Computer Networks

Physical Layer

Physical Layer

| Application |
| Presentation |
| Session |
| Transport |
| Network |
| Data Link |
| Physical |
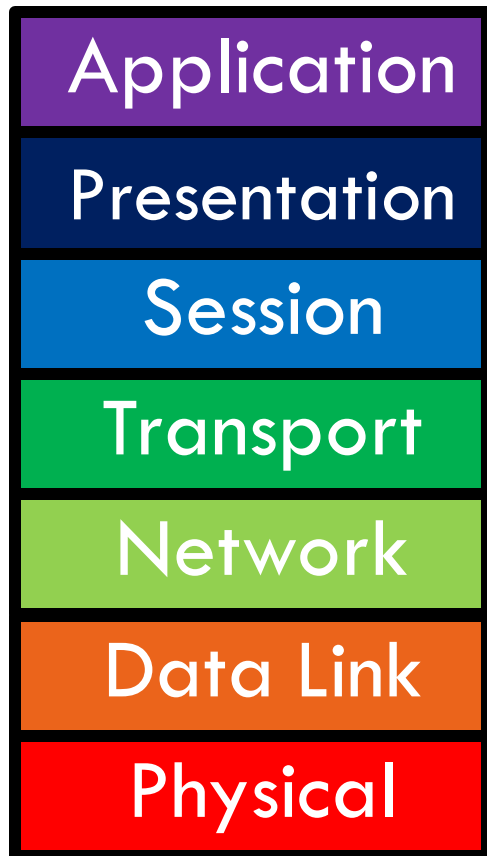
- Function:
  - Get bits across a physical medium
- Key challenge:
  - How to represent bits in analog
  - Ideally, want high-bit rate
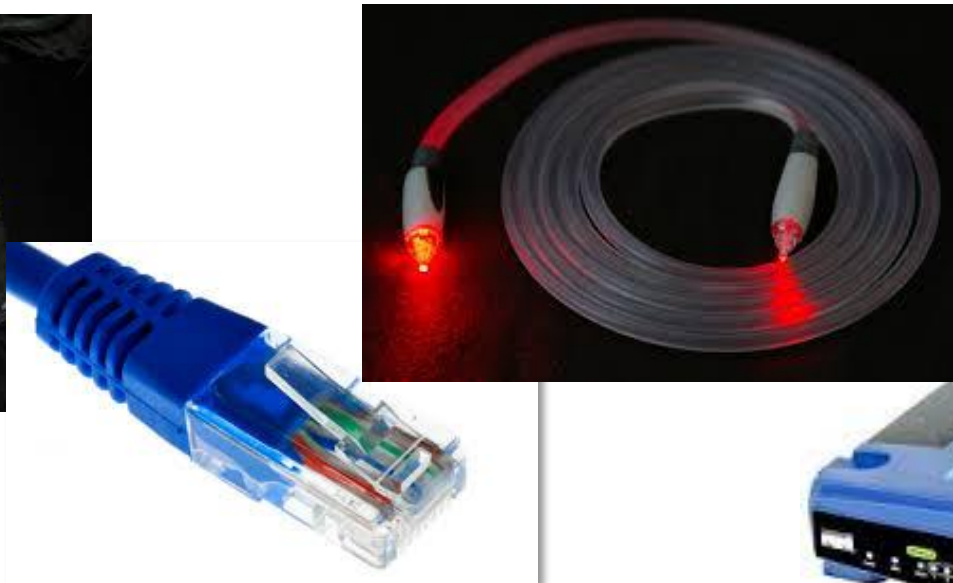 - But, must avoid desynchronization

