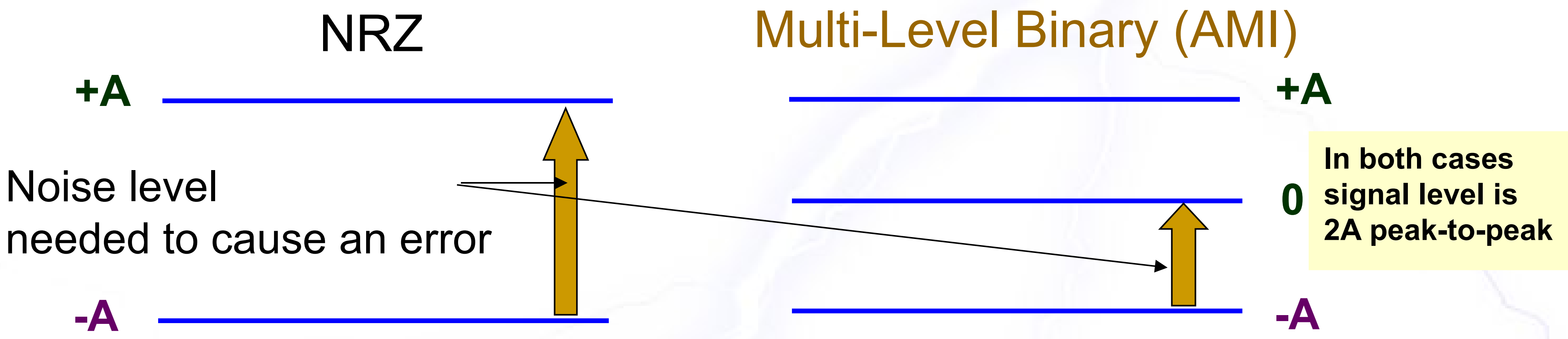
$N = \text{Log}_2\,(M)$

No. of bits sent during each signal element

No. of signal levels used

- Coding scheme not as efficient as NRZ:
  - We send only one bit at a time (1 or 0 data)
    $\Rightarrow$ Only $M = 2^1 = 2$ signal levels should be enough, but we are sending 3 levels > 2 !
  - We use 3 levels $\Rightarrow$ Enough to represent $\log_2 3 = 1.58$ bits > 1 bit !
- Receiver Design and Noise Performance
  - Now receiver must distinguish between three signal levels (+A, -A, 0) $\Rightarrow$ Need better receiver design
  - Requires approximately 3dB higher SNR for the same probability of bit error (bit error rate)

Performance with noise: NRZ Vs AMI



NRZ

Multi-Level Binary (AMI)

+A

Noise level
needed to cause an error

-A

+A

0

-A

In both cases signal level is 2A peak-to-peak

- For the same error rate: AMI requires higher SNR noise (lower noise)
  ⇒ i.e. higher E_b/N_0 (for same B and R)

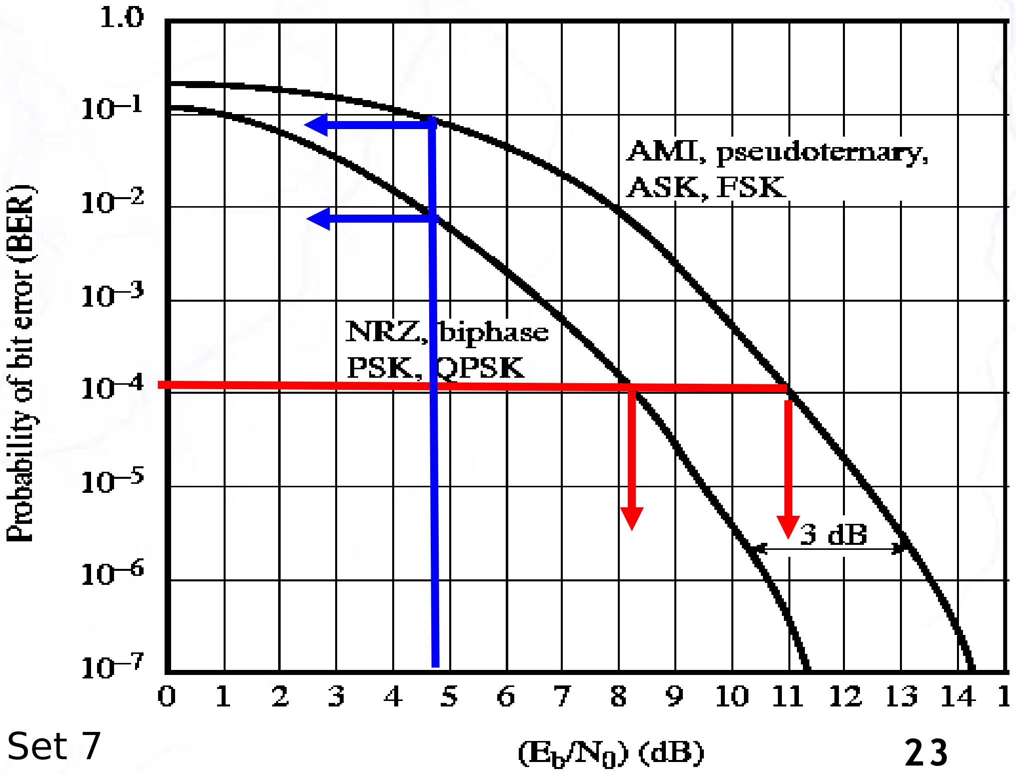
(hence the 3 dBs difference between the two curves)

- For the same SNR (same E_b/N_0)

AMI has higher error rate

- i.e. AMI has poorer performance with noise

$$\frac{E_b}{N_0} = SNR\left(\frac{B}{R}\right)$$



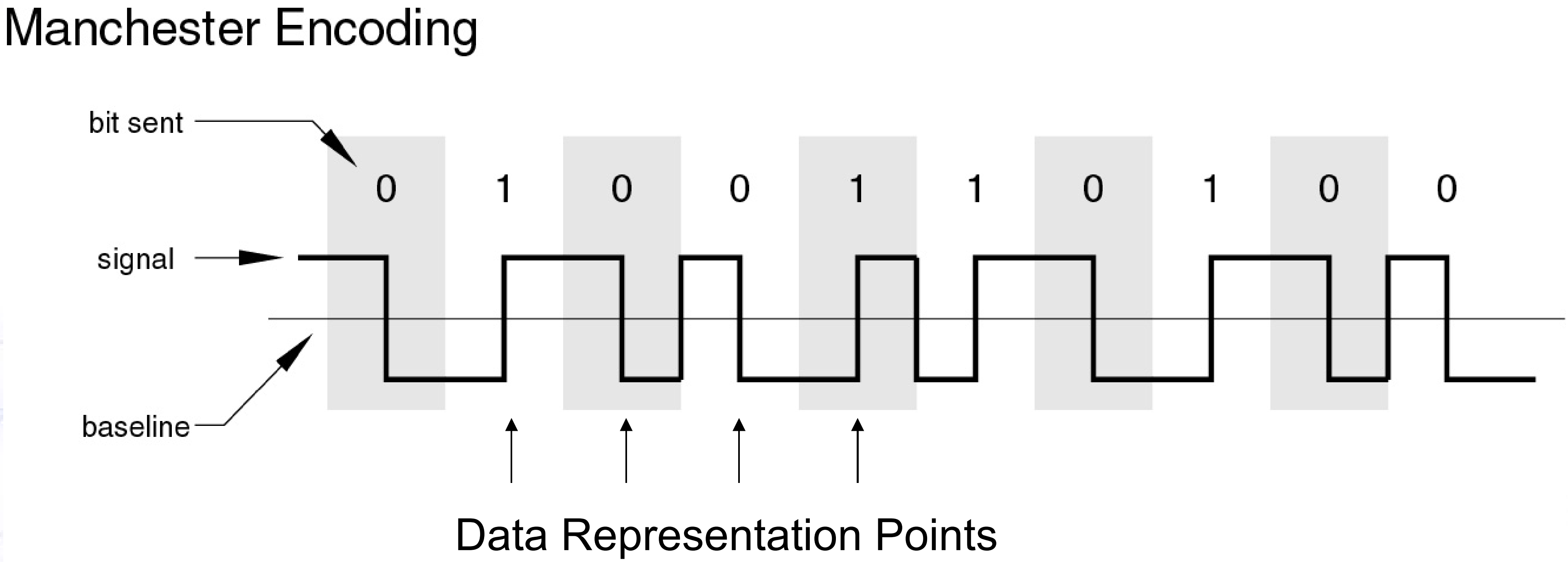
The Biphase Group (2 signal phases per bit)

- Manchester
  - Transition in middle of each bit period
  - Transition serves both as a clock edge and data representation
    - Low to high represents 1
    - High to low represents 0
  - Used by the IEEE 802.3 specification for Ethernet LAN (short distances)
- Differential Manchester
  - Dedicated mid-bit transition used **only** for clocking
  - Data representation is at start of bit:
    - No transition at start of a bit period represents 1
    - Transition at start of a bit period represents 0
      (Inverts on 0’s – opposite of NRZ-I)
  - An example of differential encoding
  - Used by IEEE 802.5 specification for Token Ring LAN

