Networking

Fall 2021

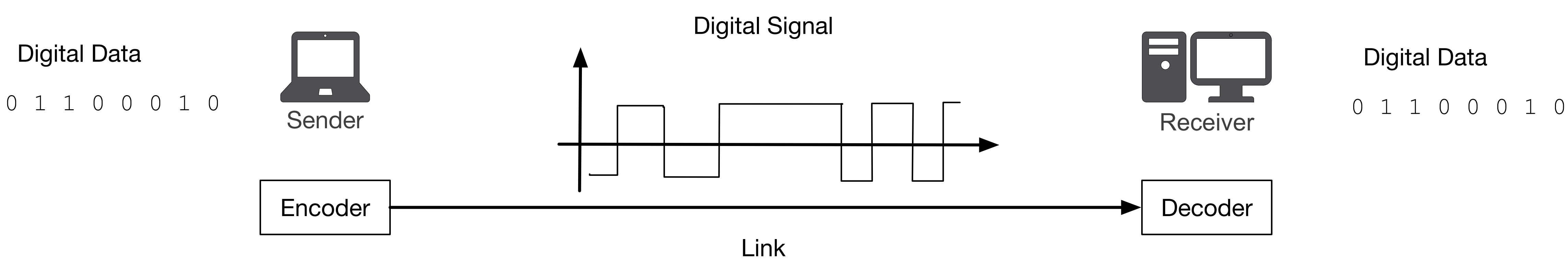
Digital Transmission

- How to transmit data digitally
  - Digital to digital conversion converts digital data to a digital signal
  - Analog to digital conversion samples an analog signal
- Transmission modes:
  - Serial
  - Parallel

Digital to Digital Conversion

Line Coding

- Line coding converts digital data to digital signals
  - Data is given as a sequence of bits in computer memory
  - Sender encodes a bit sequence into a digital signal
  - Receiver decodes into a bit sequence

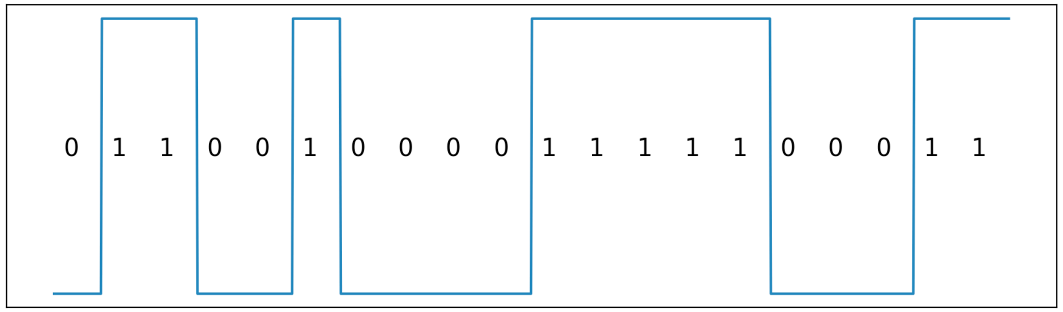


Signal Element vs. Data Element

- Data element is the smallest entity that represents information: a bit
- Signal element: shortest unit of a signal
- Typically: Data element corresponds to r signal elements

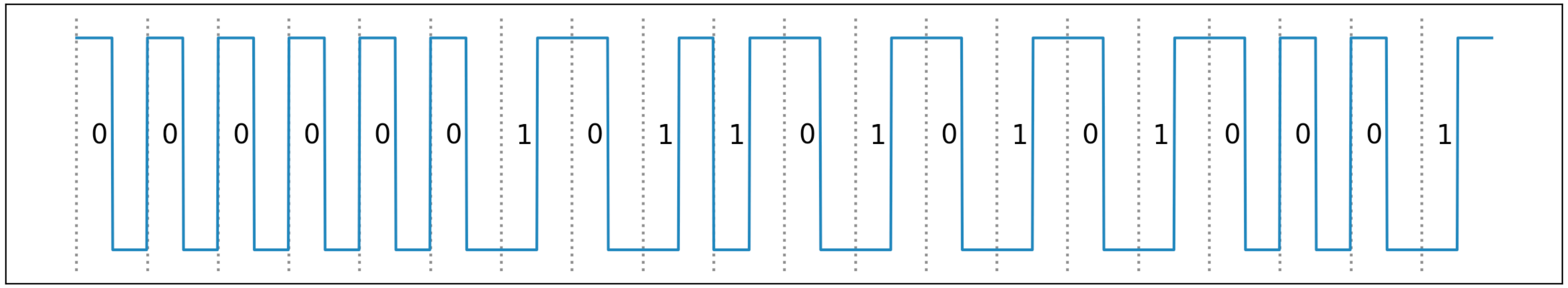
Signal Elements vs. Data Elements

- $r = 1$



  - one signal element per data bit

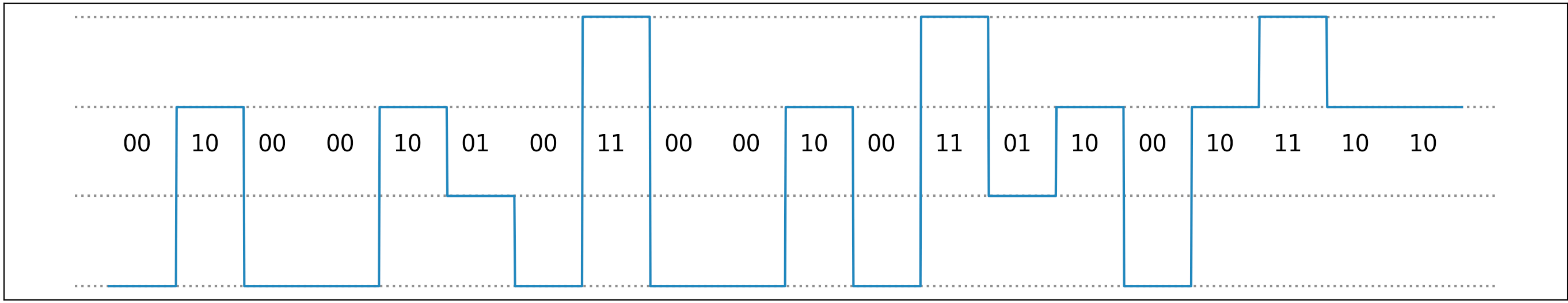
- $r = \frac{1}{2}$



  - two signal elements (up / down) per data bit
    - (Manchester encoding)

Signal Elements vs. Data Elements

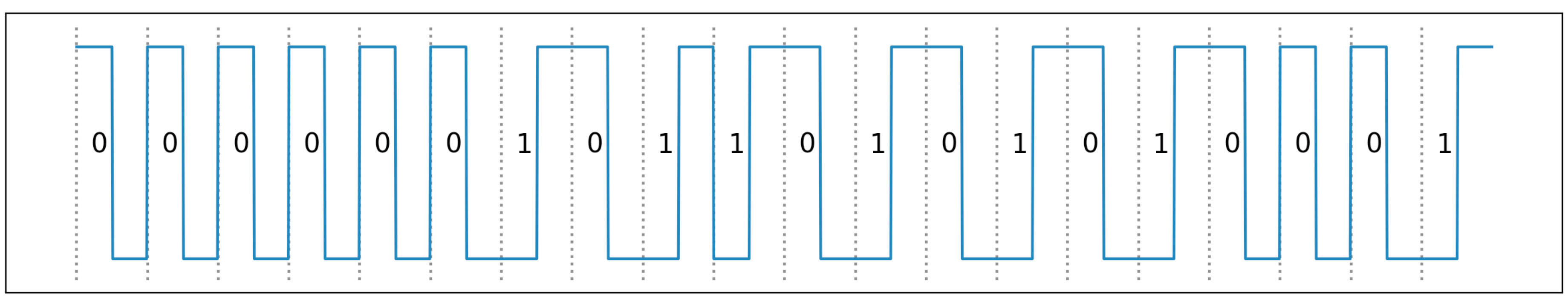
- $r = 2$



- one signal element per two data bits

Signal Elements vs. Data Elements

- Self-timing codes
  - Timing information can be obtained from a clock
    - which needs to be synchronized
  - Codes can make synchronization easier
  - Codes can be self-timing:
    - E.g. Manchester code — a transition always happen in the middle of a bit-transfer



Signal Elements vs. Data Elements

- Factor r can depend on the data
  - E.g.: Long sequences of constant signal levels make it difficult to count
    - Common coding trick: Introduce a change of signal level every so often

Baseline Wandering

- To distinguish voltage levels:
  - Receiver uses a running average of the received signal power (the baseline)
  - A long time of fixed levels can cause baseline wandering
- Additional problem: If the voltage levels do not even out, then we send energy from one end to the other

DC Components

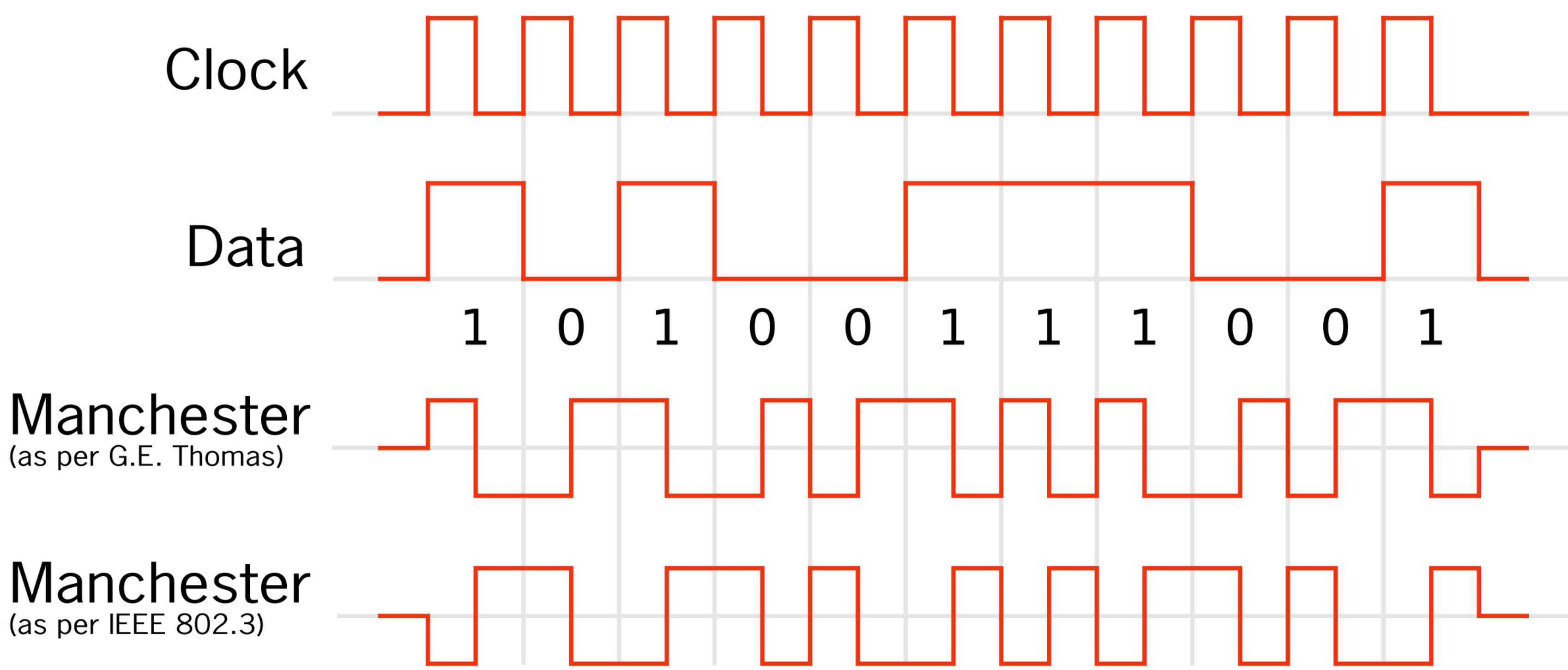
- If voltage level is constant for a time:
  - Fourier analysis shows spectrum with very low frequencies (called DC frequencies)
  - Many systems cannot transport these low frequencies
    - E.g. telephone line cannot pass frequencies below 200 Hz

Self Synchronization

- Bit intervals at the sender need to correspond to bit intervals at the receiver
    - Clocks need to be synchronized

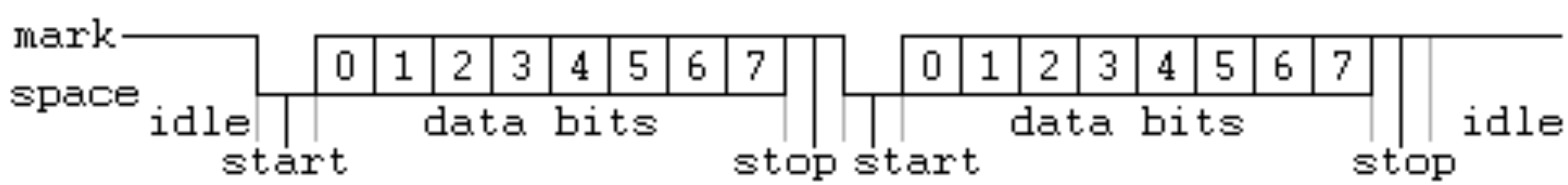
Self Synchronization

- Clocking:
    - Clock signals needed to interpret signal levels
    - Isochronous: clock signals are sent at the same time
        - Self-clocking: can derive the clock signal from the signal