Key challenge

- Digital computers
  - 0s and 1s
- Analog world
  - Amplitudes and frequencies

Simple transmission - baseband

- Bit 1: voltage or current strength
- Bit 0: no voltage

Converting bits to voltage
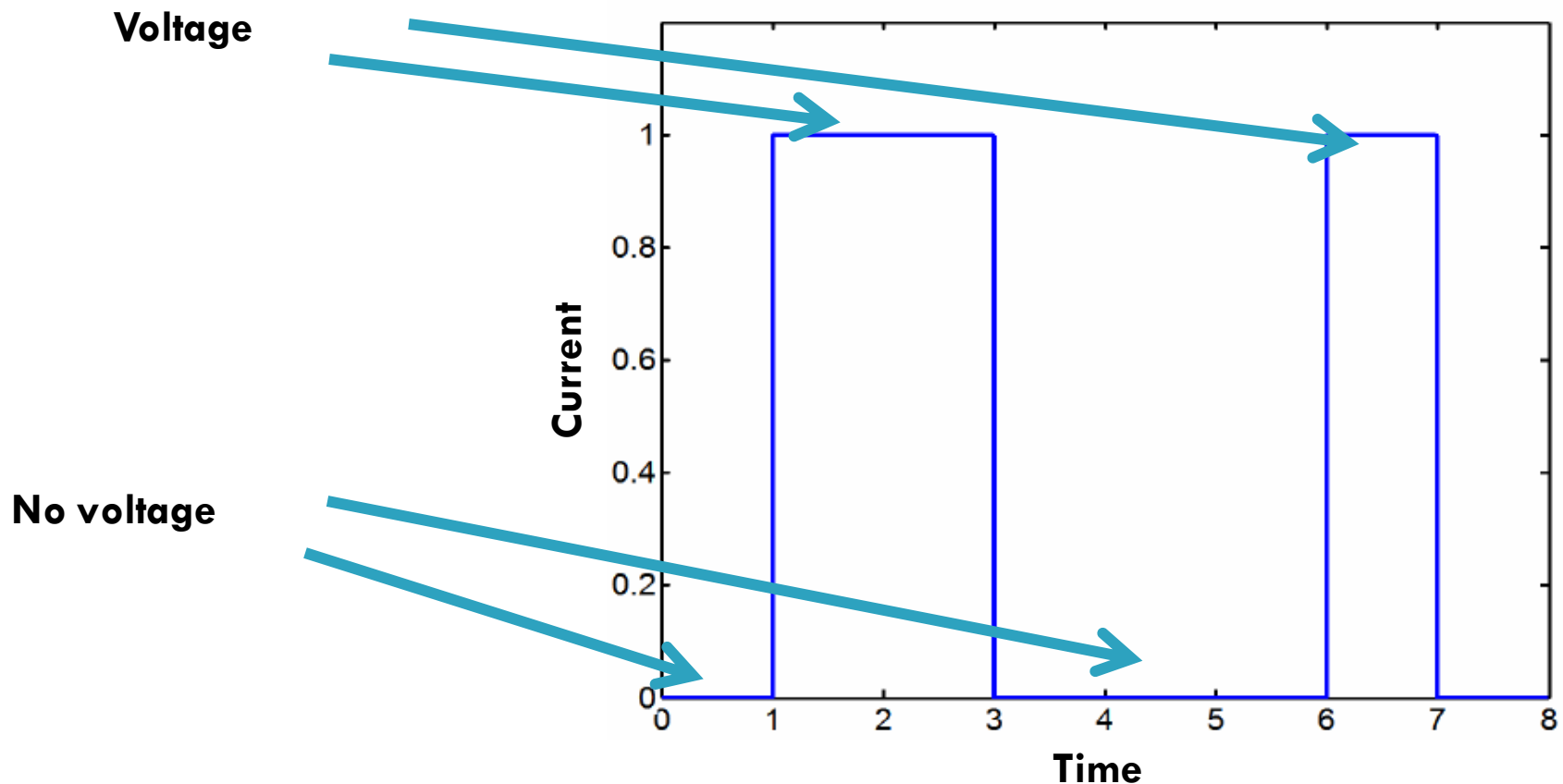
Bit 1: The switch is turned on.
Bit 0: It is turned off.