Manchester Encoding

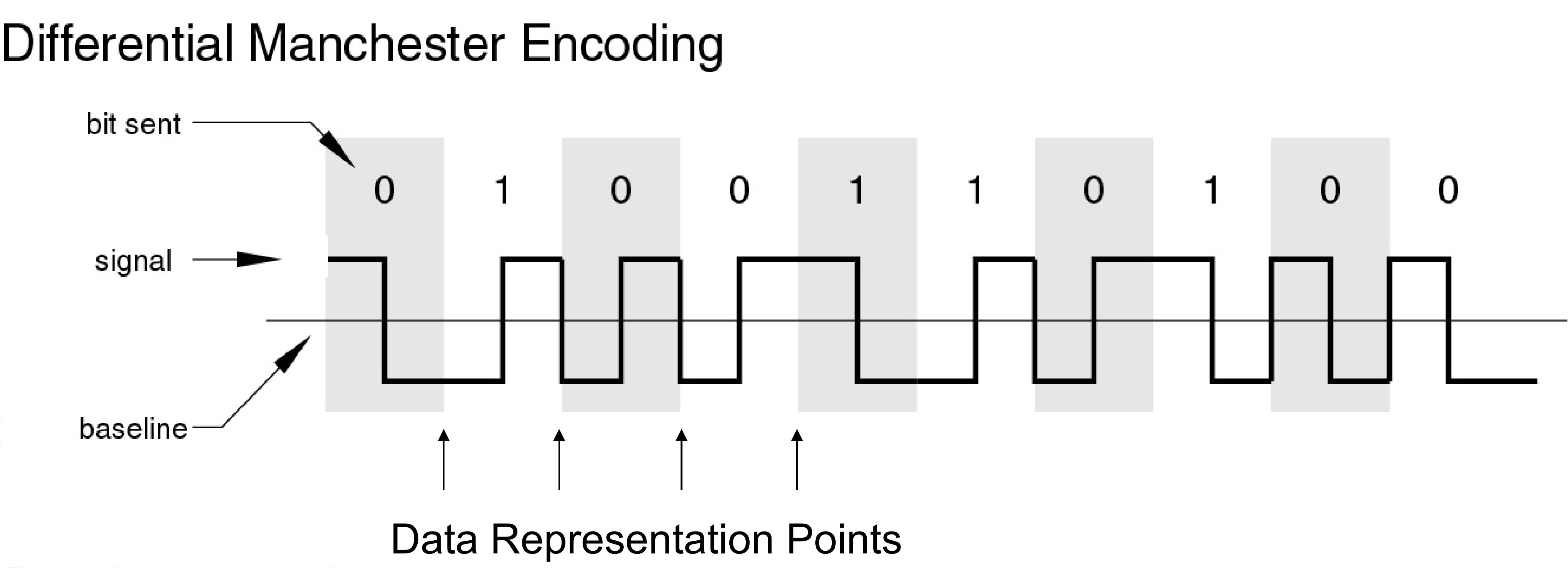
- Mandatory transition in middle of each bit period
  → Low to high represents 1
  → High to low represents 0
- Transitions at start of bit only where required

Note: This is not differential



Differential Manchester Encoding

- Mandatory mid-bit transition for clocking
- Data represented by transition or no transition at bit start:
  - → Transition (either direction) represents 0 (Invert on zeros)
  - → No transition represents 1



Biphase Pros and Cons

- Pros
  - Guaranteed mid bit transitions
    - Synchronization facility (self clocking codes)
  - Ideally no dc component (using bipolar signals)
  - Error detection
    - Detecting absence of expected (mandatory) transitions
- Cons
  - At least one transition per bit time and possibly two
    - Modulation (signaling) rate as high as twice that of NRZ
    - So, requires more bandwidth
    - Therefore, used over shorter distances (in LANs)

Data rate & Modulation (signaling) rate

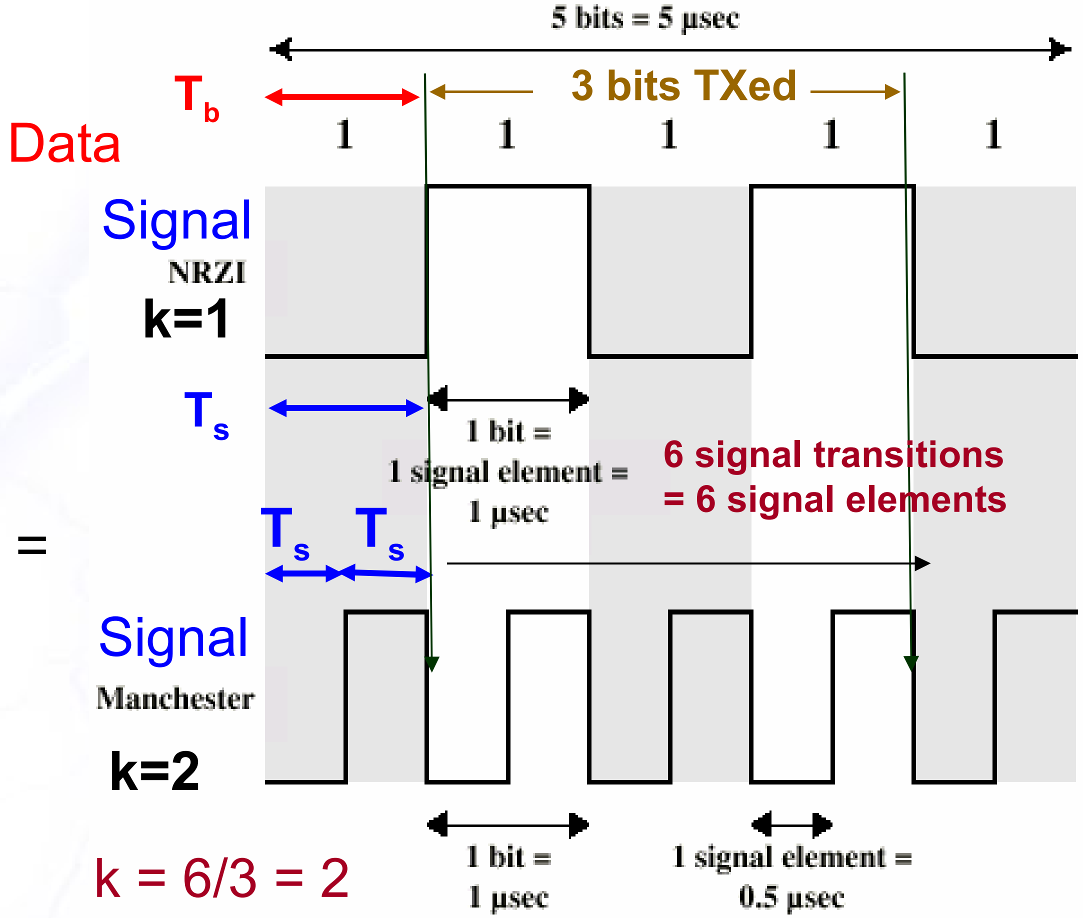
- Data rate, R = 1/T_b bps
- Signaling Rate, D = 1/T_s bauds

If we use k signal elements per bit, then:

- Signaling (modulation) rate, D = Data rate, R (bit/s)

x k (signal elements/bit)

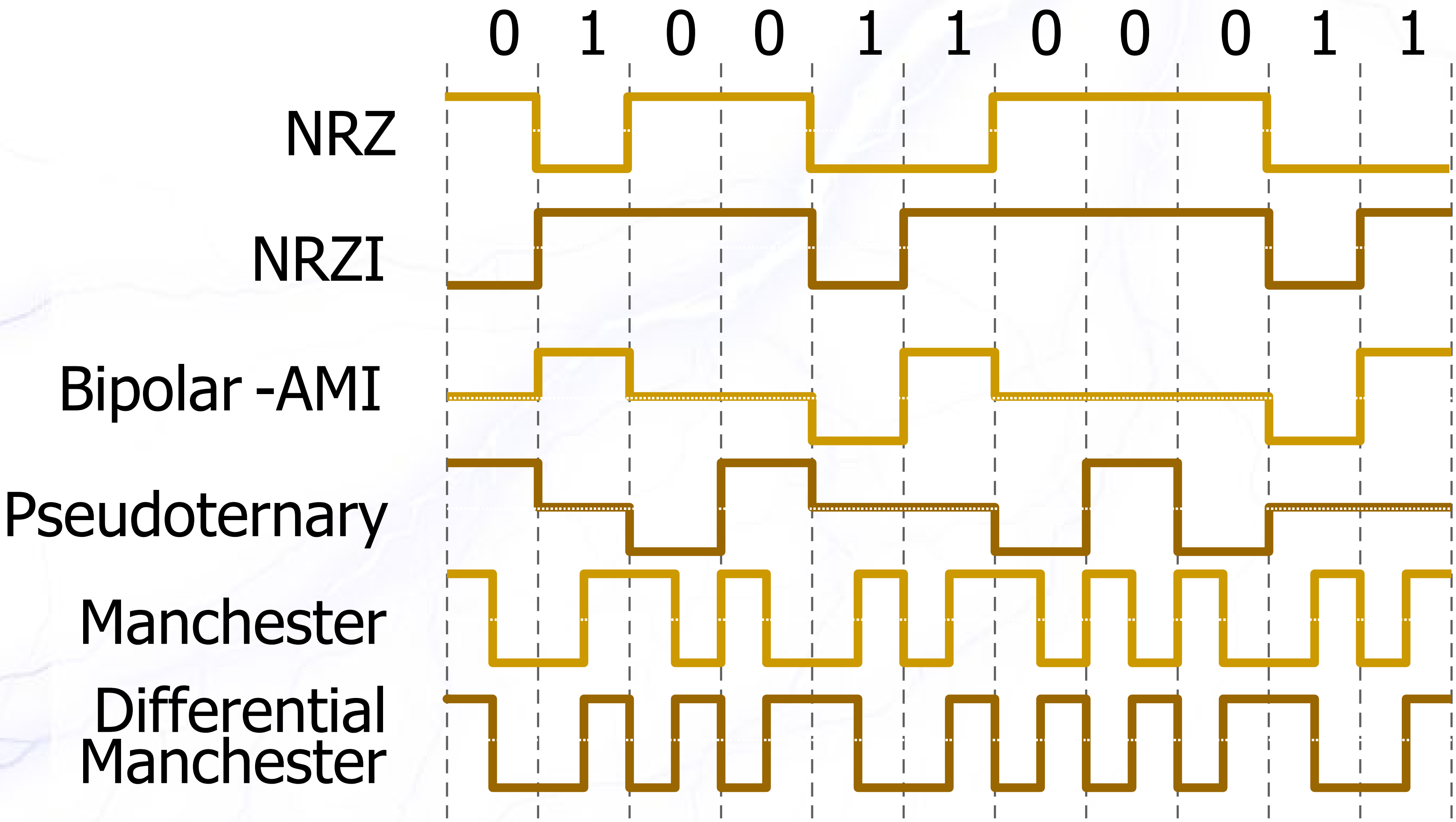
Signal elements/s (bauds)