Self Synchronization

- Clocking:
  - Anisochronous clocking: clock signals are sent at a different time
    - Self-clocking: can derive the clock signal from the signal
    - E.g. use frames which



    - Or be run-length limited (no long runs of zeroes / ones)

Signal Elements vs. Data Elements

- Data rate: number of bits sent per second
  - (bits per second / bps)
- Signal rate: number of signal elements sent per second
  - "Pulse rate", "Modulation rate", "baud rate"
- Good signal engineering:
  - Increase data rate and lower the signal rate
- Signal rate S, data rate N: $S = N/r$

Examples

8B6T

- Eight-binary-six-ternary scheme
  - Used with 100 Base-4T cable
  - Patterns of 8 bits = 1 byte are encoded as patterns of 6 ternary signals (such as -0-0++)
  - 2^8 = 256 values for each byte
  - 3^6 = 729 signal pattern
  - Select signal patterns carefully:
    - Signal patterns have weight
      - Number of “+” minus number of “-”
    - Pick only signal patterns with weight 0 or 1
    - Alternatively: Invert signal patterns with weight 1 to obtain one of weight -1
    - Therefore: no DC component

4D-PAM5

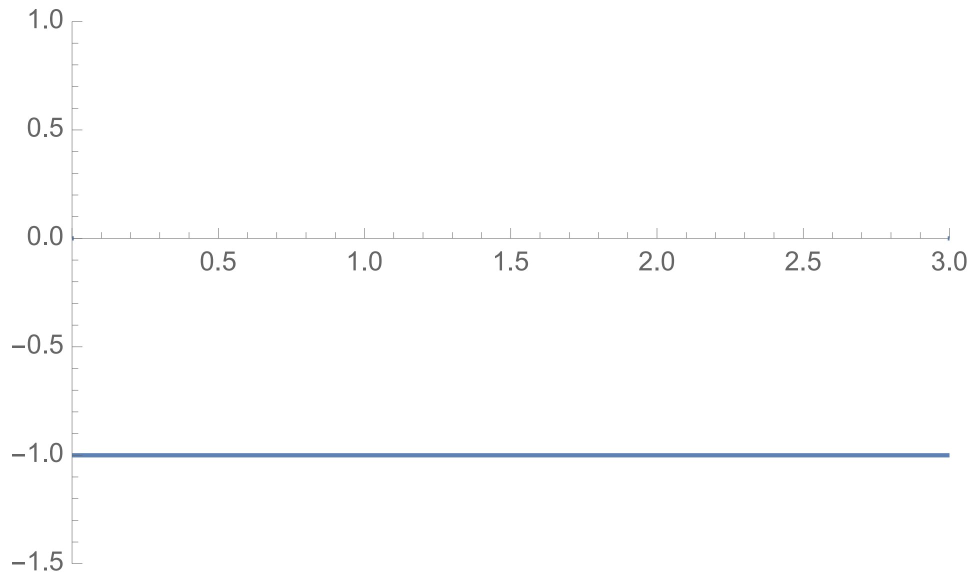
- Used for Gb LANs using copper wire with 125 Mbaud
- 4D — four dimensional: Use four wires at the same time
- Uses five voltage levels, -2, -1, 0, 1, 2
  - Level 0 is only used for error detection

Block Coding

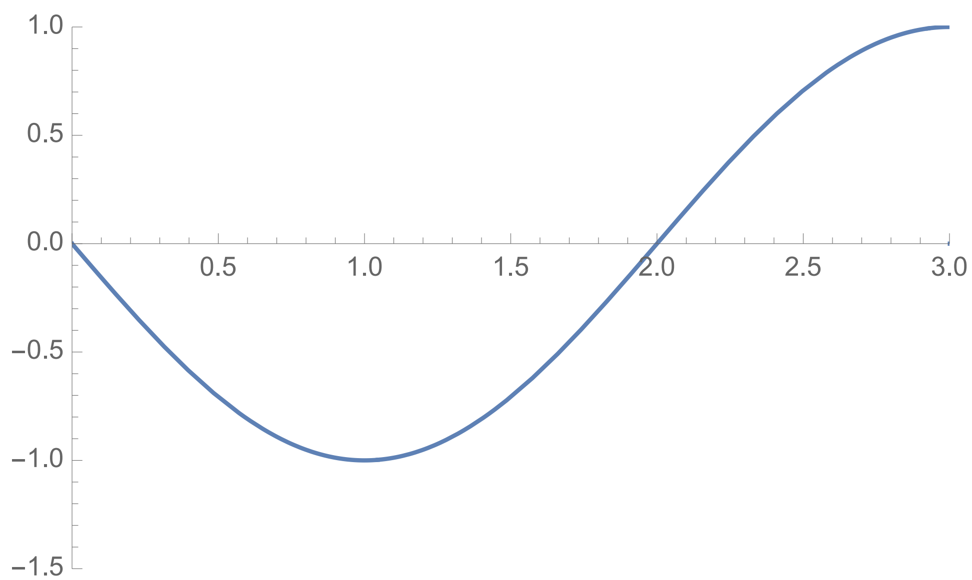
- Encode blocks of *m* bits in blocks of *n* bits with (e.g.) NRZ-I
- Example:
  - 4b/5b
  - Never more than three zeroes in a row
  - Prevents clock synchronization problems
  - But adds 20% to baud rate
  - Some unused codes can be used as metadata

0000	11110
0001	01001
0010	10100
0011	10101
0100	01010
0101	01011
0110	01110
0111	01111
1000	10010
1001	10011
1010	10110
1011	10111
1100	11010
1101	11011
1110	11100
1111	11101