Converting valtage to bits

Voltage: Bit 1
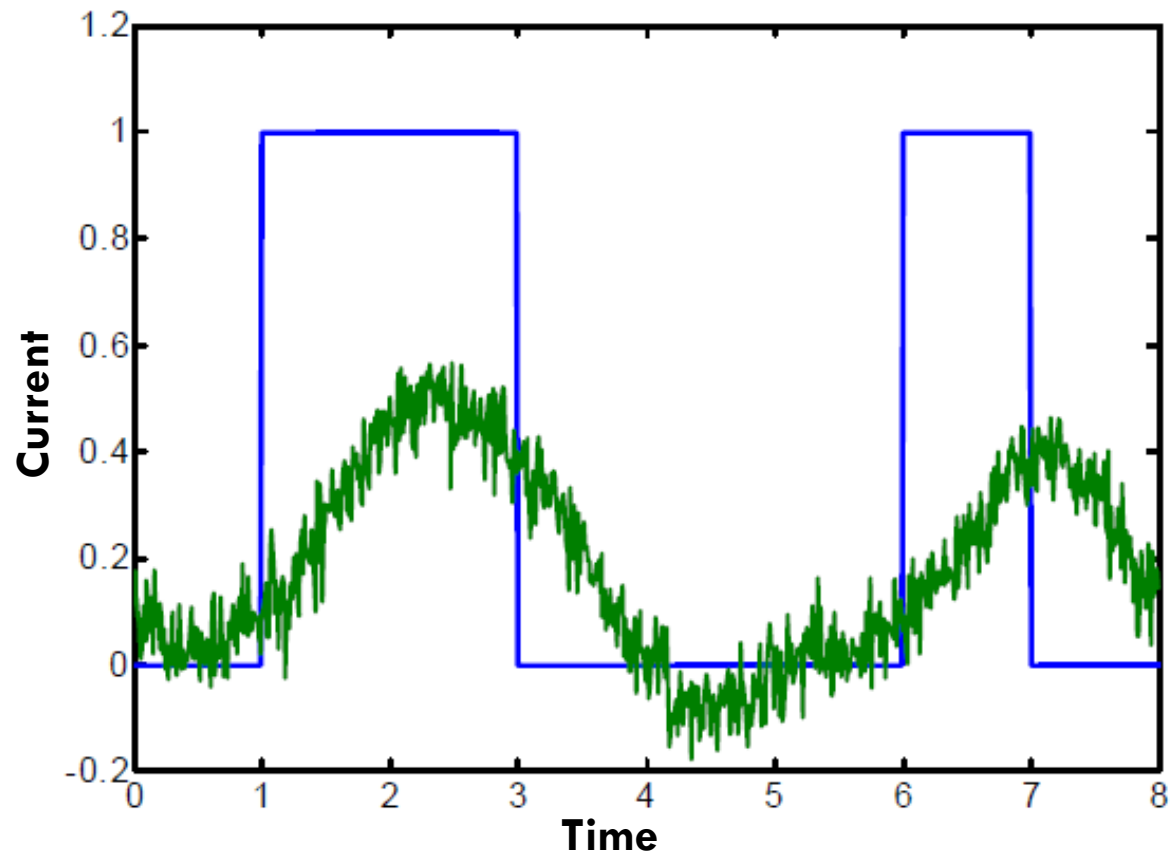No voltage: Bit 0

Transmission of „b"

- More than one bit is needed for tranmitting char „b"
- „b" in ASCII: 01100010

Transmission of „b" in a real world

□ Poor reception – a typical pattern at the receiver

Fundamentals – Singals

To understand signal propagation on a physical medium, some background is required how such signals can be analyzed/treated mathematically

First: Fourier's theorem

Any periodic function **g(t)** (with period T) can be written as a (possibly infinite) sum of sine and cosine functions; the frequencies of these functions are integer multiples of the base frequency f = 1/T.

$$g(t) = \frac{1}{2}c + \sum_{n=1}^{\infty} a_n \sin(2\pi n f t) + \sum_{n=1}^{\infty} b_n \cos(2\pi n f t),$$

where $f = \frac{1}{T}$ is the base frequency, a_n and b_n are constants, representing the amplitudes of nth sine and cosine harmonics. C is a constant.
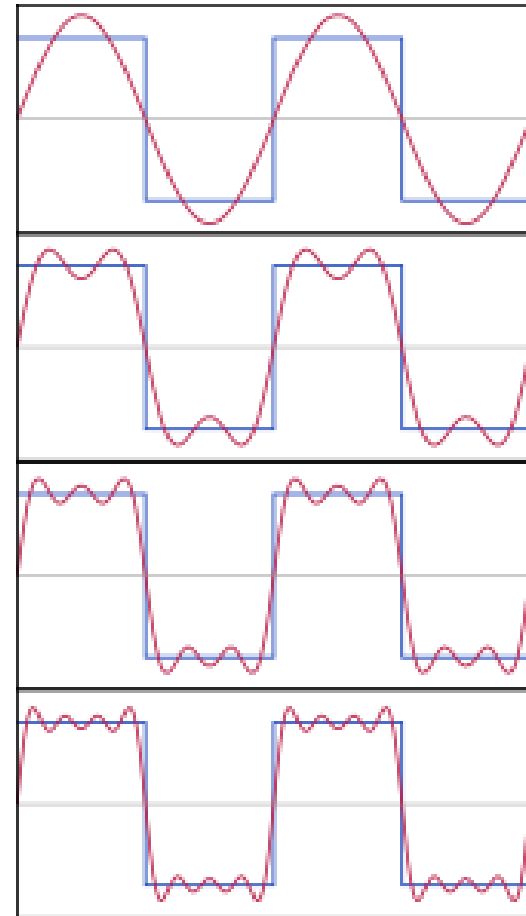
Fundamental – Terms of the Fourier series
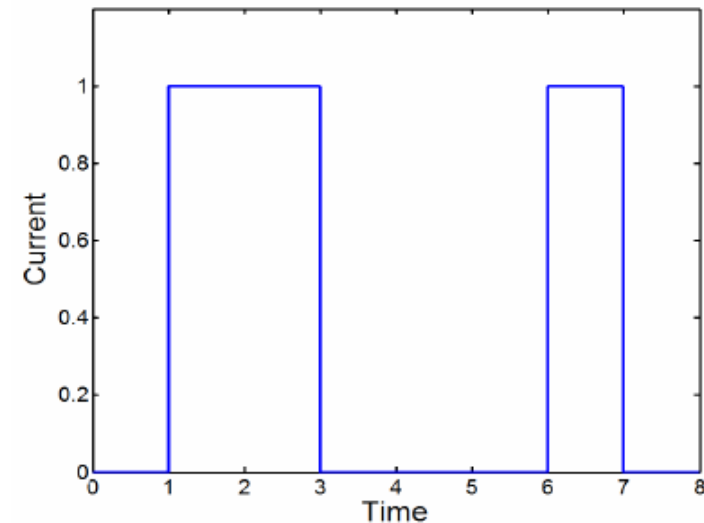
$$a_n = \frac{2}{T} \int_0^T g(t) \sin(2\pi n f t)\, dt$$