- k = No. of signal elements/bit

= No. of signal transitions (both ways)÷ No. of bits transmitted, n (over a given period of n T_bs)

1. Digital data, Digital signal Encoding



Scrambling Group: B8ZS, HDB3

- Use bit scrambling to replace data bit sequences that would otherwise produce a constant signal voltage, with a more appropriate bit sequence producing signal changes
- Helps overcome constant DC problems with Multilevel Binary codes (poor synchronization)
- So, a “filling” (replacement) bit sequence is inserted where necessary
- Criteria for a “Filling sequence”
  - Should produce enough transitions for synchronization
  - Must be recognized by receiver for replacement with original data
  - Not likely to be generated by noise (difficult for noise/interference to produce it)
  - Should occupy the same bit length as original data (so no extra overhead in the data rate)

Scrambling Group: B8ZS, HDB3

- Advantages:
  - No long sequences of zero level line signal
  - No DC component
  - No reduction in useful data rate (No extra data sent)
  - Built-in error detection capability

B8ZS

- Bipolar With 8 Zeros Substitution
- Improvement on bipolar-AMI
- If an octet of 8 zeros and the last pulse preceding was positive (+):Transmitter encodes the 8 zeros as 000+-0-+

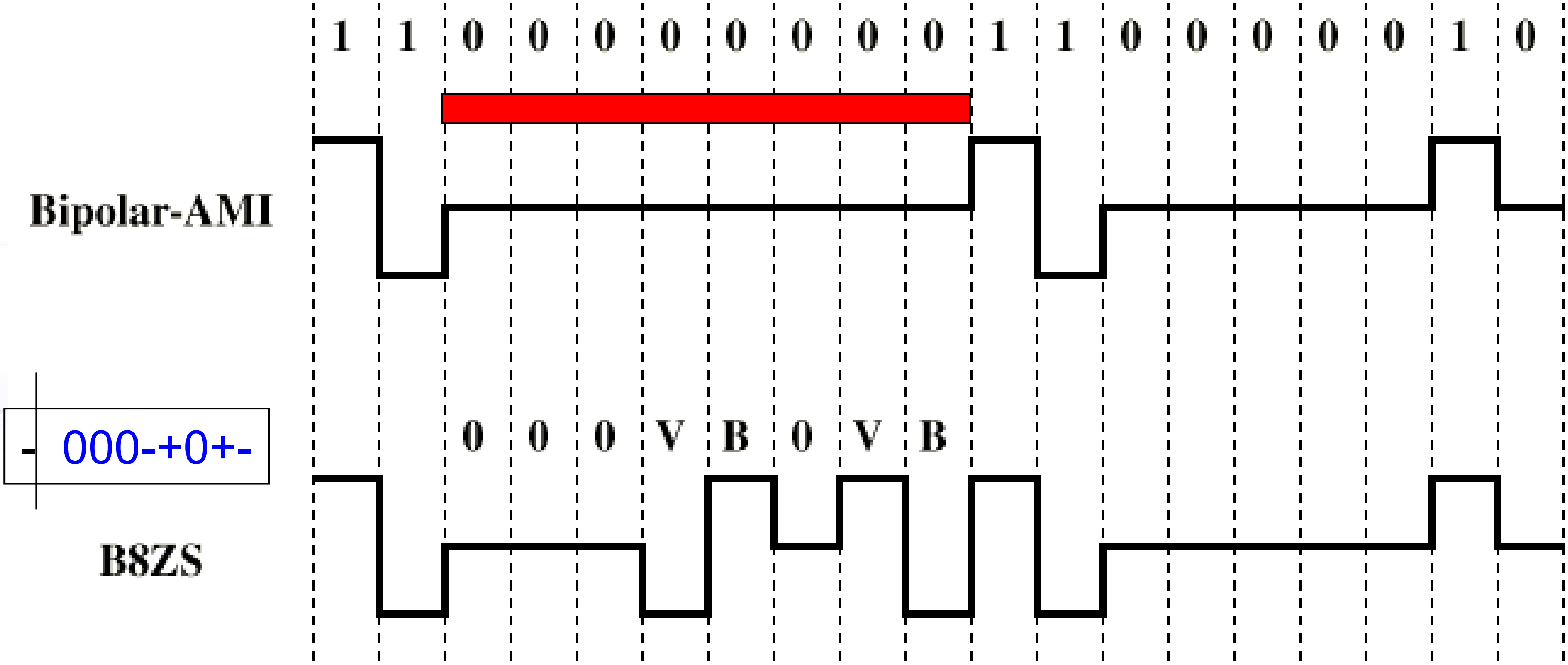
  (how many level changes does this introduce?)
- If an octet of 8 zeros and last voltage pulse preceding was negative (-): Transmitter encodes as 000-+0+-

  (shown in Fig. 5.6)
- Each insertion has *two* intentional violations of the basic AMI code rule: (violations alternate in polarity- no net DC added)

  +000+-0-+

  -000-+0+-
- A strange event ⇒ unlikely to be caused by noise
- Receiver should detect it and interpret as an octet of 8 zeros (original data)
- No additional data sent ⇒ No penalty on genuine data rate

B8ZS



V: Violation

B: Bipolar (Valid)

See how the insertion satisfies the 5 requirements:

-Detectable at RX

-Difficult for noise to generate

-Introduces transitions

-Does not introduce DC (alternate violations)

-Error detection capability

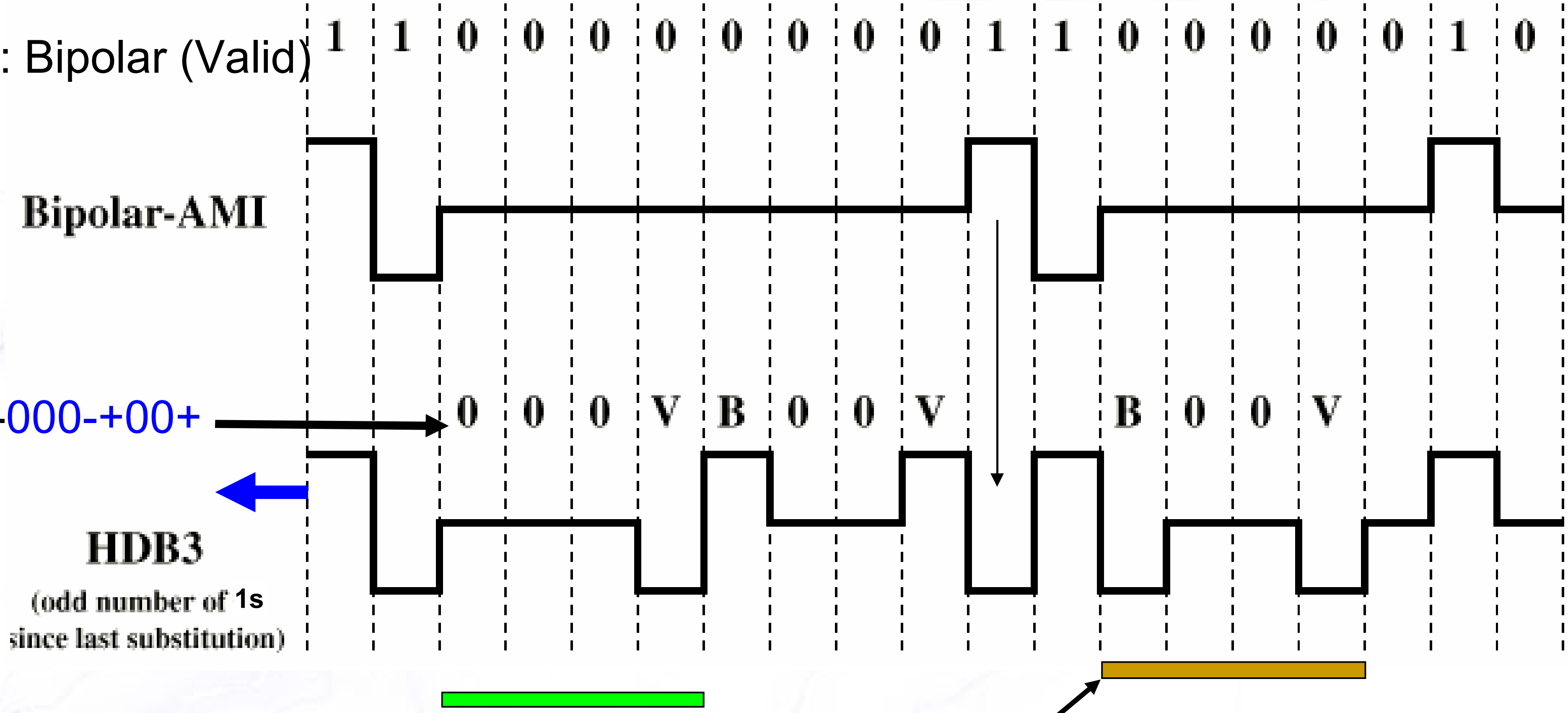
HDB3

- **H**igh **D**ensity **B**ipolar **3** Zeros
- Also based on bipolar-AMI
- 4th zero always replaced with an intentional code violation
- String of four zeros replaced with either:
  - 1 pulse - 000- or + 000+ (violation with preceding pulse)
  - or 2 pulses - +00+ or + -00- (internal violation **within** the insertion)
- What determines whether 1 or 2 pulses?
  - Successive insertion violations must *alternate* in polarity:
    - 00000000 ⇒ - 000-+00+ or + 00000000 ⇒ + 000+-00-
  - With insertions separated by n ‘1’ pulses: The new insertion is determined by the following rules:
    - If n is even, with last pulse p (+ or -) ⇒ **p00p**
    - If n is odd, with last pulse p (+ or -) ⇒ **000p**