Low Pass Channel

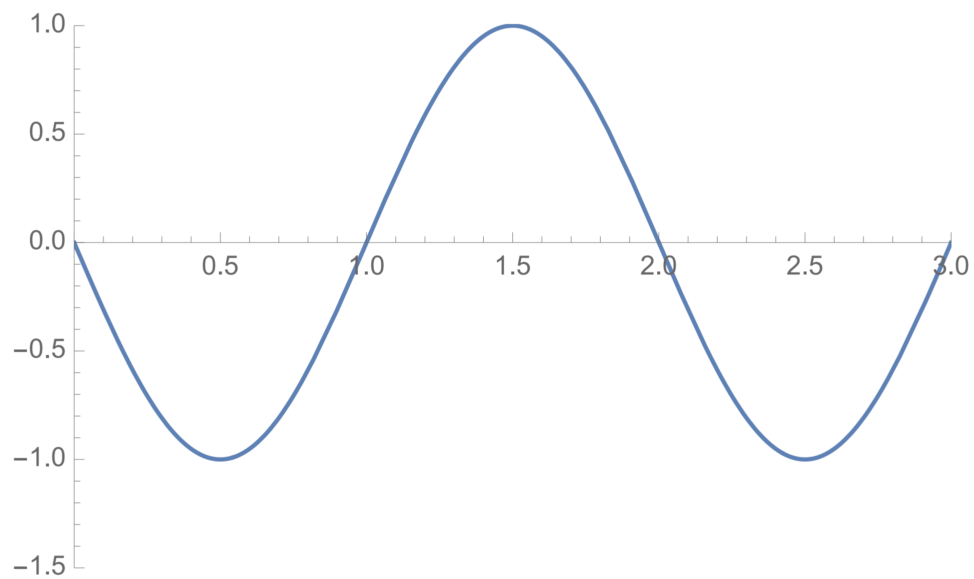


000
f=0
p=180°

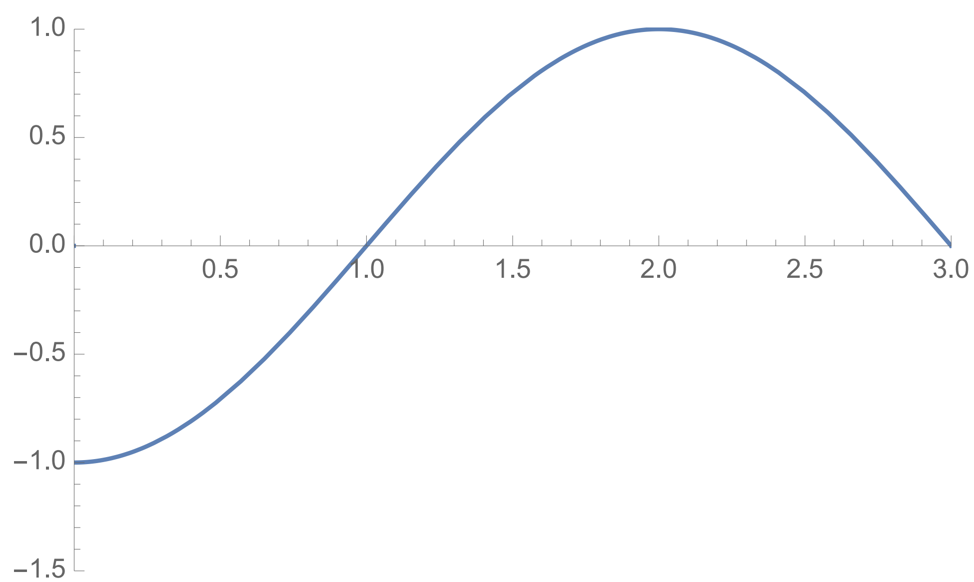


001
f=N/4
p=180°

Low Pass Channel

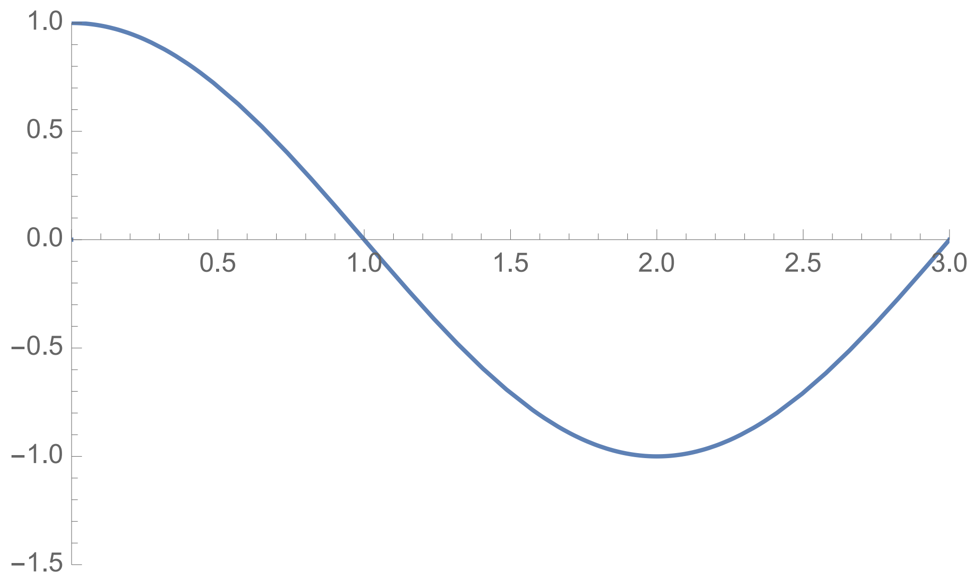


010
f=N/2
p=180°

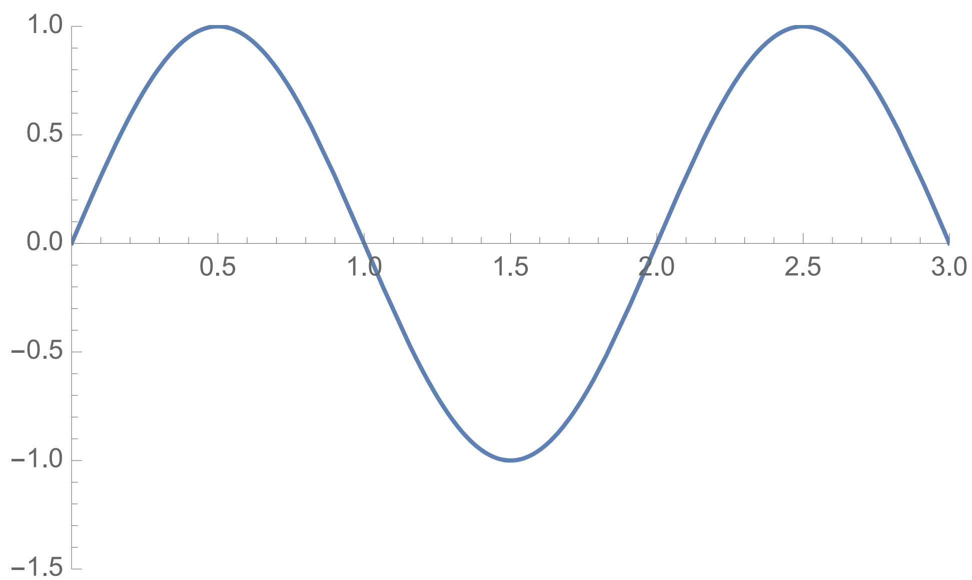


011
f=N/4
p=270°

Low Pass Channel

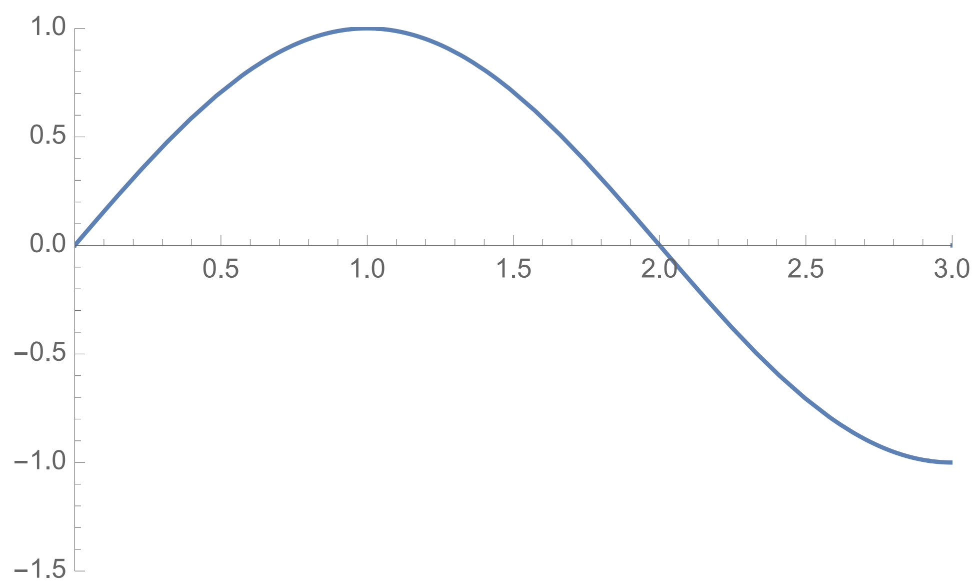


100
f=N/4
p=90°

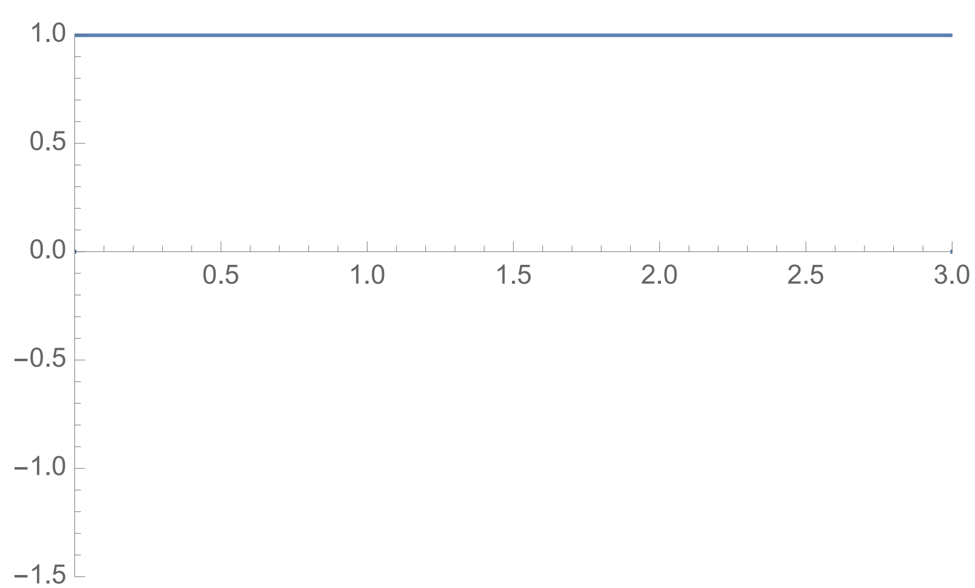


101
f=N/2
p=0°

Low Pass Channel



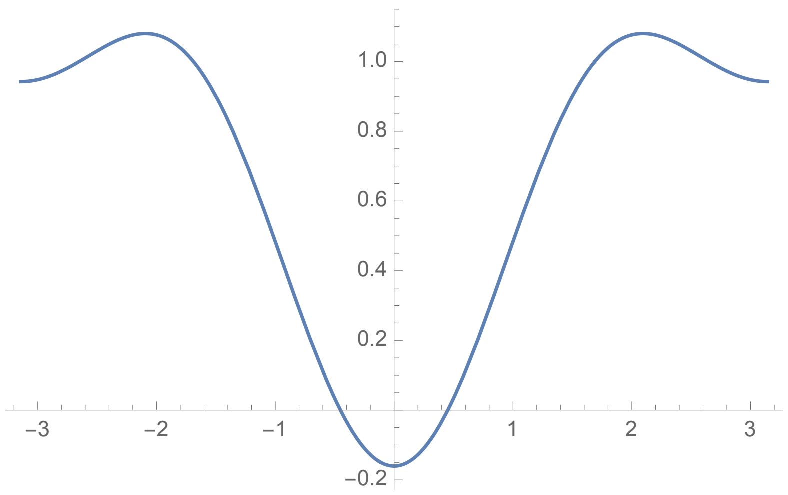
110
f=N/4
p=0°

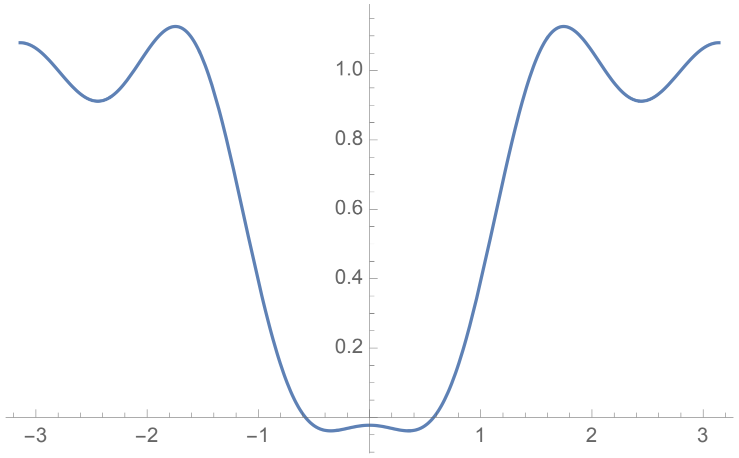


111
f=0
p=0°

Low Pass Channel

- A bandwidth of $N/2$ is sufficient if we sample at the middle of the interval
- Higher harmonics are needed to make the signal look more digital





101 encoded with third and with third and fifth harmonic

Low-pass Channel

- For better accuracy, we can use higher harmonics

Bandwidth requirements

Bit Rate	Harmonic 1	Harmonics 1,3	Harmonics 1,3,5
1 kbps	500 Hz	1.5 KHz	2.5 KHz
10 kbps	5 KHz	15 KHz	25 KHz
1 Mbps	500 KHz	1.5 MHz	2.5 MHz

Quiz

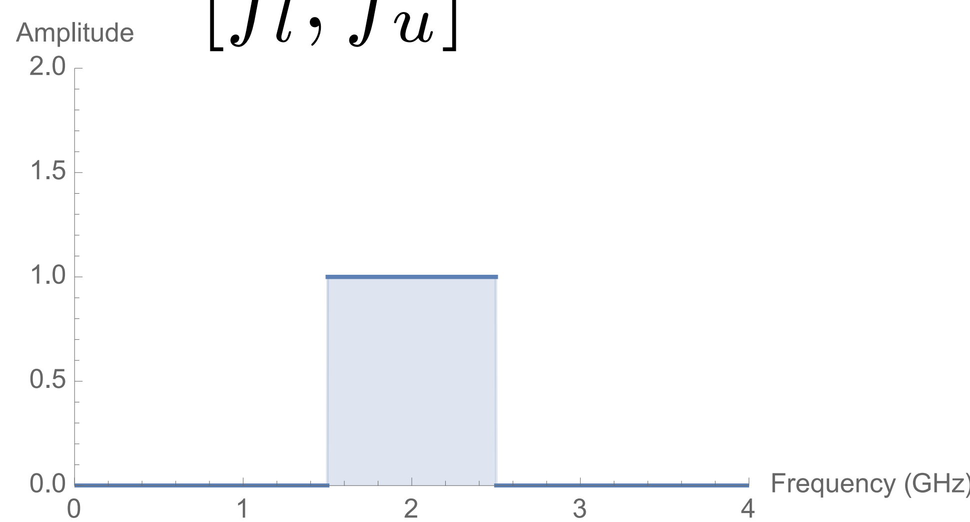
- How much bandwidth is required to send a 1 Gbps signal with 7 harmonics

- Answer:
  - (1Gbps/2b) $\times$7 = 3.5 GHz

Broadband Transmission with Modulation

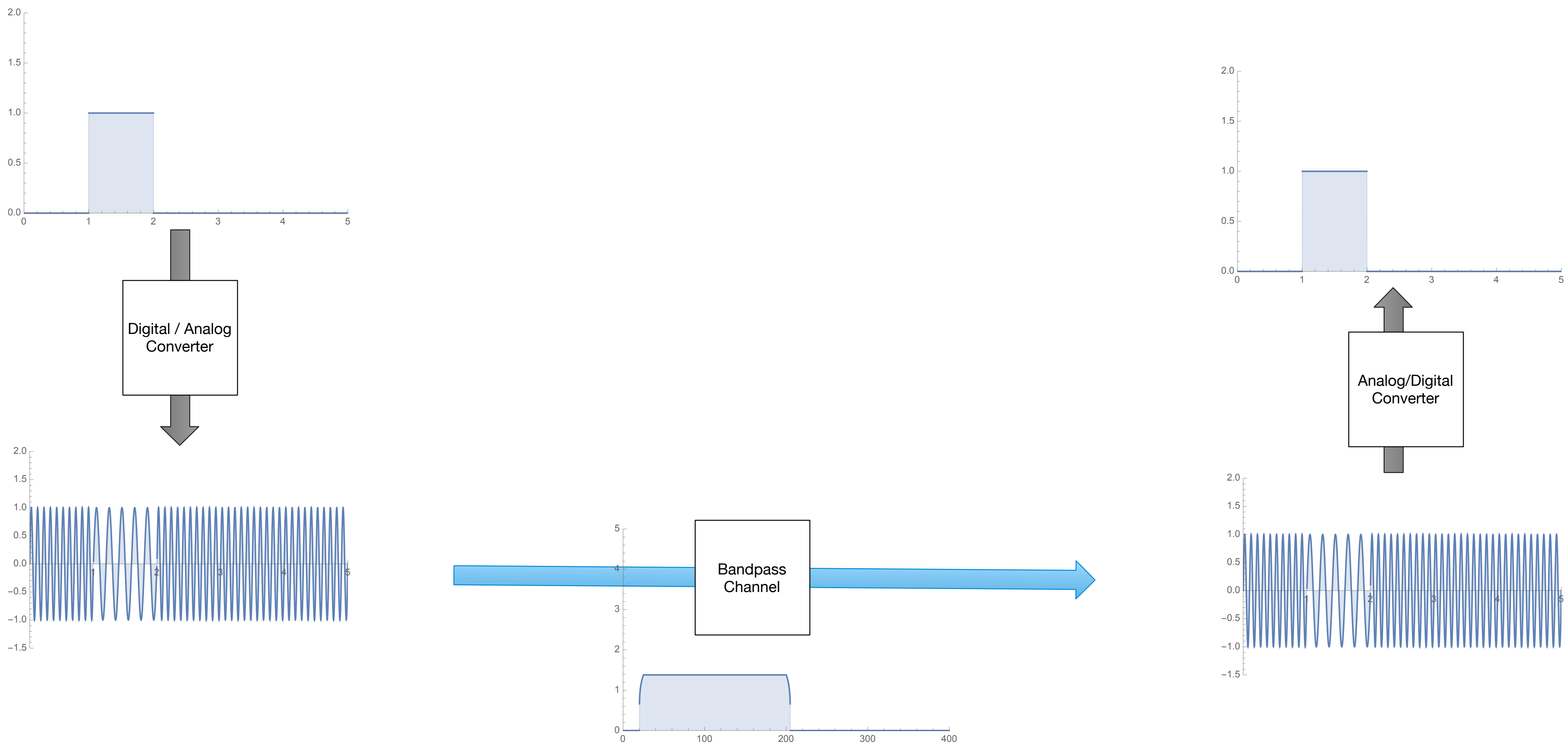
- A bandpass channel consists of an interval of frequencies

$$[f_l, f_u]$$



- This type of channel is more available than low—pass channels
- However, digital data now needs to be encoded

Broadband Transmission with Modulation



Broadband Transmission with Modulation

- Sending computer data through a telephone subscriber line
  - Line has a bandwidth of 0 - 4 KHz
  - Treated as a low-pass channel:
    - Capacity is 8kbps
  - Treated as a broadband line with a modem
- Digital Cellular Telephony
  - Analog voice is converted to a digital signal
  - Use multiple bandwidth channels to allow concurrent talks routed through the same hardware / medium