$$b_n = \frac{2}{T} \int_0^T g(t) \cos(2\pi n f t)\, dt$$
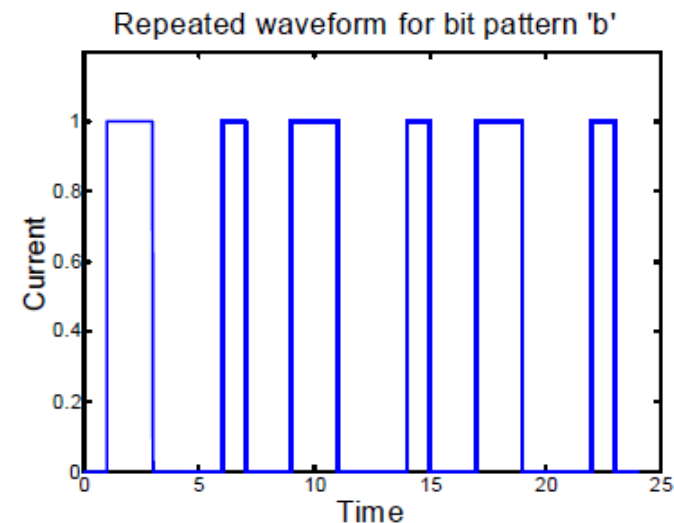
$$c = \frac{2}{T} \int_0^T g(t)\, dt$$

Application

- A digital signal is not periodic
  - E.g. the ASCII code of „b" is 8 bits long

- Use a trick: Suppose waveform is repeated infinitely often,
- For „b", resulting in a periodic waveform with period 8 bit times

Repeated waveform for bit pattern 'b'
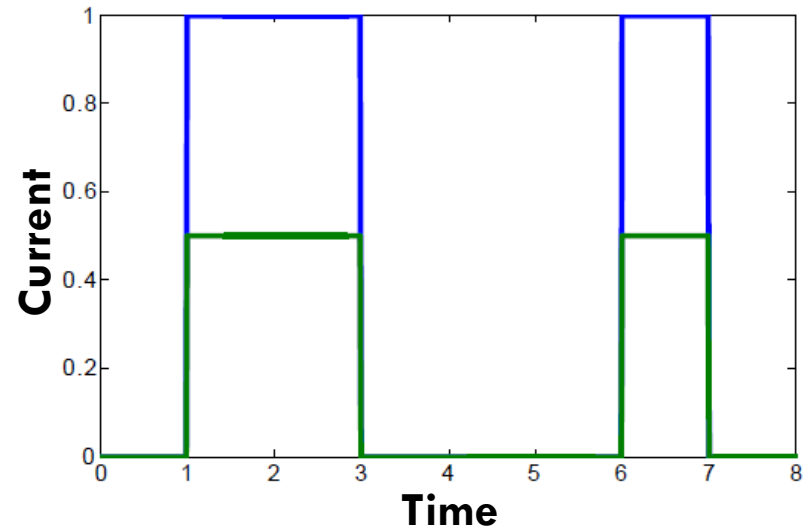
Fundamentals - Attenuation

- Attenuation: α
  - Ratio of transmitted (P_0) and received (P_1) power
  - High attenuation $=$ little power arrives at receiver
    - Making the understanding of signal difficult
  - Typically given in deciBel

$$\alpha[in\ dB] = 10 \times \log_{10} \frac{P_0}{P_1}\ (deciBel\ [dB])$$

- It depends on
  - Physical medium
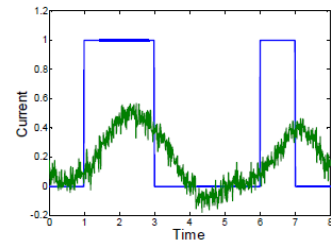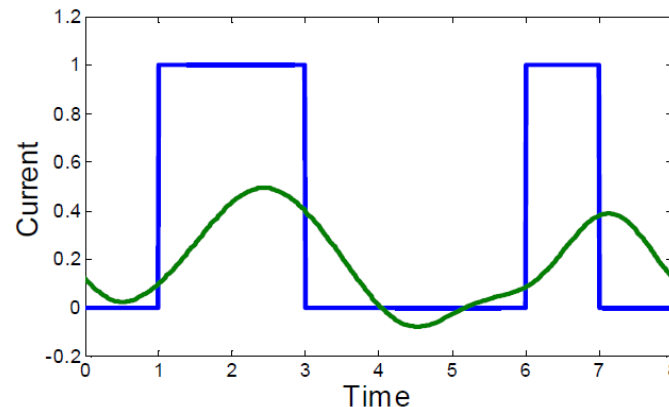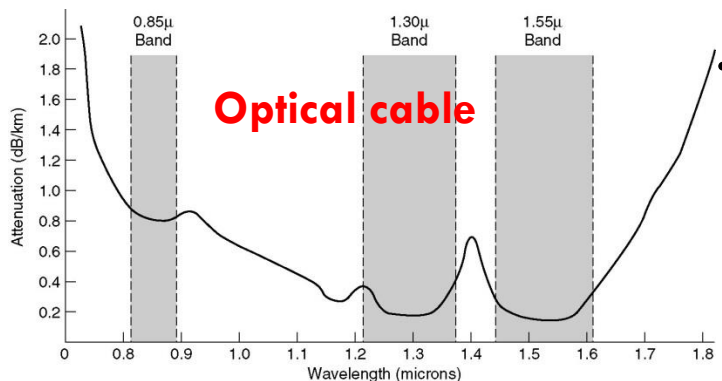 - Distance between sender and reciever
  - … others