HDB3

V: Violation

B: Bipolar (Valid)



-000-+00+

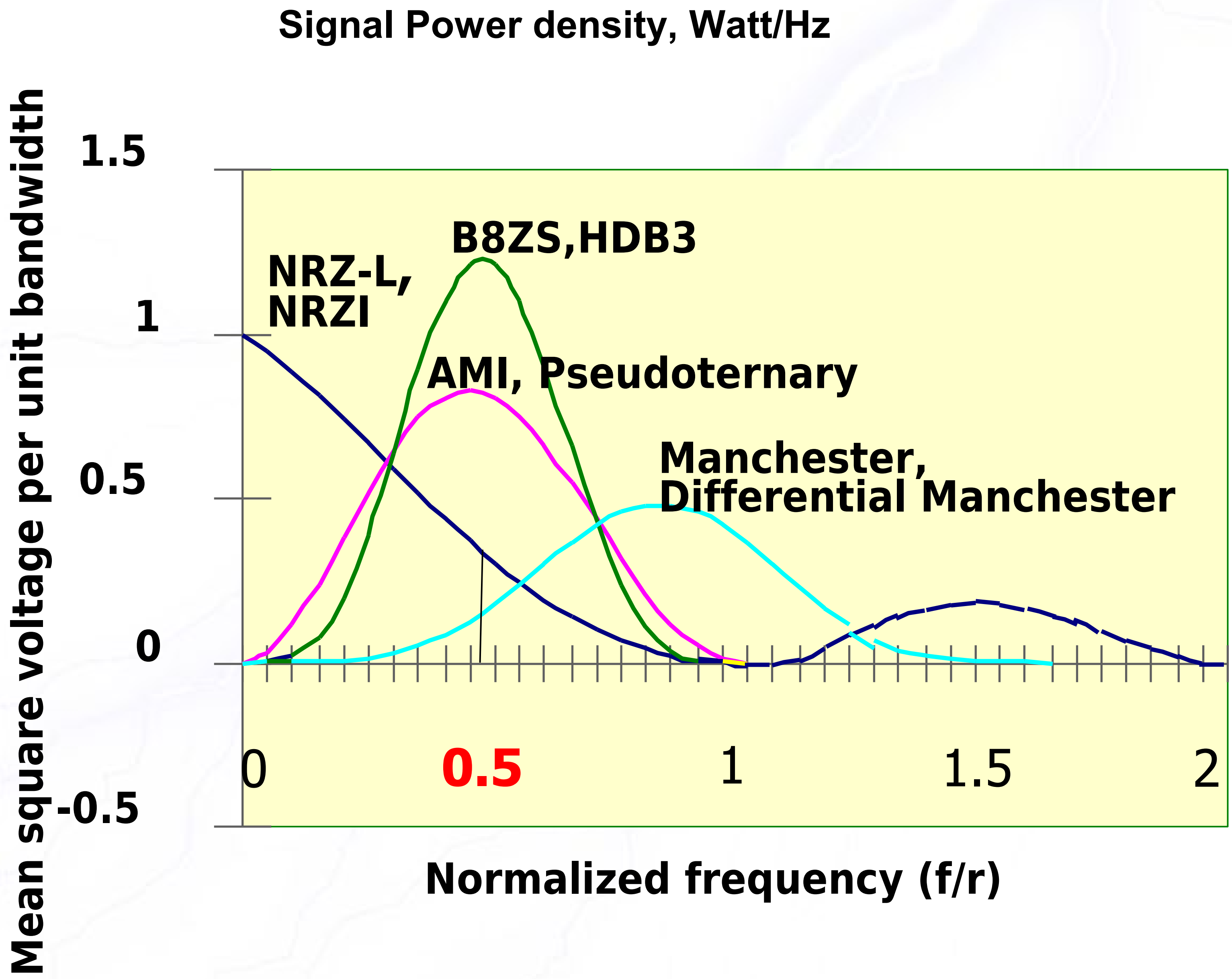
ODD number of 1s after last substitution, with the last pulse (-) ⇒ **000p** ⇒ 000-

p

EVEN number of 1s after last substitution, with the last pulse (+) ⇒ **p00p** ⇒ -00-

p

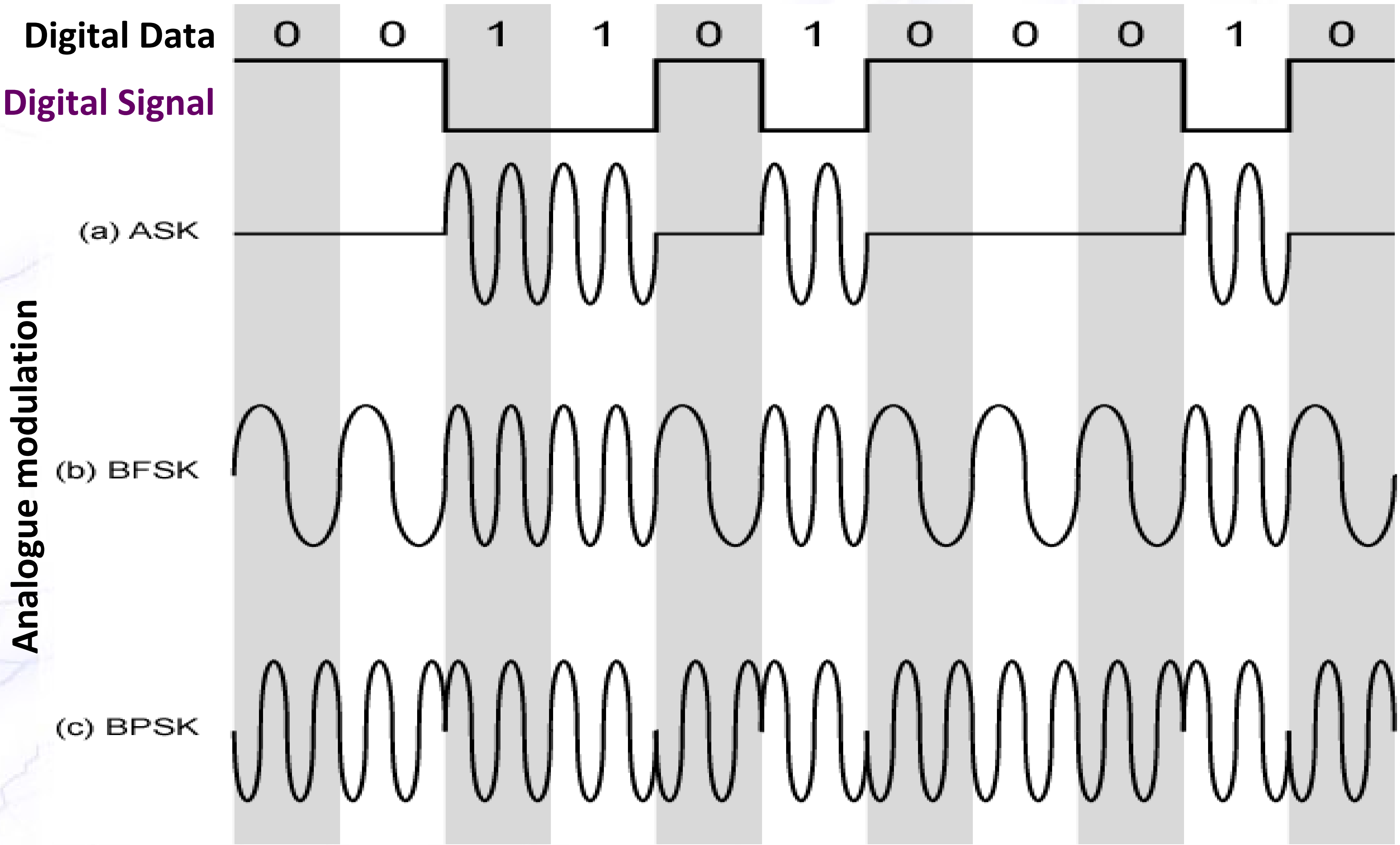
B8ZS, HDB3 Spectrum



2. Digital Data, Analog Signal Encoding

- e.g. over public telephone system
  - 300Hz to 3400Hz
  - Use modem (modulator-demodulator)
- Modulation (here called shift keying) manipulates one or more property of a carrier sine wave:
  - Amplitude shift keying (ASK)
  - Frequency shift keying (FSK)
  - Phase shift keying (PSK)

Modulation Techniques



Digital Data

Digital Signal

Analogue modulation

Amplitude Shift Keying (ASK)

- Values represented by different amplitudes of the carrier sine wave
- Usually, one amplitude is zero
  - i.e. presence and absence of carrier