Analog to Digital Conversion

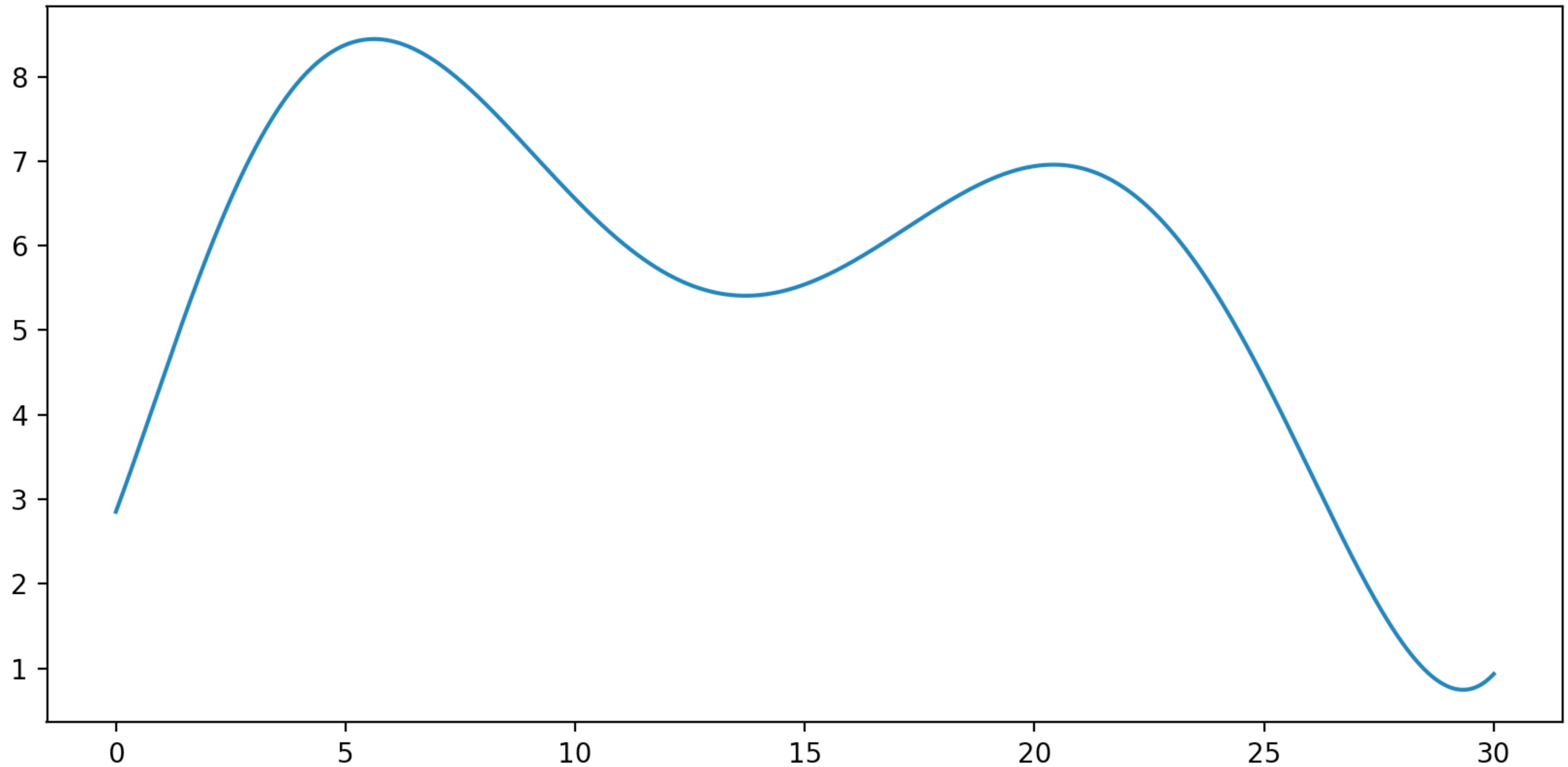
Analog to Digital Conversion

- Sometimes need to transmit analog data
  - E.g. microphone
  - E.g. camera
- Digitization: Transform data from analog to digital
  - We consider:
    - PCM: Pulse Code Modulation
    - Delta Modulation

Analog to Digital Conversion

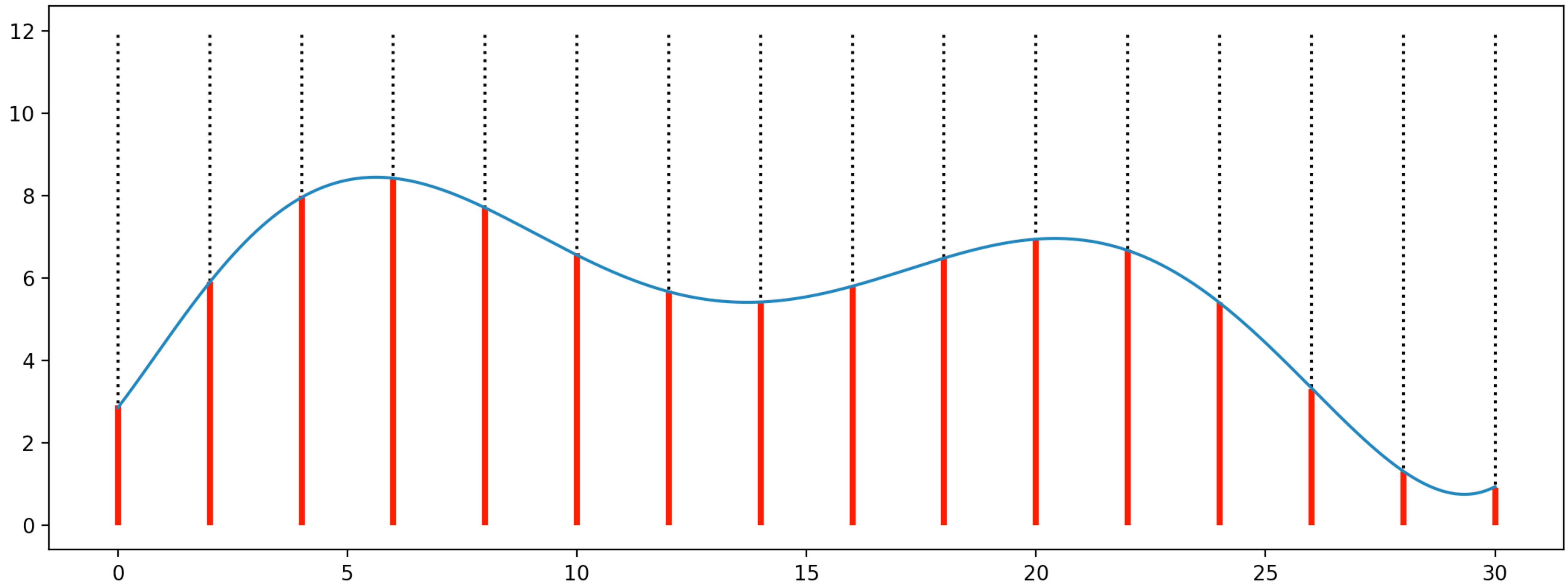
- Pulse Code Modulation
  - Sampling at given time intervals $\{i \cdot T_s \,|\, i = 0,1,\ldots\}$
  - Sampling frequency: $f_s = \dfrac{1}{T_s}$
  - Encoding: results in "Quantized Signal"

Analog to Digital Conversion



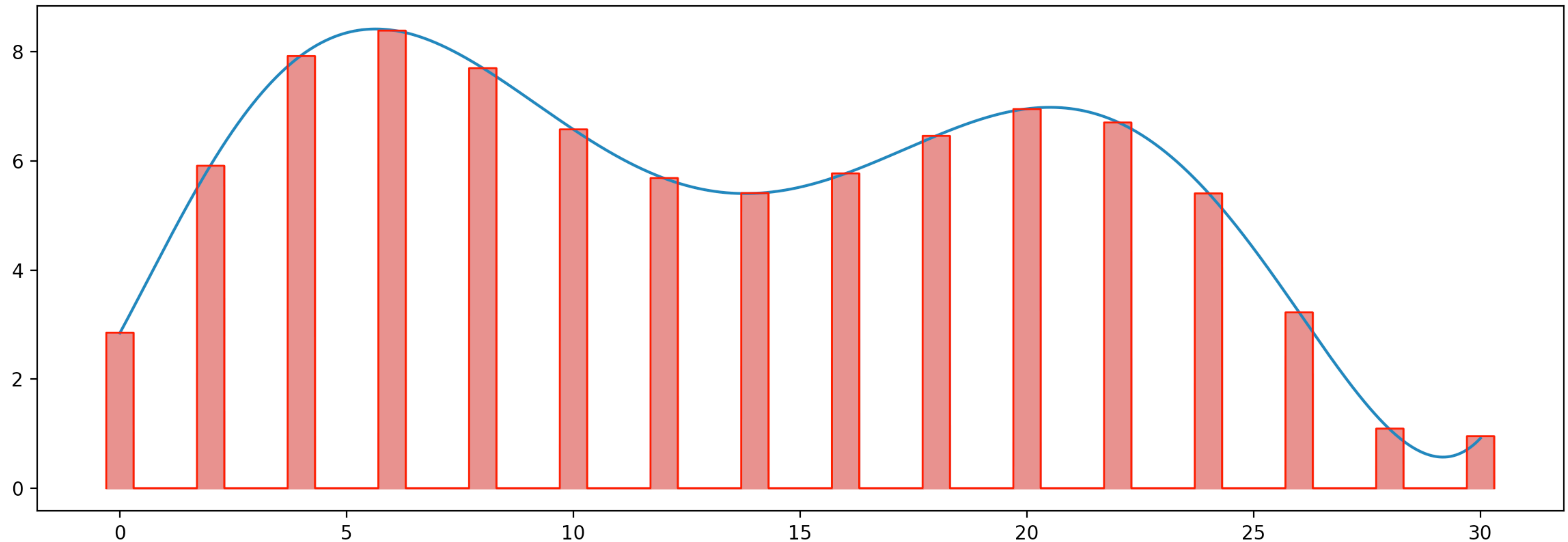
Analog Signal

Analog to Digital Conversion



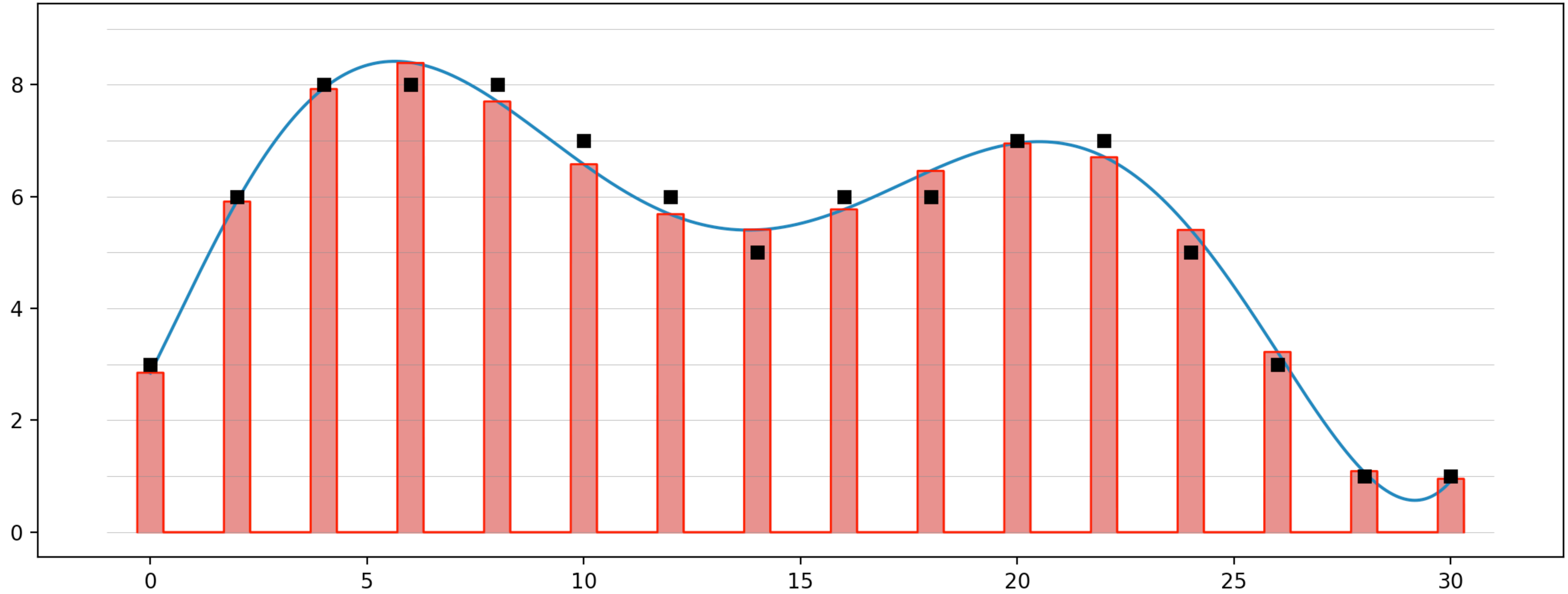
Ideal sampling: Measure pulse from analog symbols