Fundamentals - Attenuation

- ☐ In reality
  - ▪ Attenuation is not uniform, depends on frequency
  - ▪ Not all frequencies pass through a medium
  - ▪ Phase shifting
    - ▪ Different frequencies have different signal propagation speed
    - ▪ Frequency-based disortion
  - ▪ Noise

Optical cable

Symbols and bits

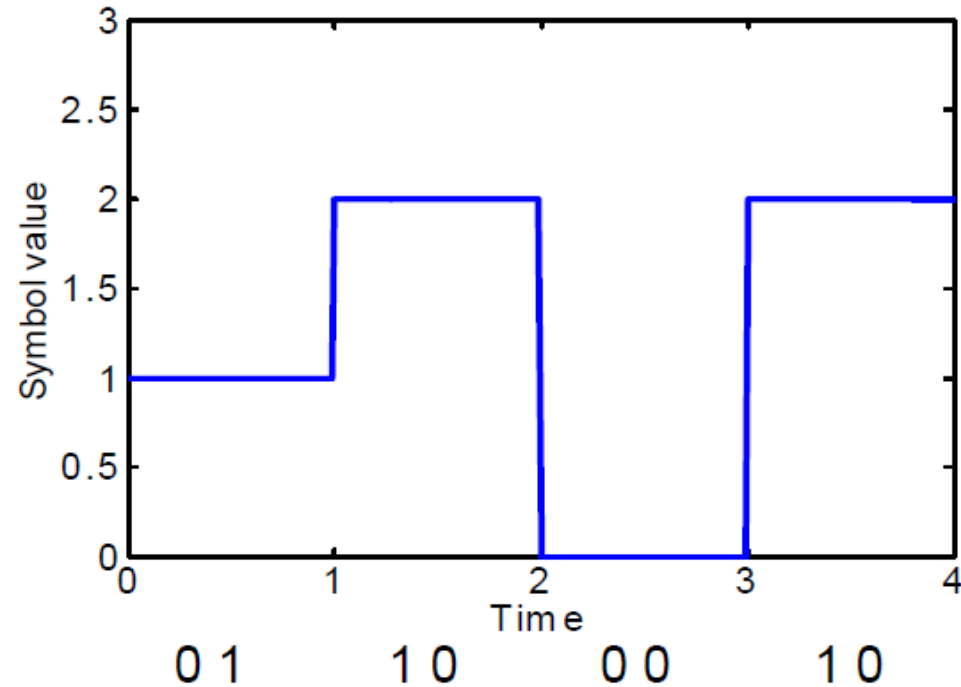- Use more symbols than 0 and 1 in the channel
- Example:
  - Having 4 symbols: A(00),B(01),C(10),D(11)
  - Symbol rate: (BAUD)
    - Transmitted symbols per sec
  - Data rate (bps):
    - Transmitted bits per sec

0 1   1 0   0 0   1 0

Example:
A 600 Baud modem with 16 symbols, one can reach data rate of 2400 bps.
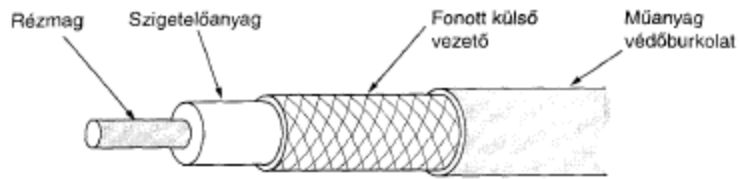
- **Magnetic storage** – e.g. never underestimate the power of a truck of hard disks
- **Twisted pair** – telephone networks; double copper wire, both analog and digital; UTP and STP
- **Coaxial cable** – Higher speed and larger distance than with twisted pair; analog (*75 Ω*) and digital (*50 Ω*)
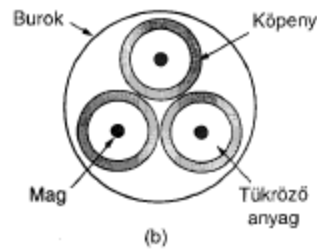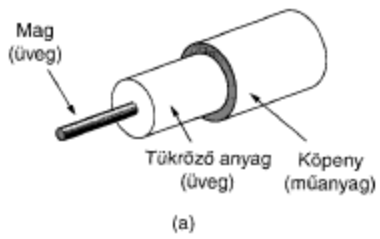
· wired 2/2

- ☐ **Optical cable** – parts: light source, media and detector; light impulse = 1 bit, no light impulse = 0 bit;

(Tanenbaum)

- ☐ **Optical cables:**

Fundamentals – wireless transmission

- **Frequency:** the rate per second of a vibration constituting an electromagnetic wave.
  - Notation: f
  - Measured in: Hertz (Hz)

- **Wavelength:** the distance between successive crests of a wave
  - Notation: λ

- **Speed of light:** signal propagation speed of electric signals in a physical media
  - Notation c
  - In vacuum: kb. $3 * 10^8 \frac{m}{s}$
  - In copper or optical cable: 2/3 x c(vacuum)
- **Relationship: λf = c**