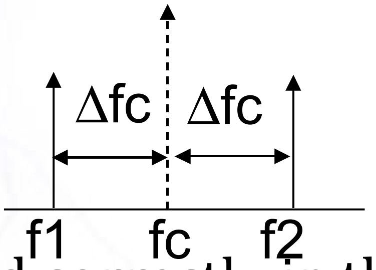
$$s(t) = \begin{cases} A\cos(2\pi f_c t) & \text{binary } 1 \\ 0 & \text{binary } 0 \end{cases}$$

  - e.g. switching the light sent through a fiber on and off
- Susceptible to noise and sudden changes in gain
- Up to 1200bps on voice grade lines
- Used over optical fiber

Frequency Shift Keying (FSK)

- Most common form is binary FSK (BFSK)
- The two binary data values represented by two different frequencies (near and on both sides of a central carrier frequency f_c)

$$s(t) = \begin{cases} A\cos(2\pi f_1 t) & \text{binary } 1 \\ A\cos(2\pi f_2 t) & \text{binary } 0 \end{cases}$$



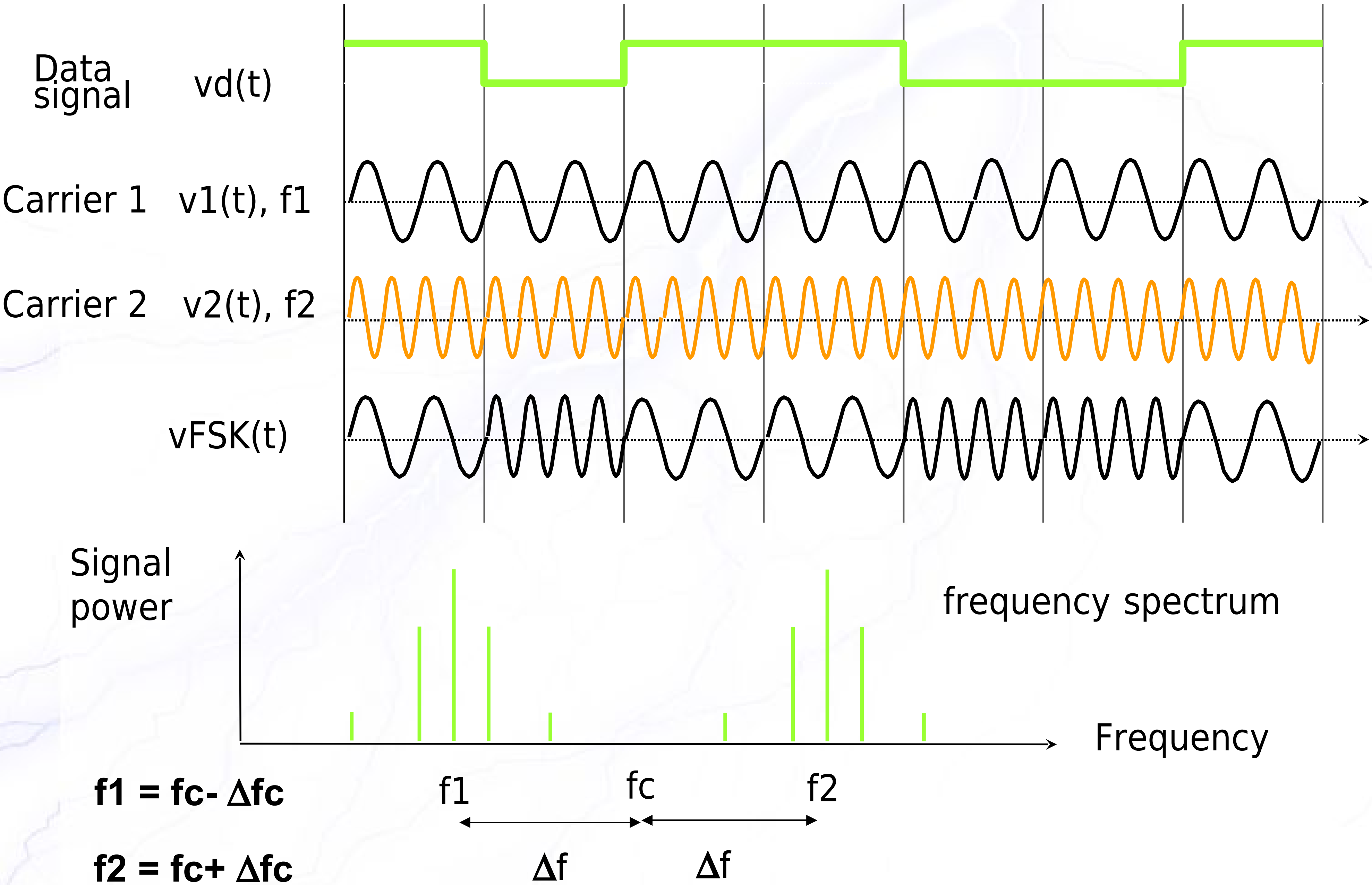
- Less susceptible to noise than ASK

(Same as with FM Radio: Frequency can be detected correctly in the presence of noise better than amplitude)

Applications:

- Up to 1200bps on voice grade lines
- Also used at High frequency radio (3-30 MHz)
- And at even higher frequencies on LANs using coaxial cables

FSK

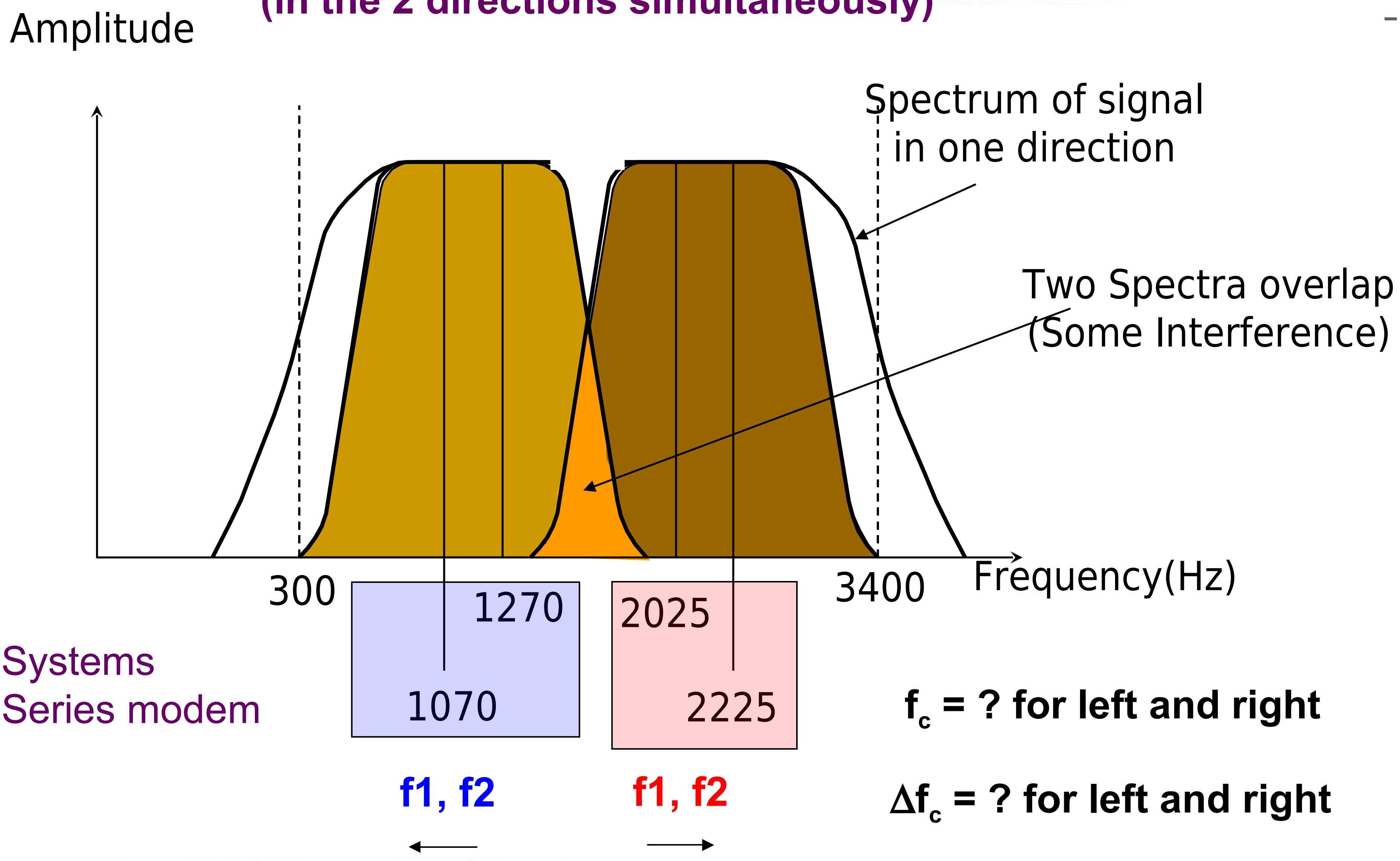


$f1 = fc - \Delta fc$

$f2 = fc + \Delta fc$

FSK for digital data on Voice Grade Lines

Full Duplex Communication
(in the 2 directions simultaneously)



Bell Systems
108 Series modem

f_c = ? for left and right

Δf_c = ? for left and right

Multiple FSK (MFSK)

To improve BW utilization (efficiency) we send one of multiple signal symbols (frequencies) every signal element ⇒ More than 1 bit at a time

- More than two frequencies used
- An example of multi-level coding (M levels)
- Each signalling element conveys more than one bit (L bits, $L = \log_2 M$)
- This increases bandwidth efficiency

  (high BE = C/B values) (Higher data rates for the same signalling rate)
- But in general, multi-level coding is more prone to error due to noise