Analog to Digital Conversion



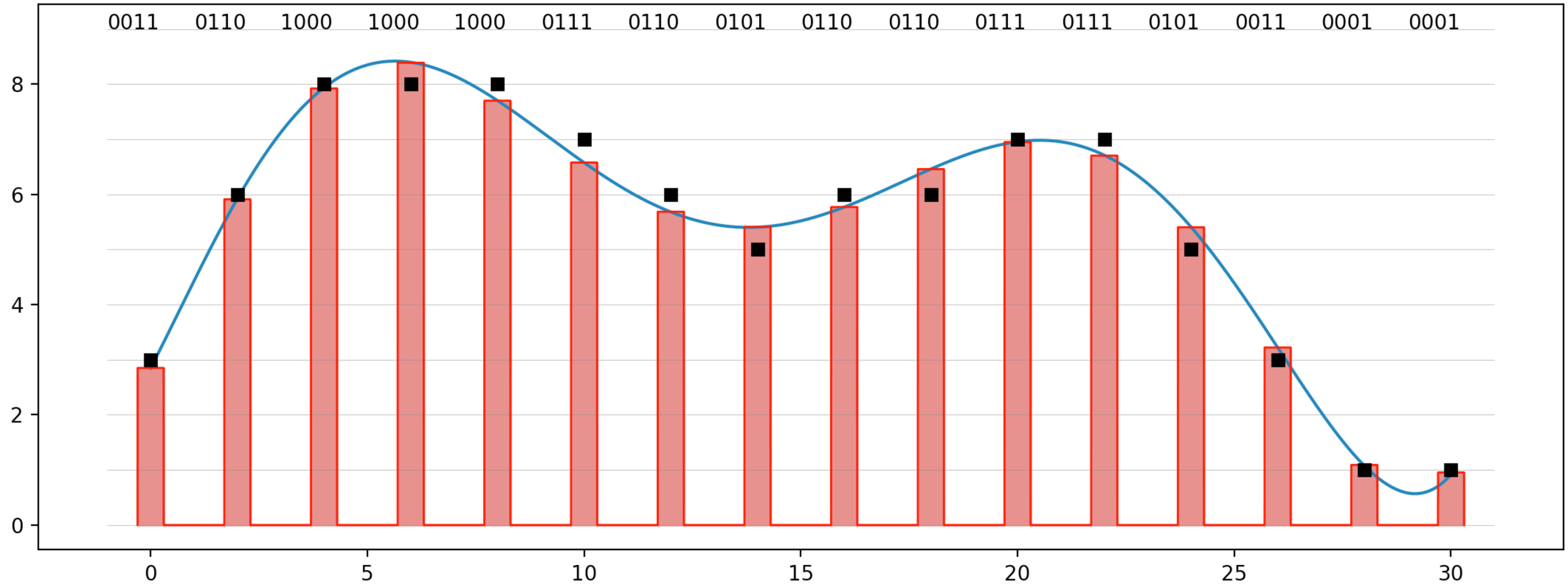
Natural sampling:
Get the average value of analog signal of a small interval by using a high-speed switch
"Flat-top sampling"

Analog to Digital Conversion



Quantize signal level
This introduces a quantization error

Analog to Digital Conversion



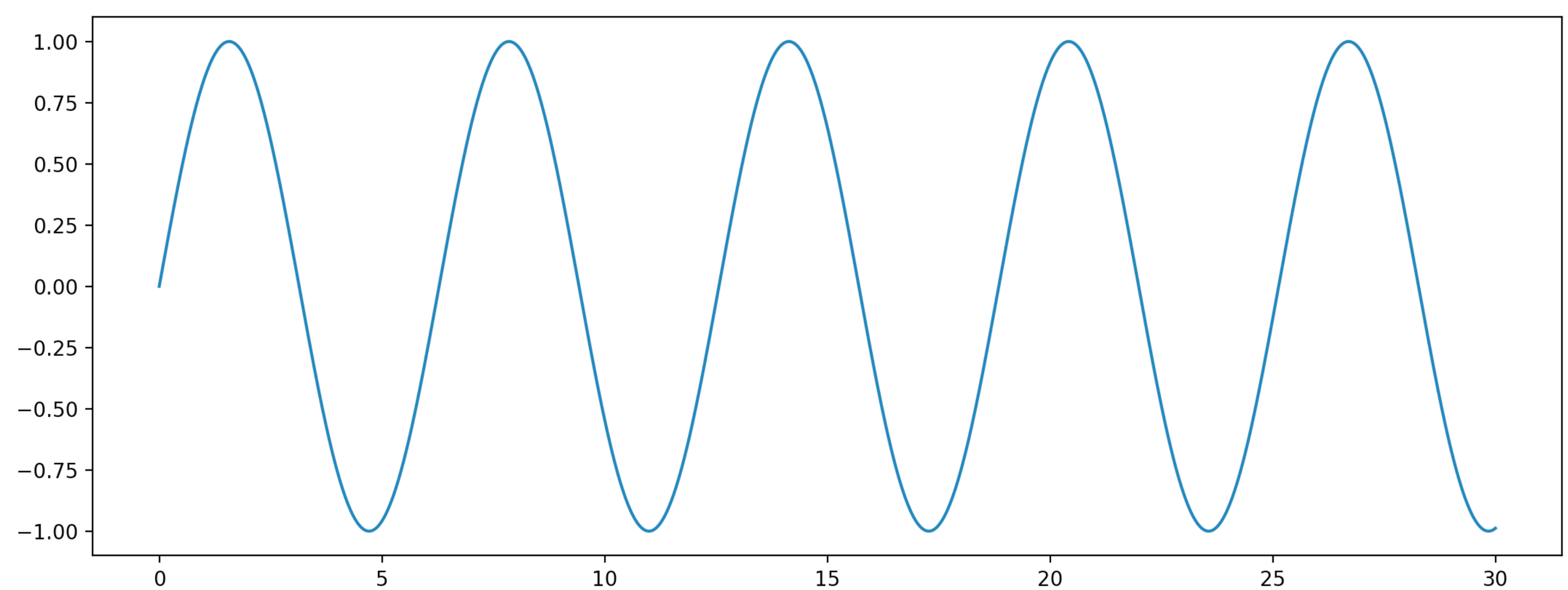
Encoding: Translate the quantized values to digital data

Analog to Digital Conversion

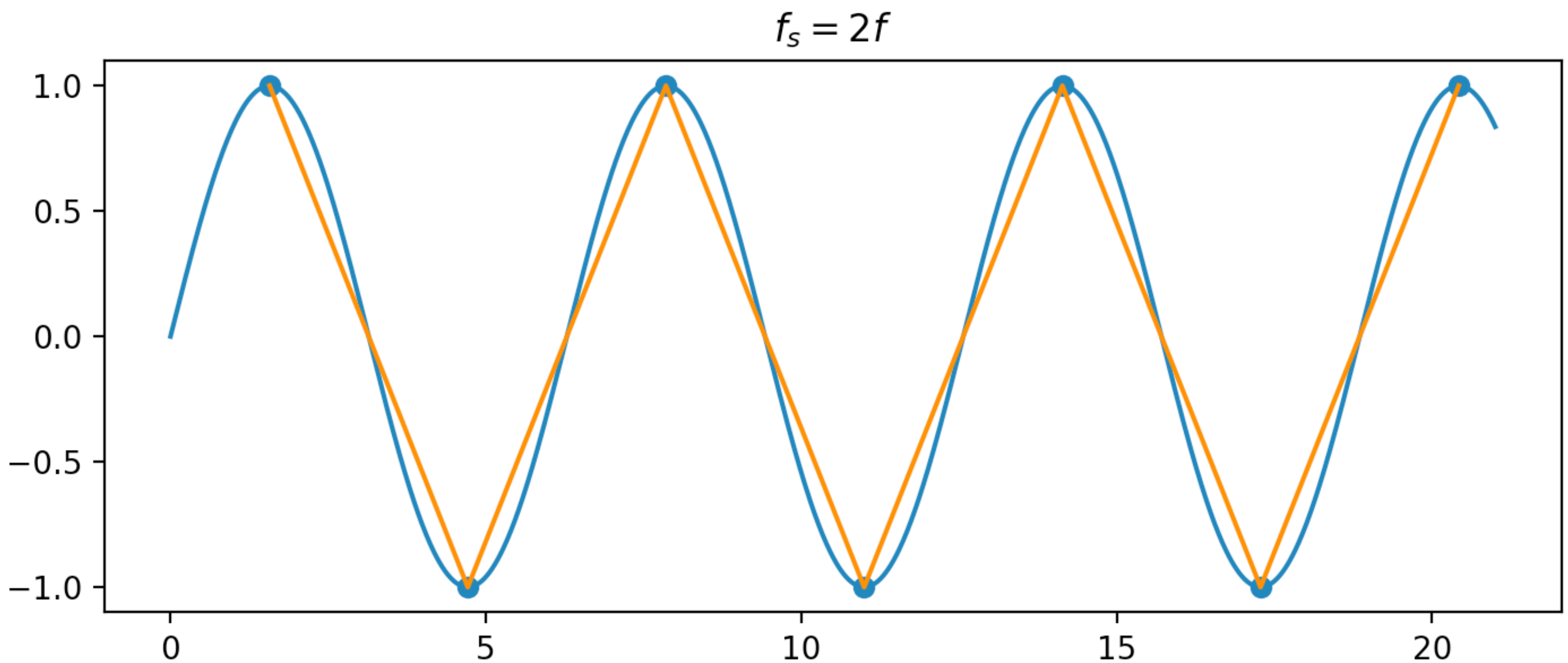
- Nyquist theorem:
  - Sampling rate must be at least twice as high as highest frequency contained in the signal

Analog to Digital Conversion

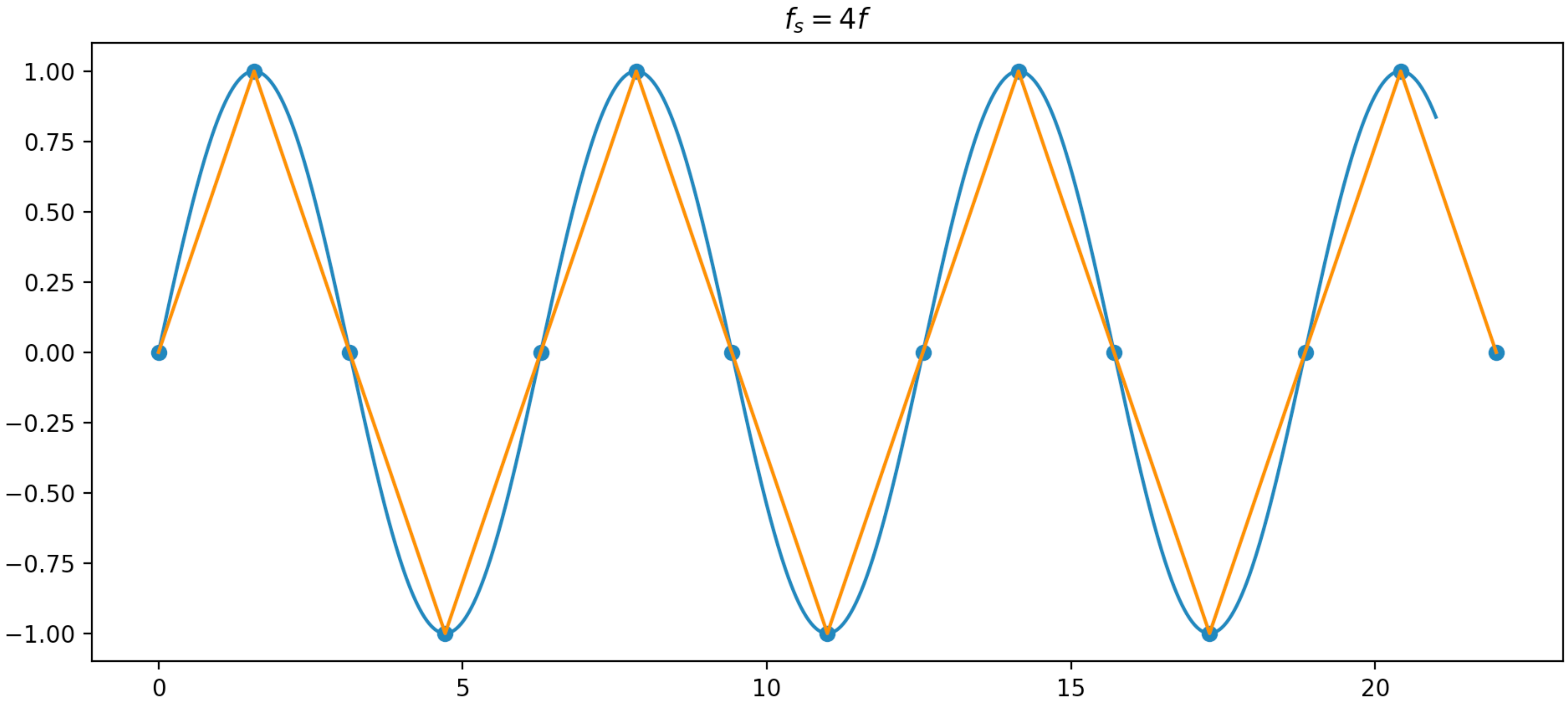
- Example:
  - Measure the position of a clock handle