... wireless

- **Radio frequency transmission** – simple; large distances; indoor and outdoor; frequency-dependent propagation properties

- **Microwave transmission** – propagation along a straight line; attenuation; cheap
- **Infrared and millimeter-wave** – small distances; cannot go through objects
- **Visible light** – laser; high speed, cheap; weather conditions;

Internet in a cable TV network
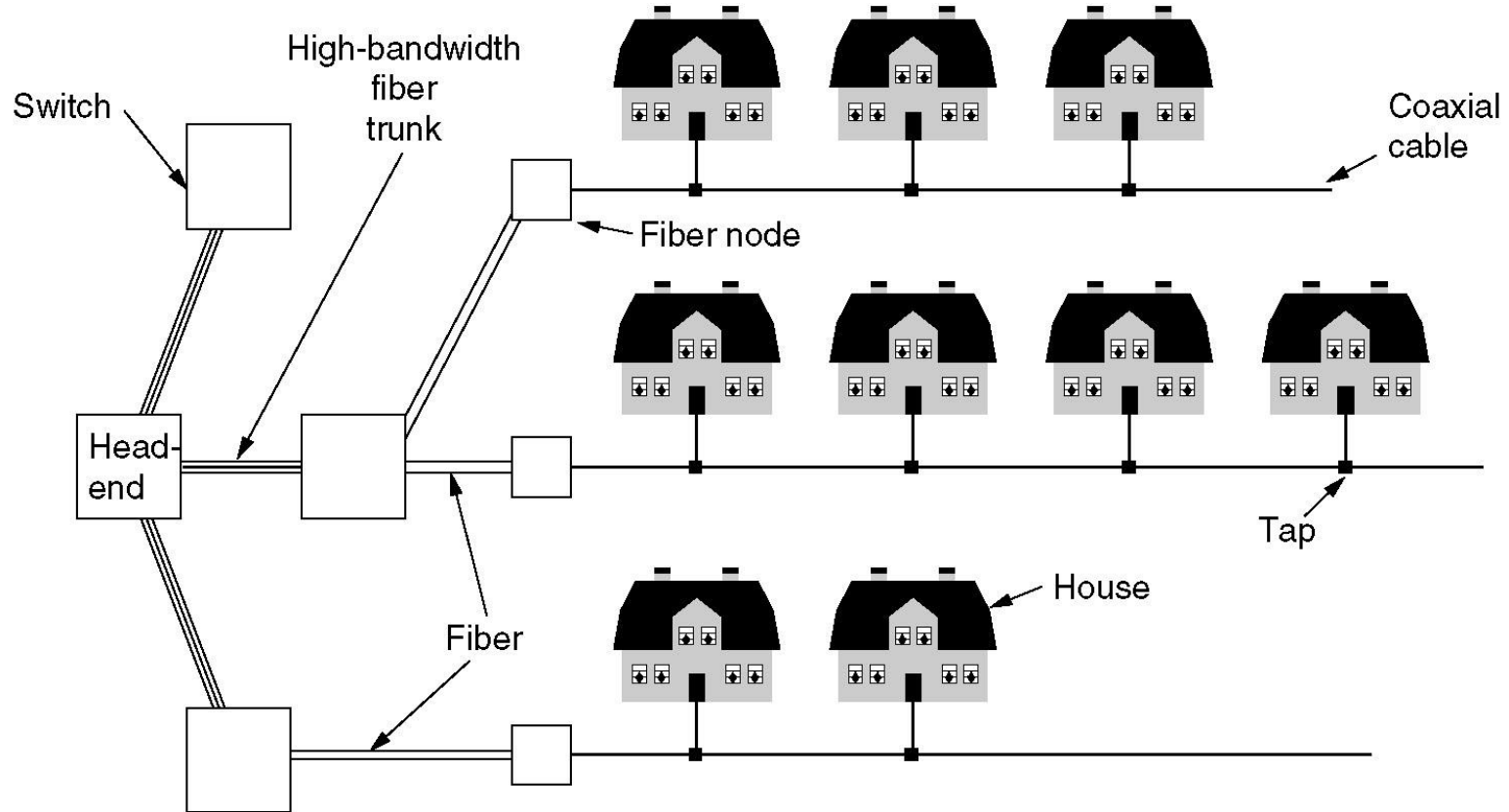
(a)