  (Unless you do something about it, e.g. orthogonally)

Multiple FSK (MFSK)

$$s_i(t) = A\cos 2\pi f_i t, \qquad 1 \le i \le M \tag{5.4}$$

$f_i = f_c + (2i - 1 - M)f_d$

f_c = the carrier frequency

f_d = the difference frequency (Half the frequency separation Δfc as before)

M = number of different signal elements = 2^L

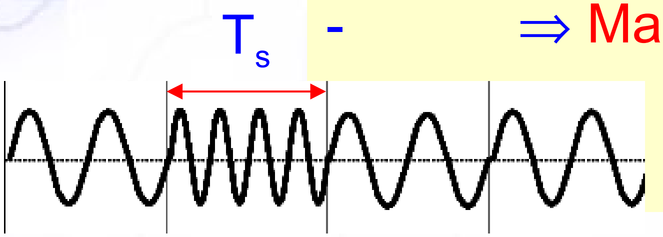
L = number of bits per signal element

i.e. different frequencies

- Frequency separation = 2 f_d
- Bandwidth Required = M ($2f_d$)
-
- Minimum T_s (signal element duration) = $1/(2f_d)$
- ⇒ Max signaling rate D = $1/T_s = 2f_d$

⇒ Max data rate R = D L = $2f_d$ L

Important Parameters



The closer the two frequencies are, the larger Ts needed to discriminate between them

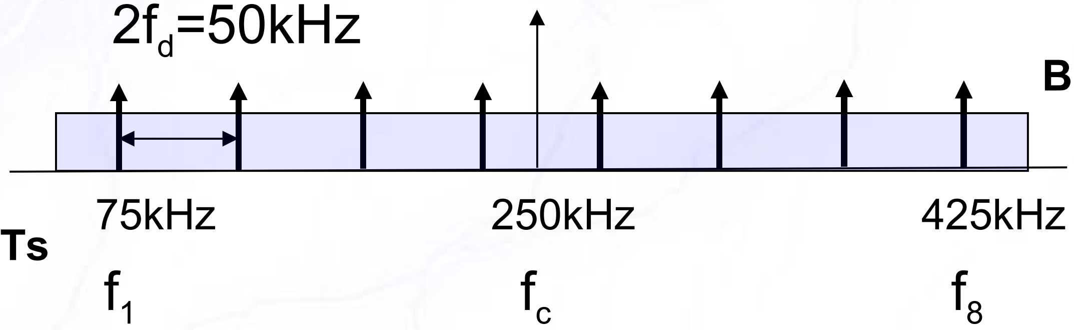
Multiple FSK (MFSK)

$$f_i = f_c + (2i - 1 - M)f_d$$

Example 5.1 With $f_c = 250$ kHz, $f_d = 25$ kHz, and $M = 8$ ($L = 3$ bits), we have the following frequency assignments for each of the eight possible 3-bit data combinations:

$f_1 = 75$ kHz 000 $f_2 = 125$ kHz 001 $f_3 = 175$ kHz 010 $f_4 = 225$ kHz 011

$f_5 = 275$ kHz 100 $f_6 = 325$ kHz 101 $f_7 = 375$ kHz 110 $f_8 = 425$ kHz 111



Min T_s = 1/ ($2f_d$)
= 1/50 KHz
= 20 μs

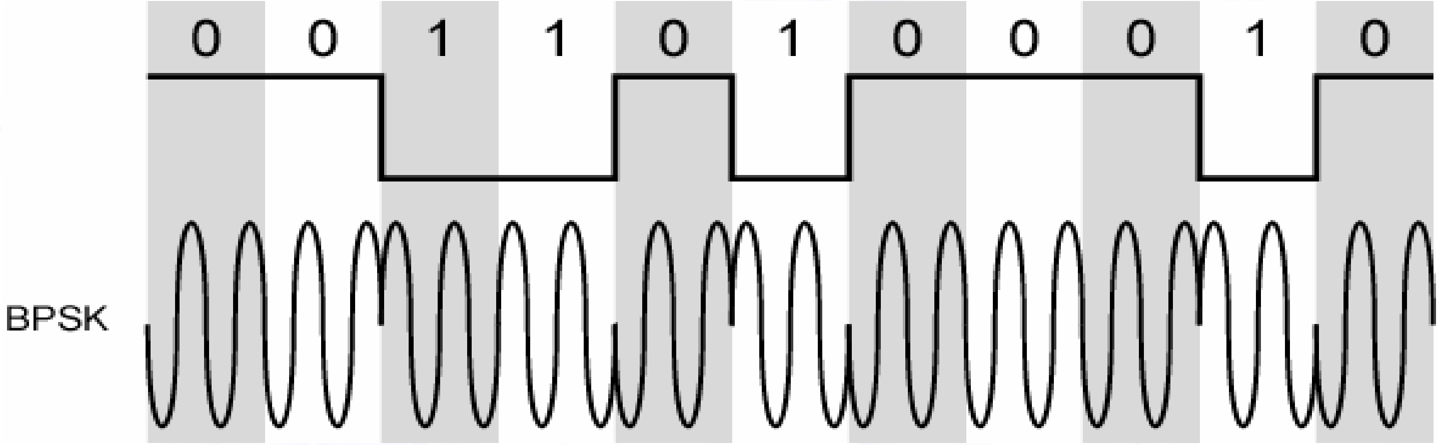
Max signaling rate = 1/Ts
= $2f_d$
= 50 kBauds

Bandwidth = M ($2f_d$)
= 8 x 50
= 400 kHz
(< 2 f_c, so OK)

Max Data rate = Max Signaling rate x L = 50 KHz x 3 = 150 Kbps

Phase Shift Keying (PSK)

- Phase of carrier signal is shifted to represent data
- Binary PSK: Absolute
  - Two phases (spaced at 180°) represent the two binary digits



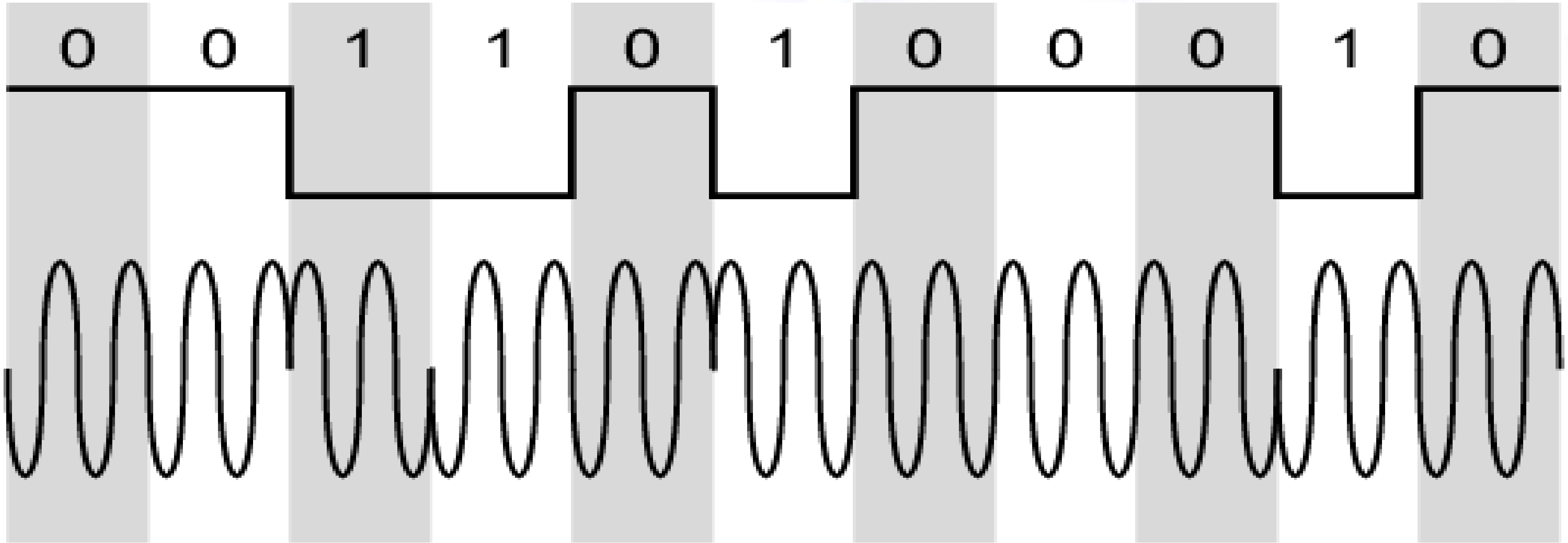
$$s(t) = \begin{cases} A\cos(2\pi f_c t) \\ A\cos(2\pi f_c t + \pi) \end{cases} = \begin{cases} A\cos(2\pi f_c t) & \text{binary } 1 \\ -A\cos(2\pi f_c t) & \text{binary } 0 \end{cases} \qquad (5.5)$$

$$s_d(t) = A\,d(t)\cos(2\pi f_c t) \qquad (5.6)$$

Where d(t) = +1 for ‘1’ data and -1 for ‘0’ data

Differential PSK (DPSK)

Phase shifted relative to the previous signal element, rather than some reference signal:



- **0**: Do not reverse phase **1**: Reverse phase (as with NRZI, invert on 1))
  (A form of differential encoding)
- Advantage:

  \- No need for a reference oscillator at RX to determine **absolute** phase

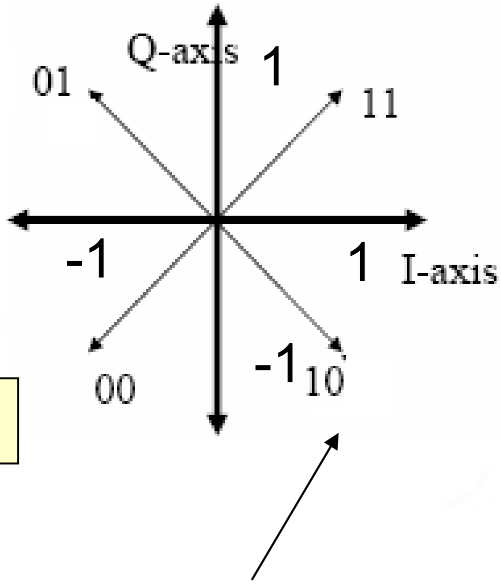
Quadrature PSK (QPSK)

- 4 different phases spaced at $\pi/2$ (90°)
- Multilevel signaling, so:
  - More efficient use of bandwidth (i.e higher data rate for the same signaling rate)
- Each signal element represents $\log_2 4 = 2$ bits

$-3\pi/4$

$$s(t) = \begin{cases} A\cos(2\pi f_c t + \frac{\pi}{4}) & \text{binary } 11 \\ A\cos(2\pi f_c t + \frac{3\pi}{4}) & \text{binary } 01 \\ A\cos(2\pi f_c t + \frac{5\pi}{4}) & \text{binary } 00 \\ A\cos(2\pi f_c t + \frac{7\pi}{4}) & \text{binary } 10 \end{cases}$$

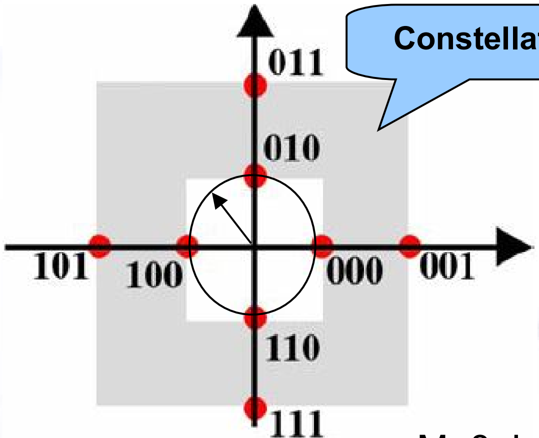
$-\pi/4$



Bit pair transmitted

Quadrature Amplitude Modulation (QAM)

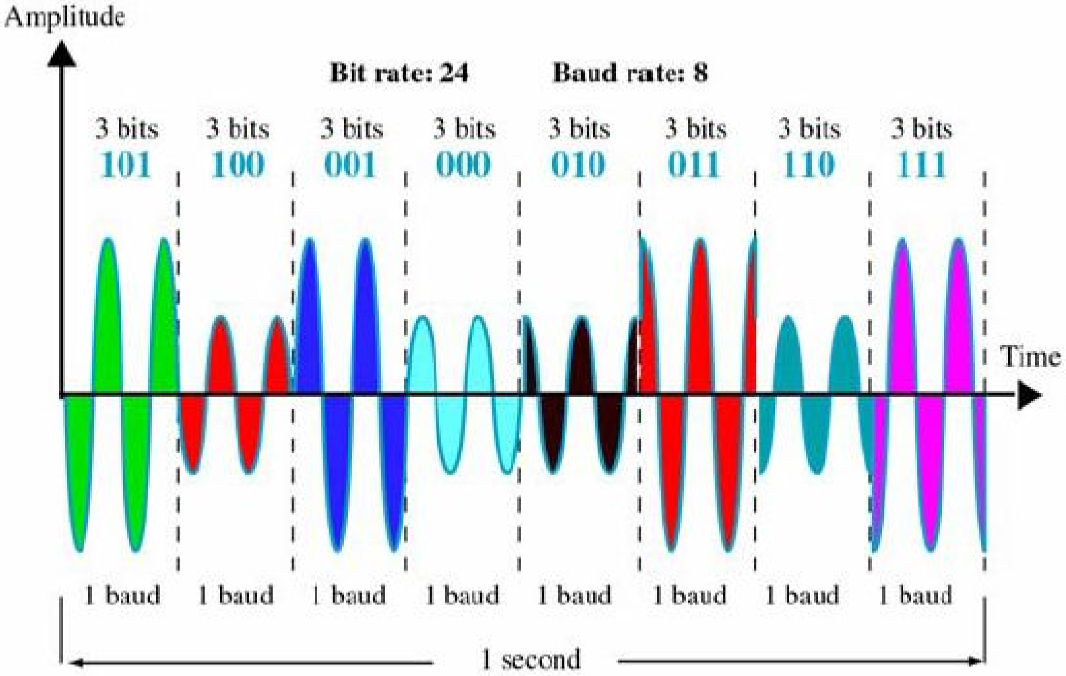
- An extension of the QPSK just described
- Combines both ASK and PSK
- For example, ASK with 2 levels and PSK with 4 levels give 4 x 2 i.e. 8-QAM
- M = 8, L = 3
- Up to M=256 is possible
- Large bandwidth savings
- But some susceptibility to noise
- QAM used on asymmetric digital subscriber line (ADSL) and some wireless systems



Constellation

8-QAM
2 amplitudes, 4 phases

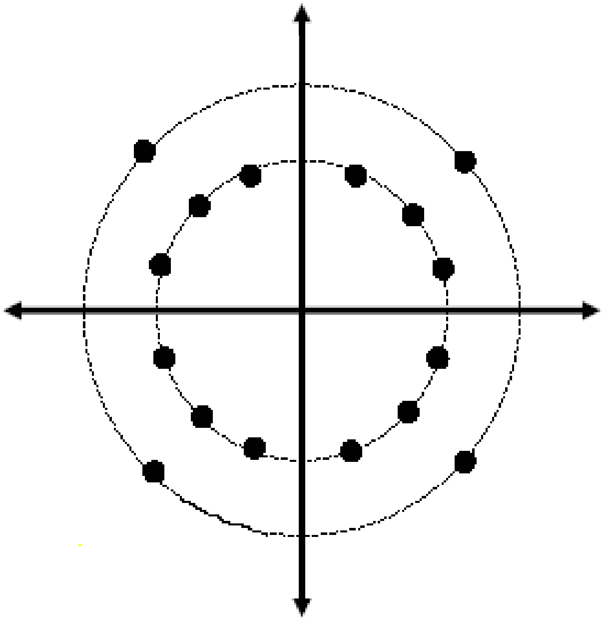
M=8, L = 3



True Multilevel PSK (MPSK)

- Can use more phase angles and more than one amplitude
- For example, 9600 bps modems use 12 phase angles, four of which have 2 amplitudes
- Gives 16 different signal elements ⇒ M = 16 and L = $\log_2(16) = 4$ bits
- Every signal element carries 4 bits (Data sent 4 bits at a time)
- Baud rate D required is only 9600/4 = 2400 bauds (required BW is low ... i.e. can use on a voice grade lines!)

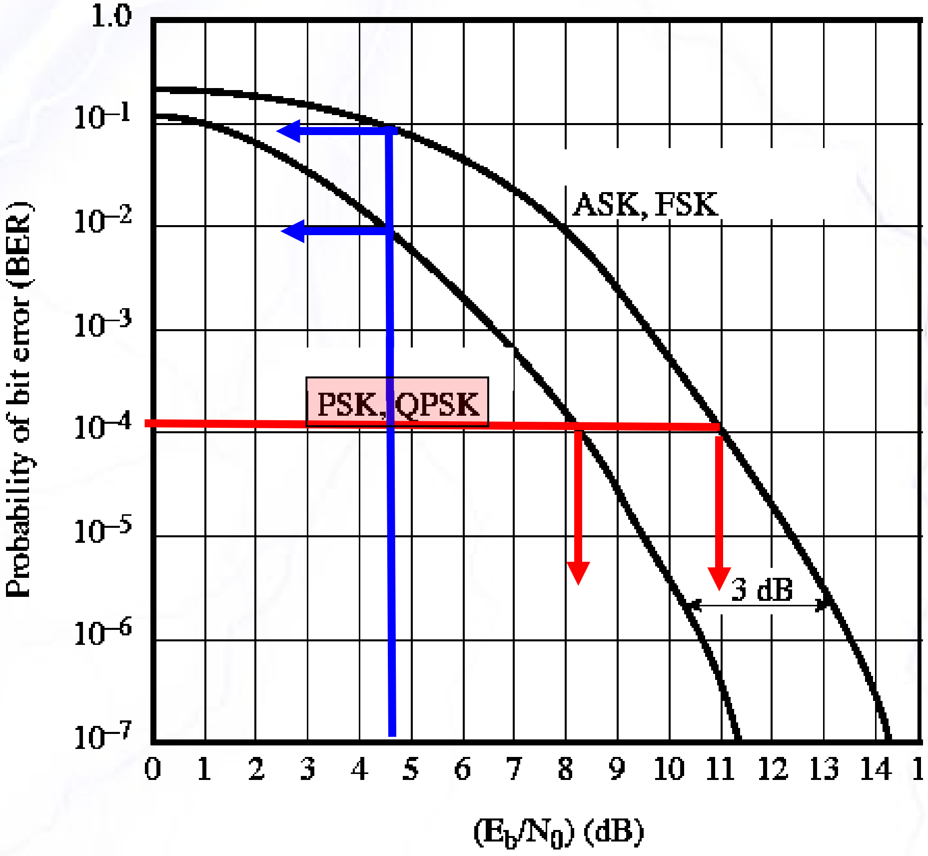
- Complex signal encoding allows high data rates to be sent on voice grade lines having a limited bandwidth