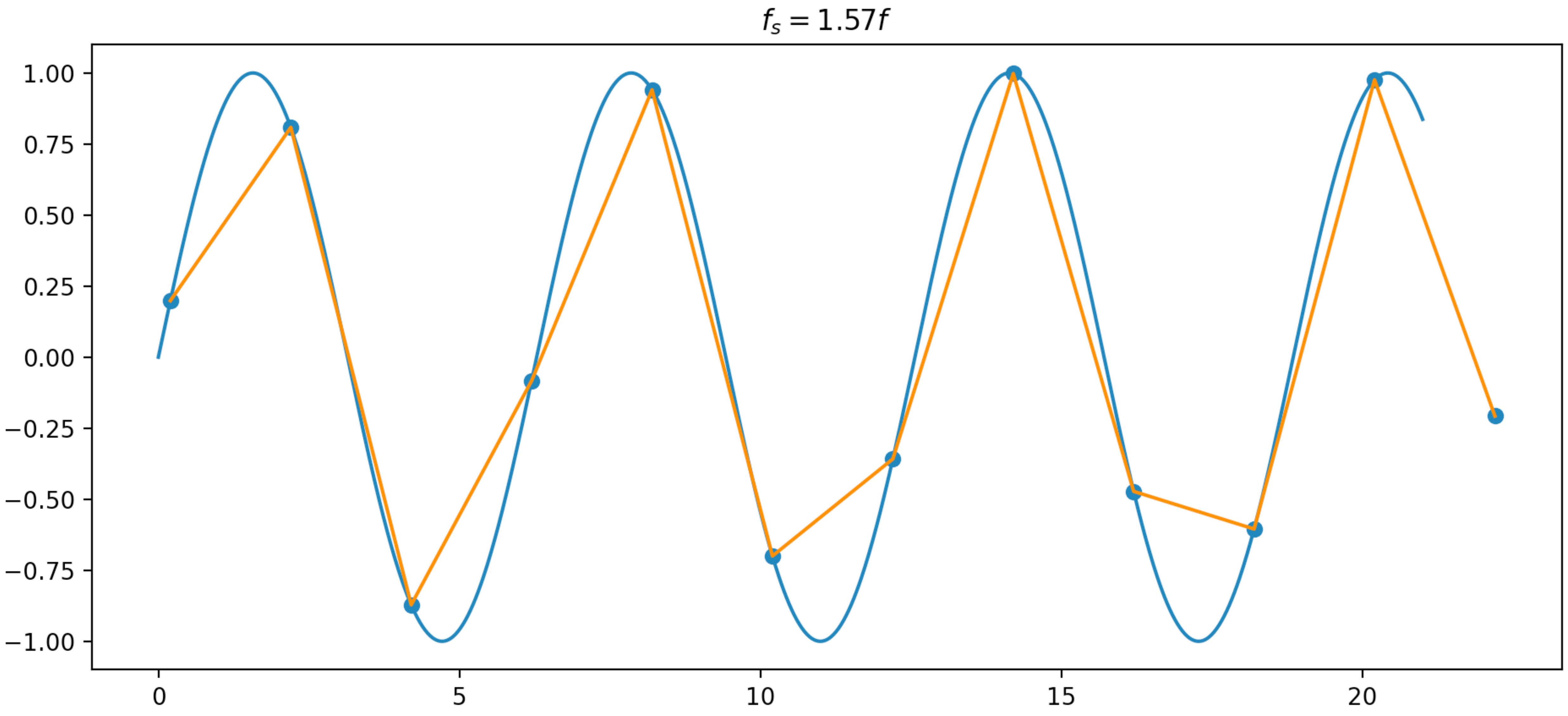
Analog to Digital Conversion



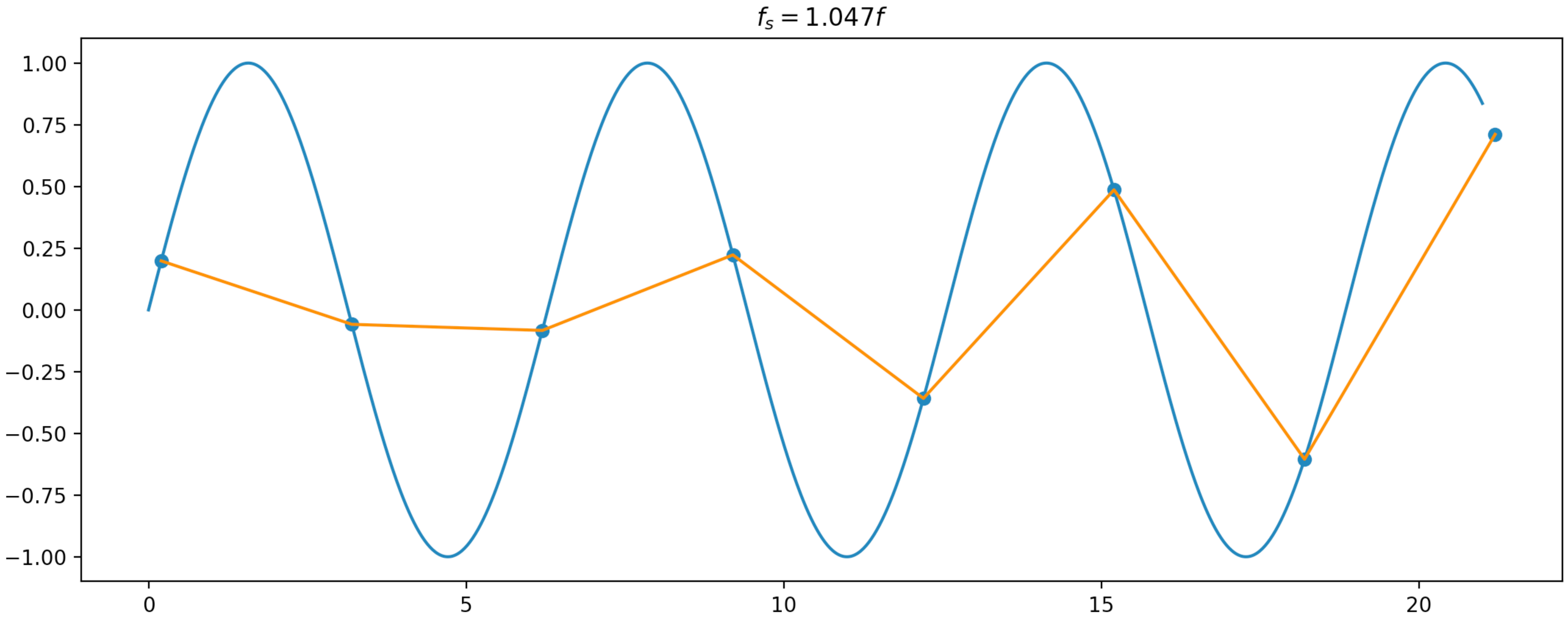
Analog to Digital Conversion



Analog to Digital Conversion



Analog to Digital Conversion



Analog to Digital Conversion

- Encoding:
  - Bit-rate = Sampling rate $\times$ number of bits per sample
    - $= f_s \times n_b$

Analog to Digital Conversion

- Quiz:
  - We want to digitize the human voice. The human voice has frequencies between 0 and 4000 Hz. Assume 8b per sample. What is the minimum bit rate?

- Answer:
  - We need to sample at rate 2×4000Hz
  - This gives $8000 \cdot 8$bps $= 64$Kbps

Analog to Digital Conversion

- Decoding:
  - Generate the quantized signal and smooth it via a low-pass filter

Analog to Digital Conversion

- Apply Nyquist sampling theorem on channel
  1. Low-pass bandwidth channel with bandwidth B
  2. Digital signal uses L levels ($r = 1/\log_2(L)$)
  3. Signal is passed through a low-pass filter to frequencies above B hz.
  4. Resulting signal is sampled at $2 \times B$ samples per second
  5. We can do no better than quantizing with L levels
  6. Resulting bit rate is:

$$N_{\text{max}} = 2 \times B \times \log_2(L) \text{ bps}$$

- This is the Nyquist Theorem

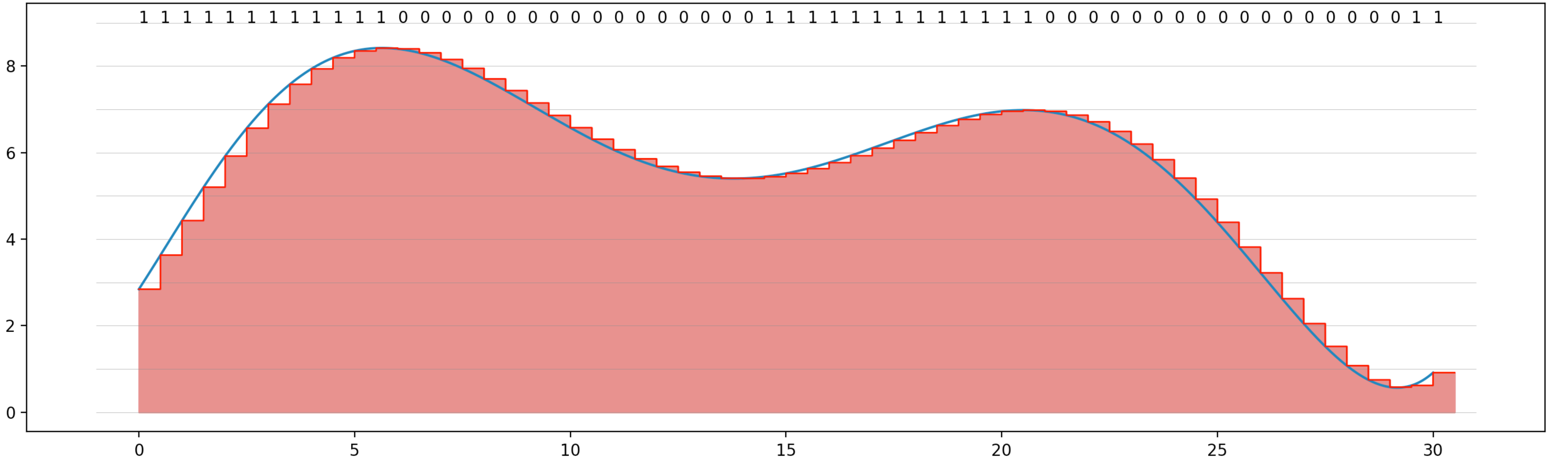
Analog to Digital Conversion

- Quiz:
  - If the signal has L levels.
  - Given a desired data rate of N bps, calculate the required bandwidth?

- Answer:
  - $N_{\text{max}} = 2 \times B \times \log_2(L)$
  - $B = \dfrac{N}{2 \times \log_2(L)}$

Analog to Digital Conversion

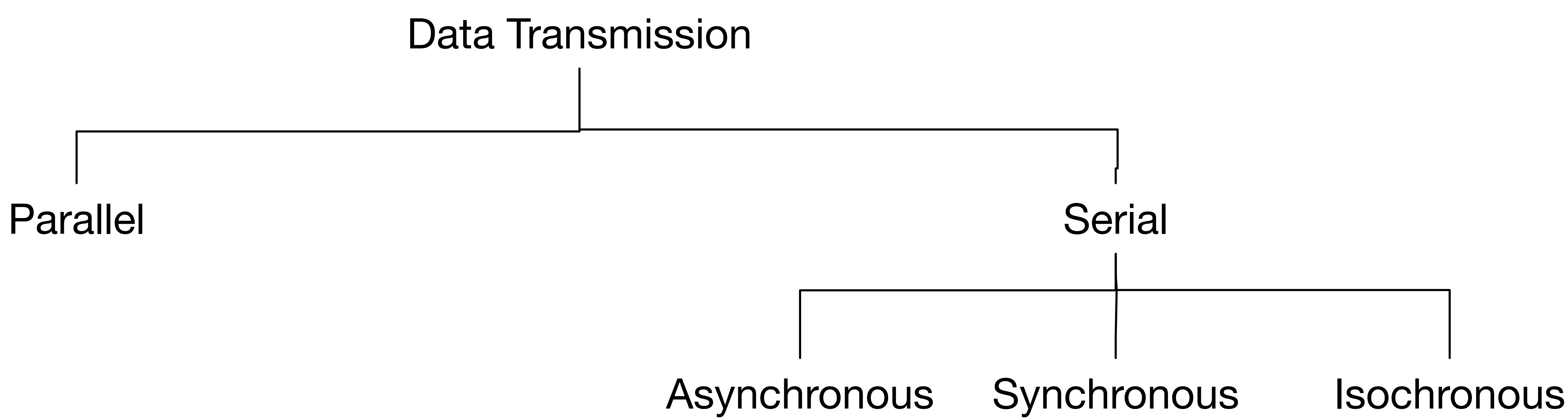
- Delta Modulation
    - Store previous signal value
    - Compare with current value:
    - Go up: 1, Go down: 0



Analog to Digital Conversion

- Delta modulation:
  - Better version: Adaptive delta modulation
    - Use more bits to represent the difference

Transmission Modes



Transmission Modes

- Parallel transmission:
  - Uses n wires to transmit n signals simultaneously
  - Can add more wires for control & clocking
- If there would be no electromagnetic interference:
  - Could transmit n times content then over a single wire