Internet in a cable TV network
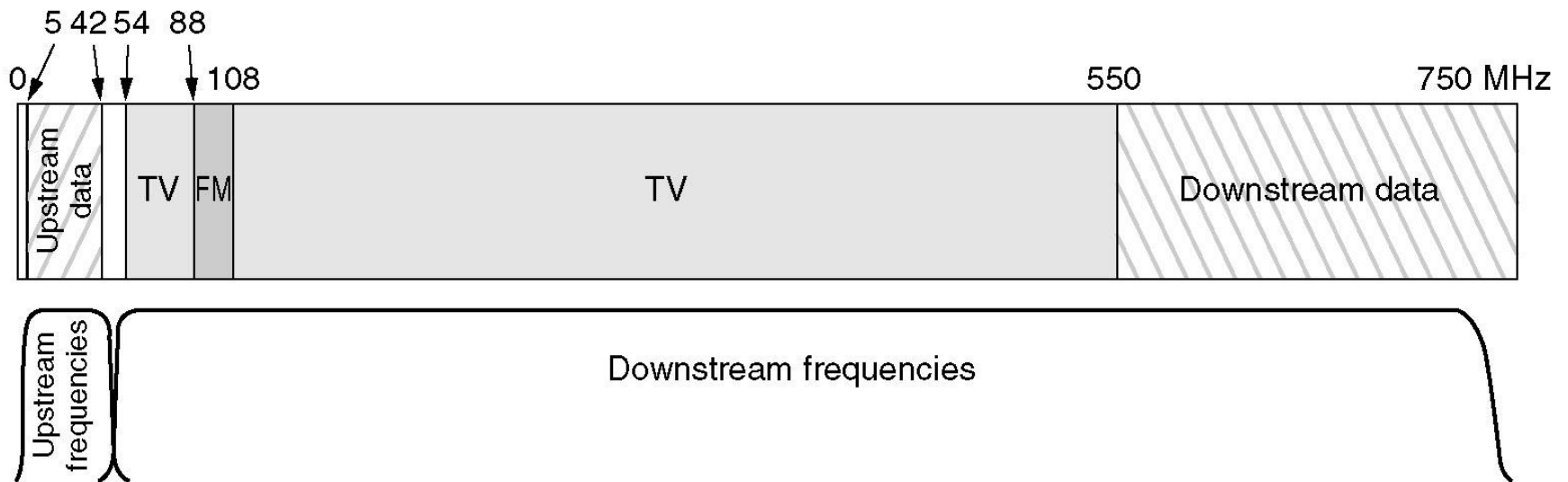
Already discussed…

Data transmission

Assumptions

- We have two discrete signals, high and low, to encode 1 and 0
- Transmission is synchronous, i.e. there is a clock that controls signal sampling

Sample

Time →
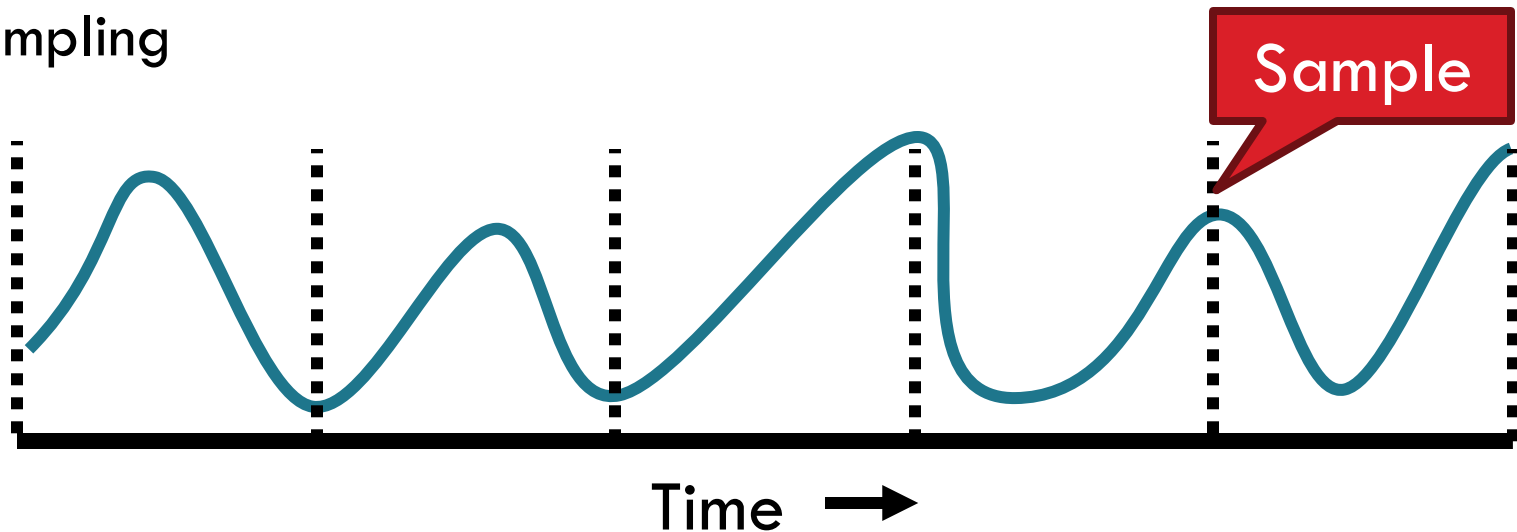
- Amplitude and duration of signal must be significant

Non-Return to Zero (NRZ)