Performance of D-A Modulation Schemes

b. Performance with noise: ASK, FSK, PSK, QPSK

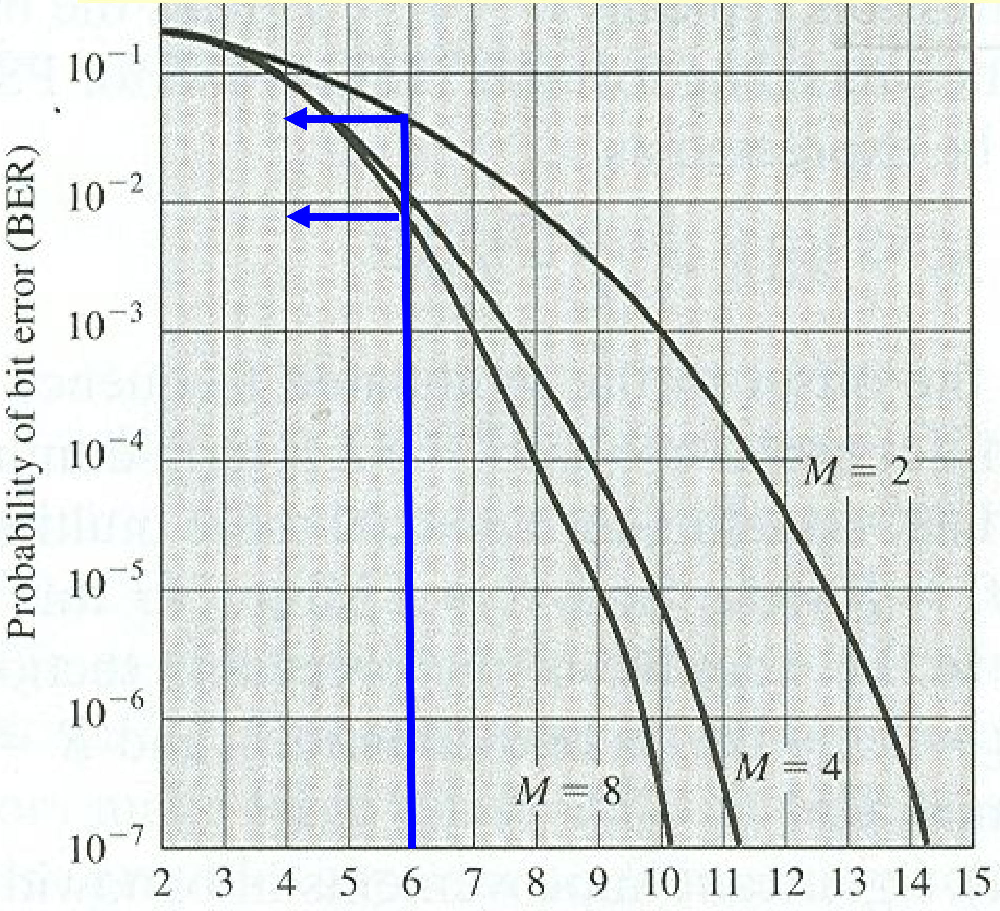
- Bit error rate (BER) Plotted Vs E_b/N_0 (dBs)
- Curves to the left give better performance:
  - Lower S/N required for same Error rate
  - Lower Error rate obtained for same SNR
- Why QPSK and PSK give the same performance?
  - 2 phase levels (+1,-1) in *both* cases
  - Remember QPSK gave 4 phase levels for the price of 2!



Performance of D-A Modulation Schemes

b. Performance with noise: MFSK, MPSK

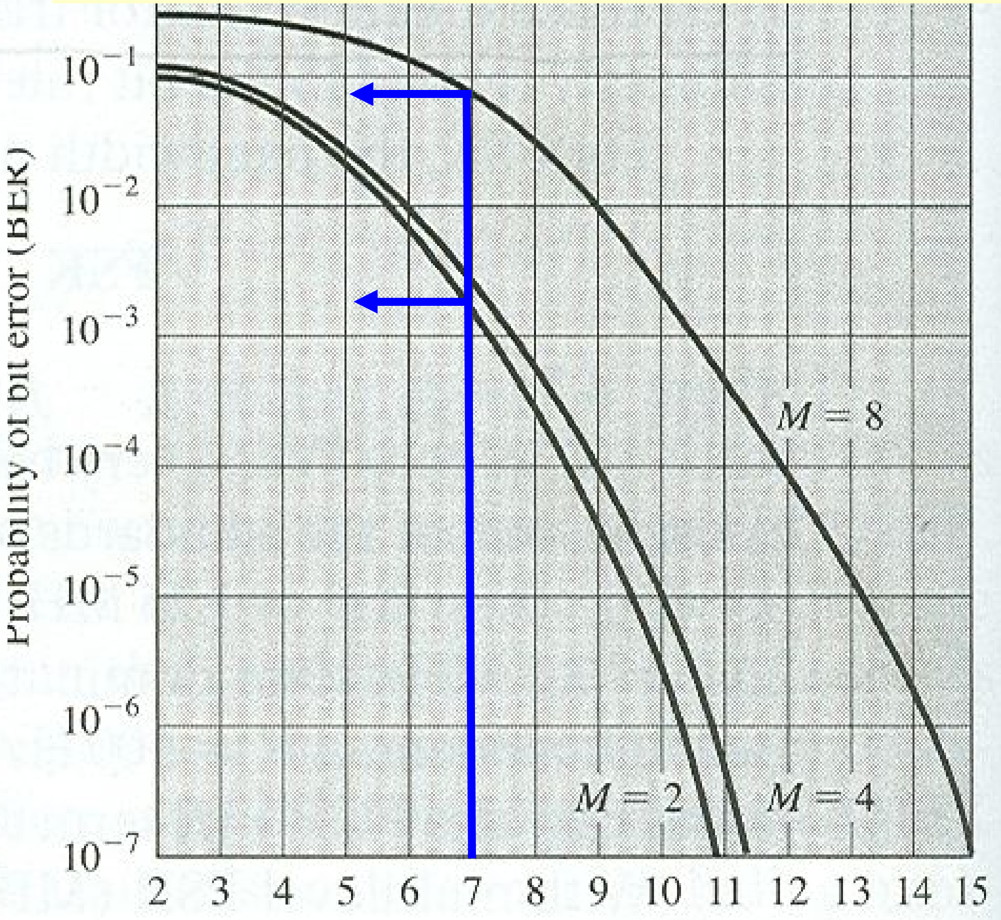
Larger M → Better error performance!



(a) Multilevel FSK (MFSK)

Orthogonal FSK

Larger M → Poorer error performance



(b) Multilevel PSK (MPSK)

As expected

E_b/N_0 in terms of the bandwidth efficiency (BE) (for binary transmission)

$$BE_{dB} = \left.\frac{R}{B_T}\right|_{dB}$$

B_T is the Transmission Bandwidth

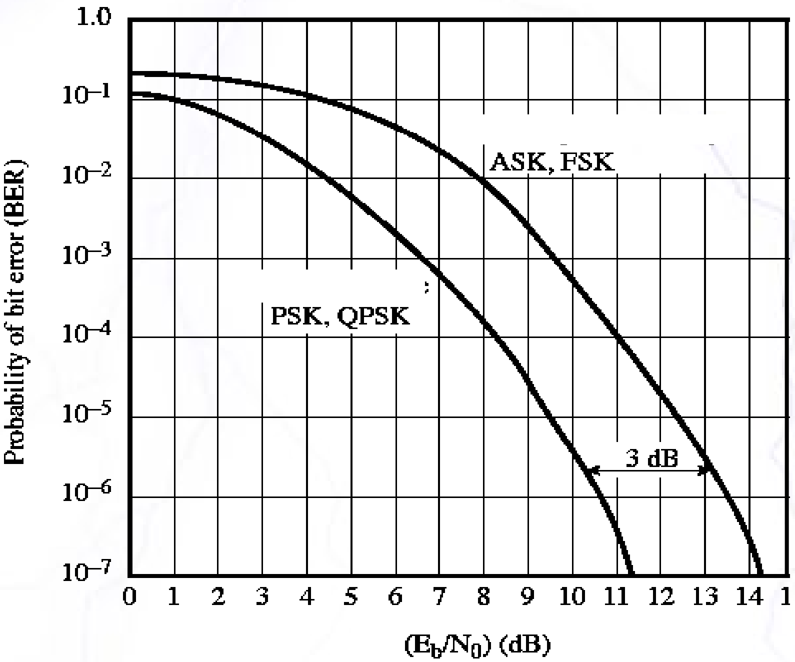
$$\frac{E_b}{N_0} = \frac{\frac{ST_b}{N}}{B_T} = \frac{\frac{\frac{S}{R}}{N}}{B_T} = \frac{\frac{\frac{S}{N}}{R}}{B_T}$$

$$\left.\frac{E_b}{N_0}\right|_{dB} = \left.\frac{S}{N}\right|_{dB} - \left.\frac{R}{B_T}\right|_{dB}$$

$$= \left.\frac{S}{N}\right|_{dB} - BE_{dB}$$

Example

- What is the bandwidth efficiency (BE) for ASK and PSK, for a bit error rate (BER) of 10^{-7} on a channel with a SNR of 12dB ?



- For ASK (binary): At BER = 10^{-7}, E_b/N_0 = 14.3 dBs
- Substituting in:

$$\frac{E_b}{N_0} = SNR_{dB} - [BE]_{dB}$$

- $BE_{ASK,FSK}$ = -14.3 + 12 = -2.3 dBs → R/B_T = $10^{-.23}$ = 0.6
- However, for PSK → E_b/N_0 = 11.3 dBs):

  BE_{PSK} = R/B_T = 1.2 (doubled: 3dB higher- improvement)