Transmission Modes

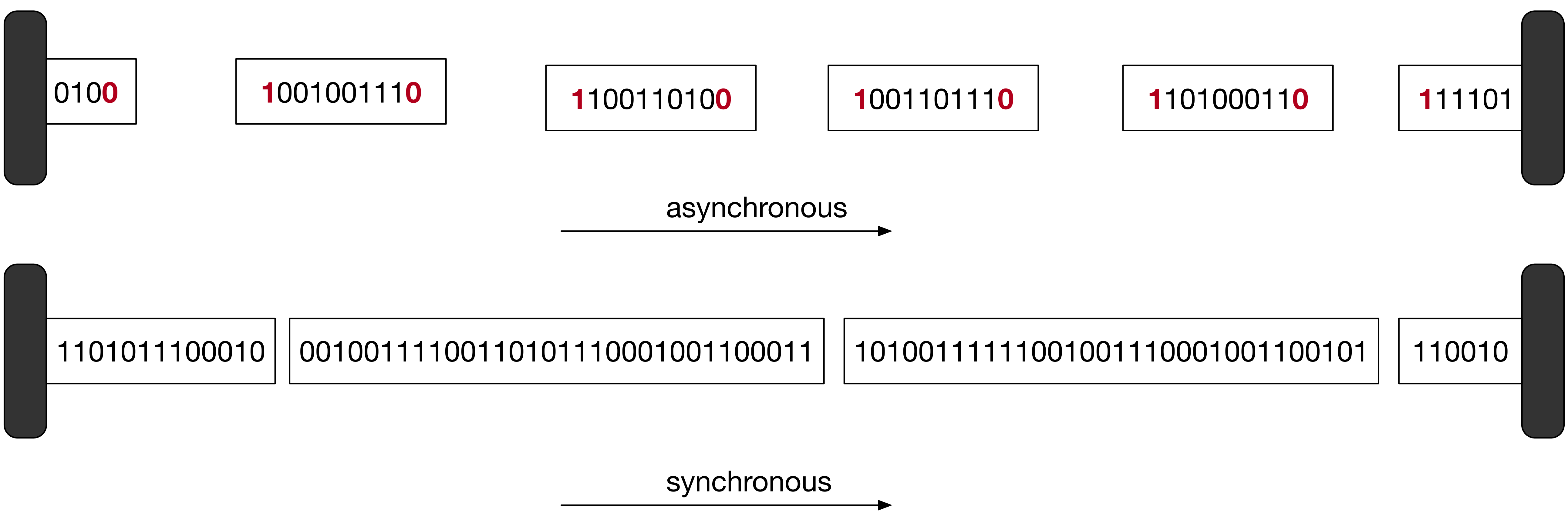
- Asynchronous transmission
  - Timing is unimportant
  - Data is grouped
  - At the beginning of transmission of a group: start bit
  - Send data group: Each element at a fixed time
  - At the end: end bit(s)
  - Followed usually by a gap

Transmission Modes

- Quiz:
  - Asynchronous transmission:
    - If we group data in bytes, how many bits are transferred?
- Answer:
  - 8 bits data + 1 start bit + 1 end bit (+ gap)

Transmission Modes

- Synchronous transmission
  - Data is grouped into larger units: Data frames
  - Receiver uses timing to recover individual data units



Transmission Modes

- Isochronous:
  - Real-time audio / video: Uneven delays between frames is not accepted
  - Data arrives at a fixed rate

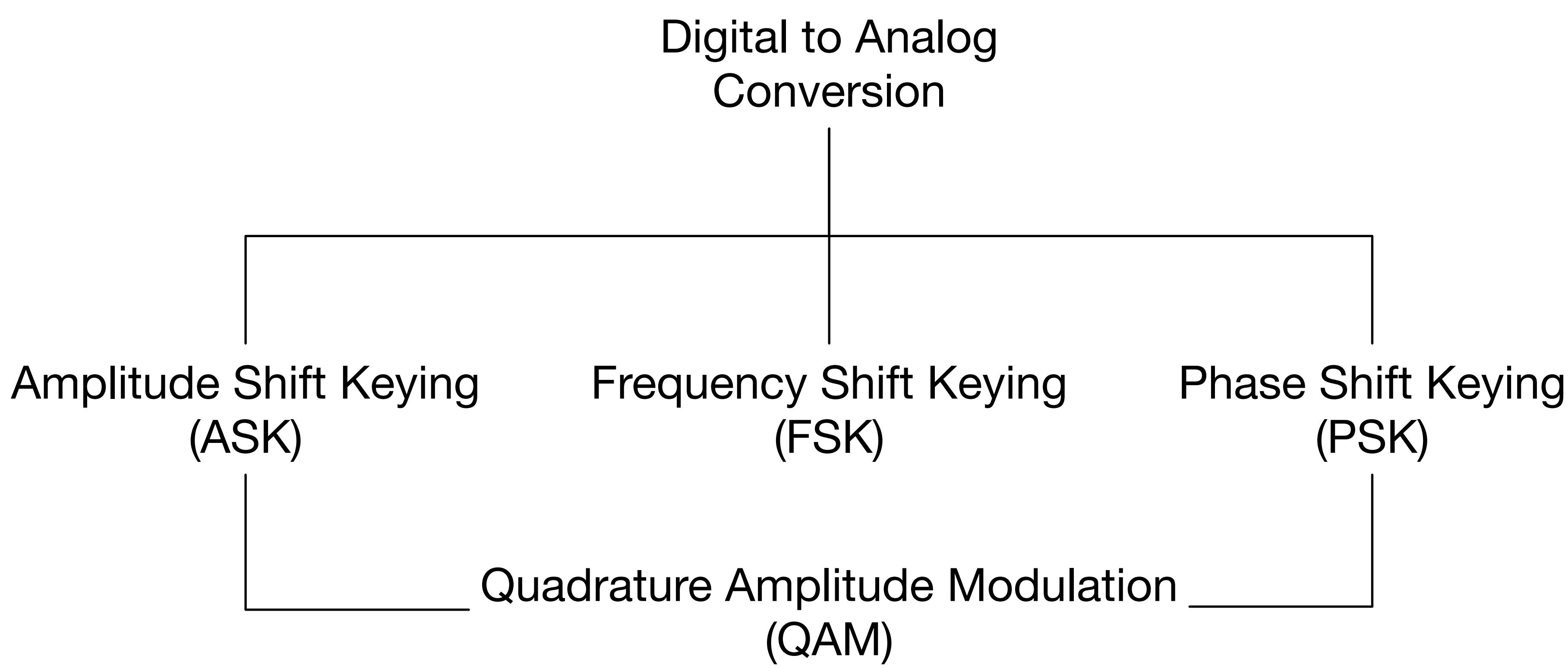
Analog Transmission

Analog Transmission

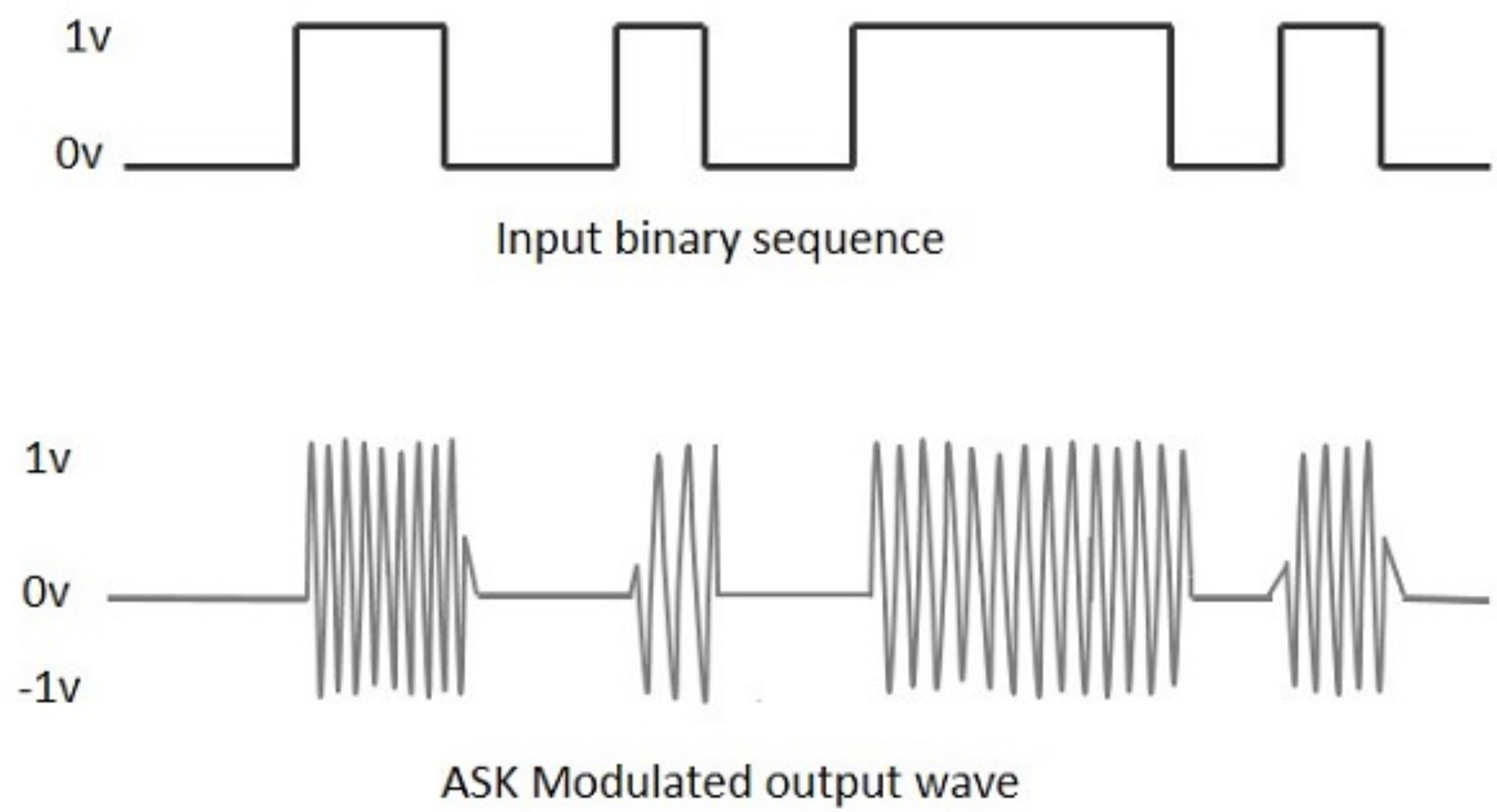
- Digital to analog conversion
- Analog to analog conversion

Digital to Analog Conversion

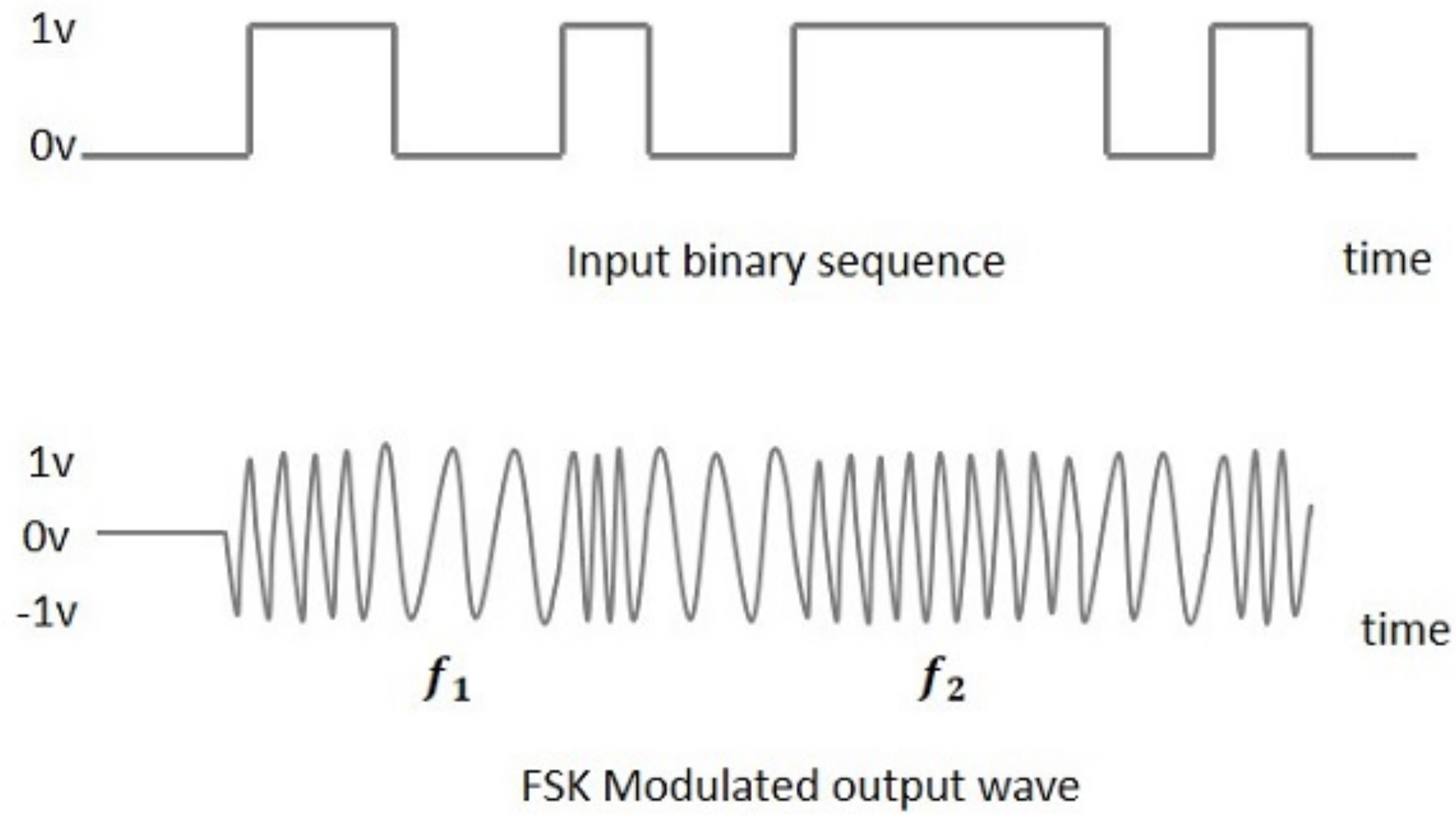
- Convert digital data to bandpass analog signal



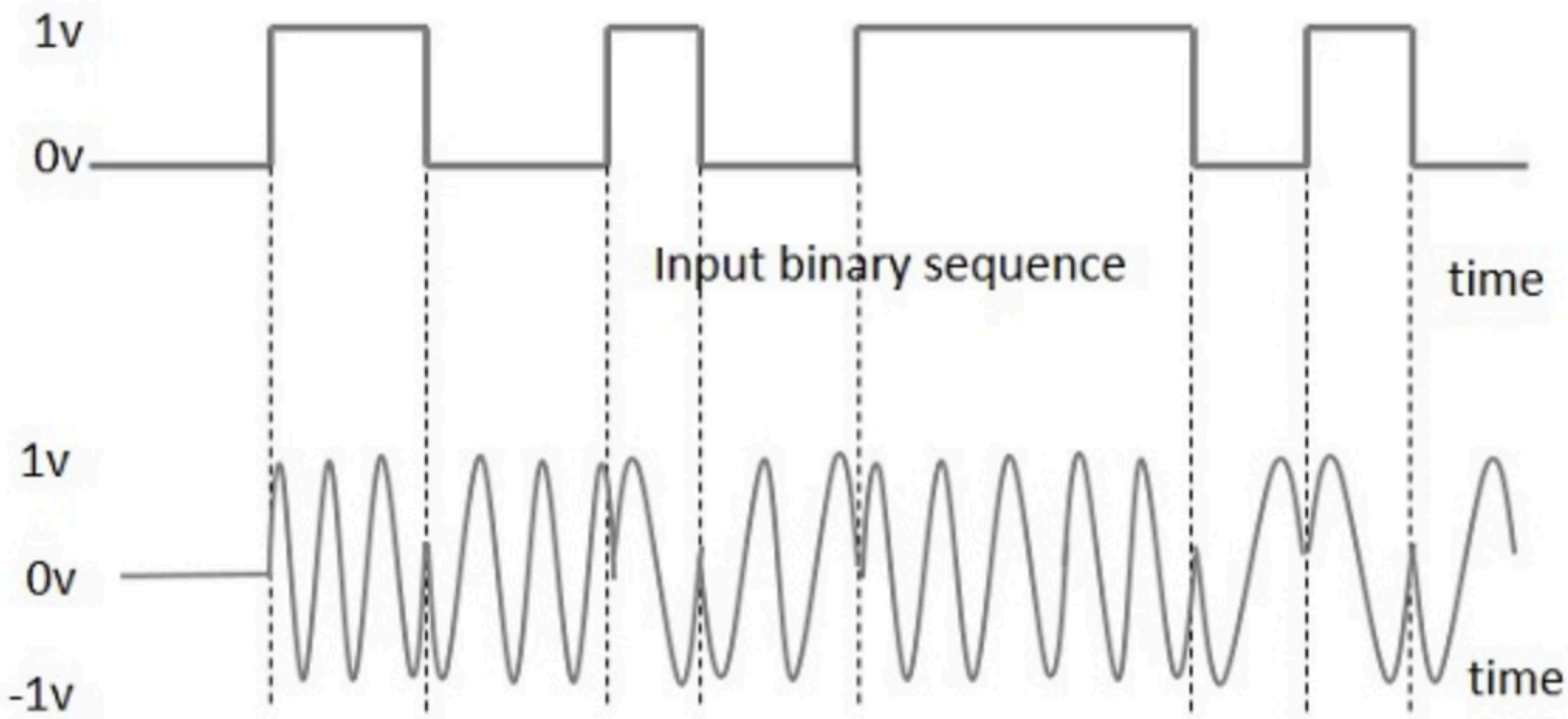
Digital to Analog Conversion



Digital to Analog Conversion



Digital to Analog Conversion



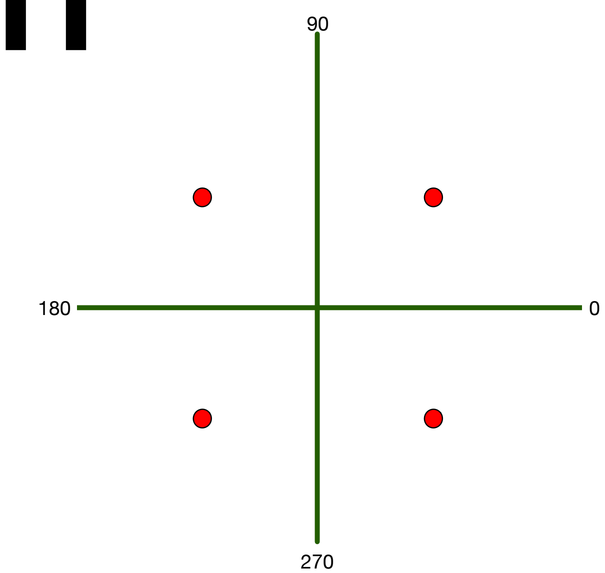
Binary Phase Shift Key

Digital to Analog Conversion

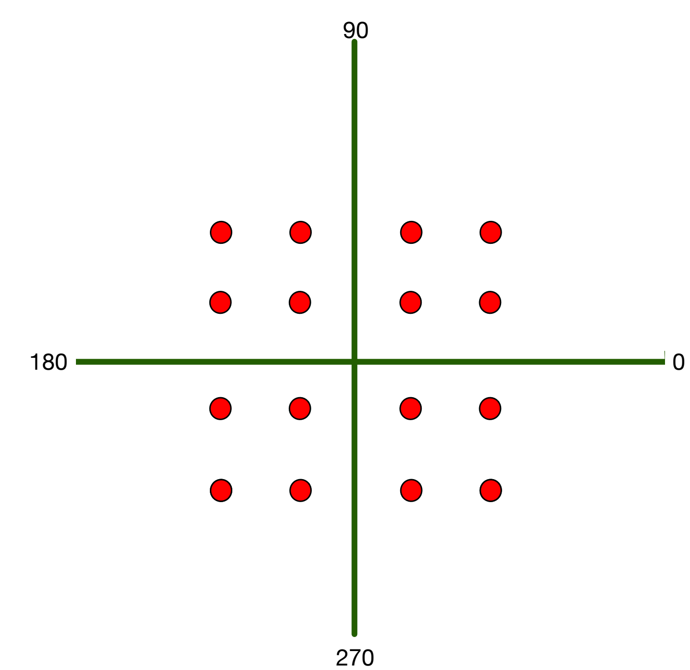
- Quadrature Phase Shift Key
  - Use 2-bits at a time
  - Transmit one bit using amplitude modulation via signal with phase 0º
  - Transmit one bit using amplitude modulation via signal with phase 180º
  - Result is a sine wave with phase 45º, -45º, 135º, -135º

Digital to Analog Conversion

- Can combine schemes to combine amplitude and phase
  - QPSK: 4 shifts
  - QAM-16: 16 combinations of amplitude and shift (4b per data symbol)
  - QAM-64: 64 combinations or 8 data bits per symbol



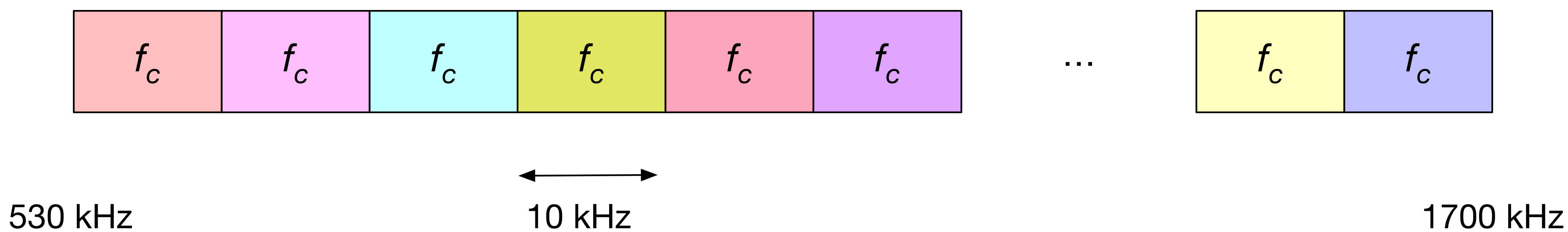
QPSK



QAM-16

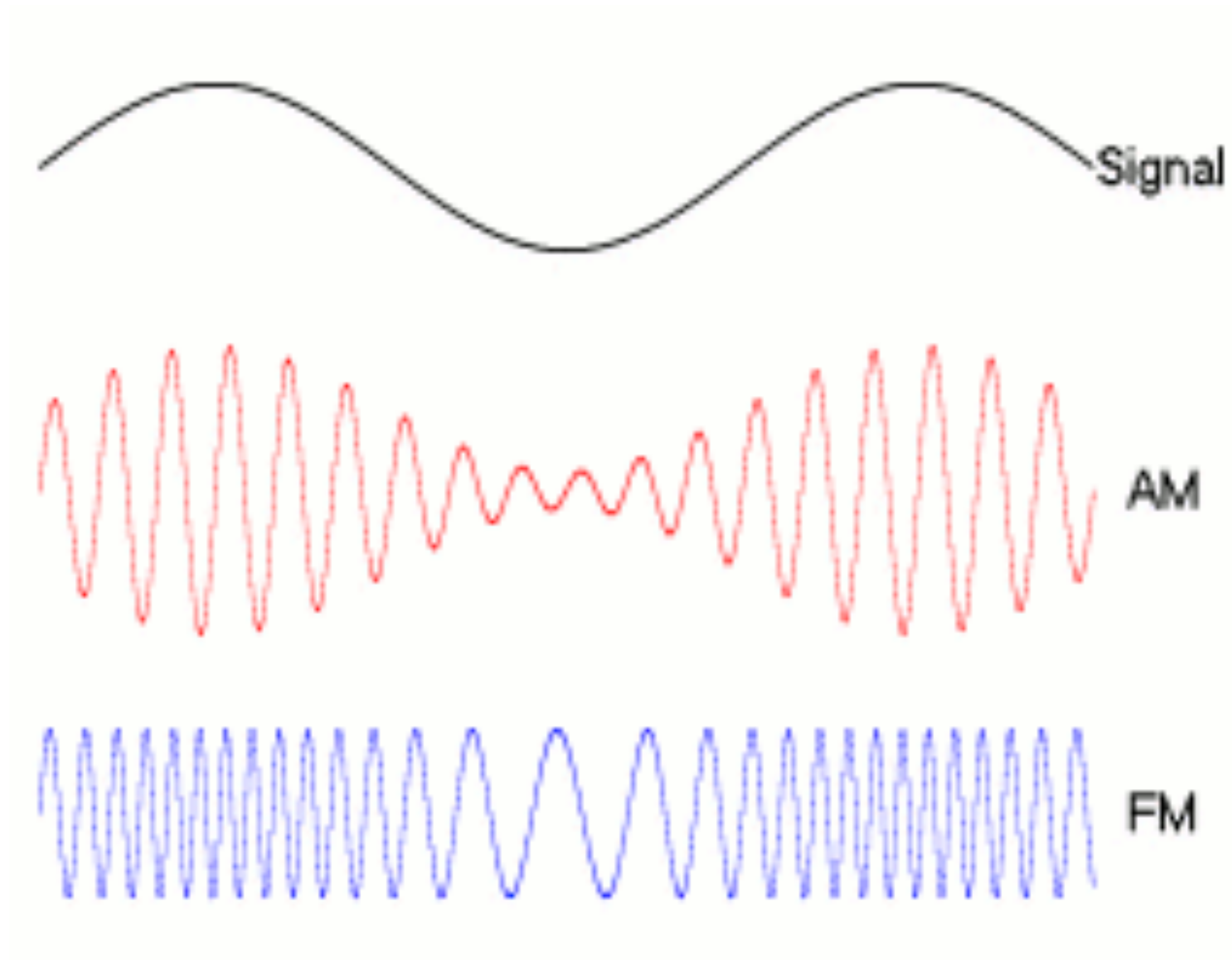
Analog to Analog Conversion

- Analog to Analog
  - Make the signal fit for a bandpass medium
  - E.g. AM radio bands:



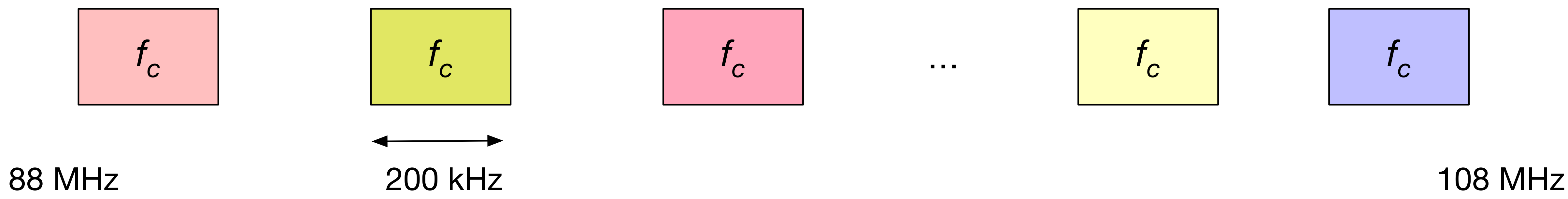
  - Amplitude Modulation
  - Frequency Modulation
  - Phase Modulation

Analog to Analog Conversion



Analog to Analog Conversion

- FM Radio Bands



Analog to Analog Conversion

- Phase modulation
  - Like FM with change in the frequency proportional to the derivative of the amplitude of the message signal