- 1 → high signal, 0 → low signal
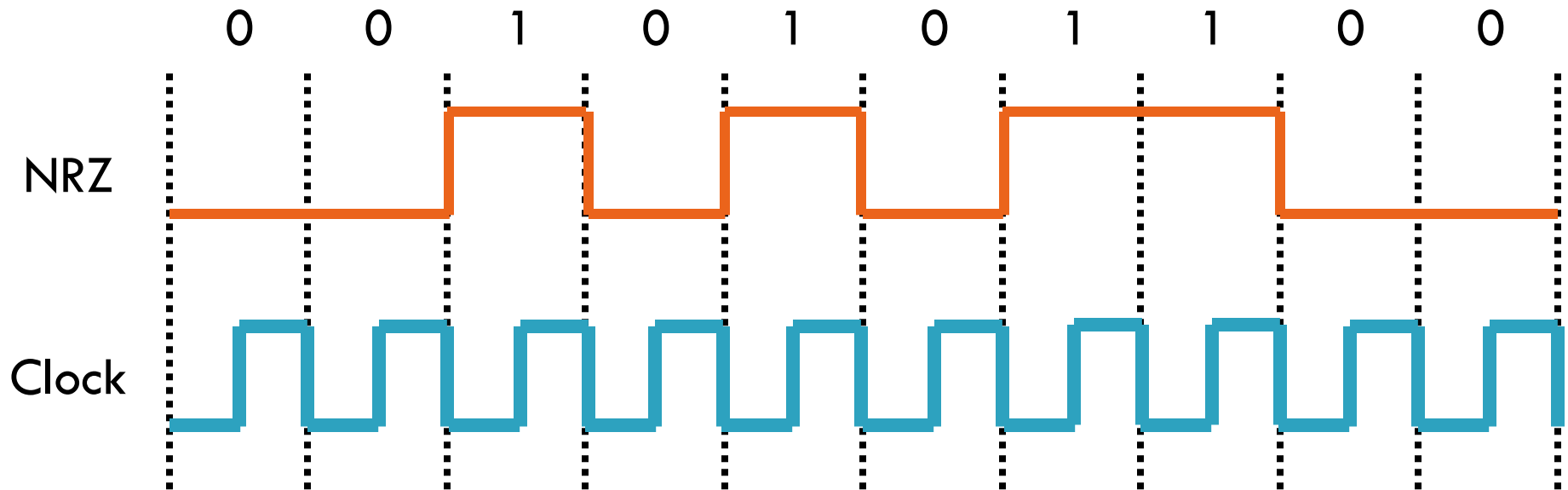
- Problem: long strings of 0 or 1 cause desynchronization
  - How to distinguish lots of 0s from no signal?
  - How to recover the clock during lots of 1s?

Desynchronization

□ Problem: how to recover the clock during sequences of 0's or 1's?

| 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |

NRZ

| 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |
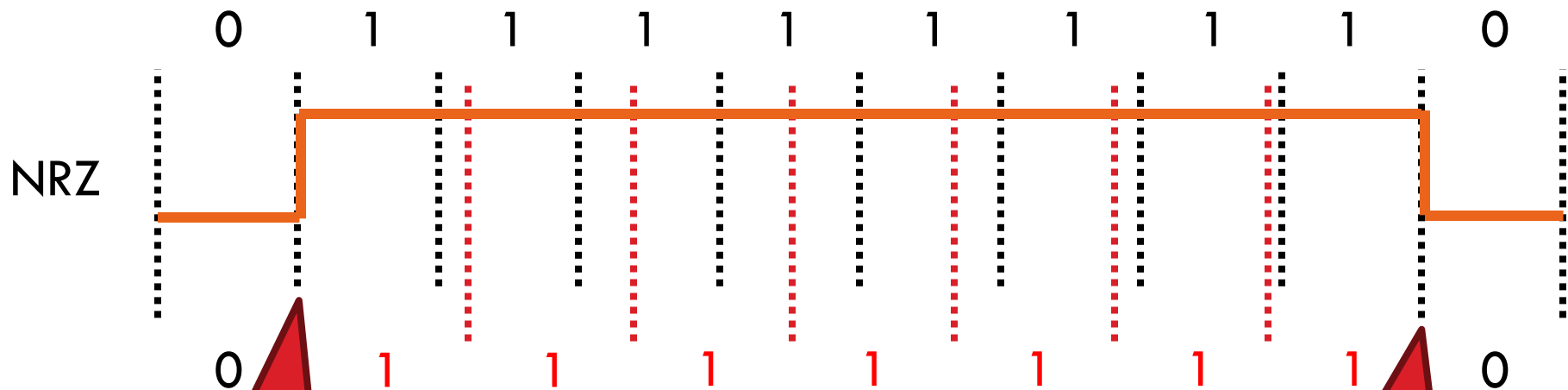
Transitions signify clock ticks

Receiver misses a 1 due to skew

- Clock drift is major problem – two different clocks never stay in perfect synchrony

Options to tell the receiver when to sample

- Relying on permanently synchronized clocks does not work
    1. Explicit clock signal
        - Needs parallel transmission over some additional channel
        - Must be in synch with the actual data, otherwise pointless !
   - Useful only for short-range communication
    2. Synchronize the receiver at crucial points (e.g., start of a character or of a block)
        - Otherwise, let the receiver clock run freely
        - Relies on short-term stability of clock generators (do not diverge too quickly)
    3. Extract clock information from the received signal itself
        - *Self-clocked signals*
        - Put enough information into the data signal itself so that the receiver can know immediately when a bit starts/stop

Non-Return to Zero Inverted (NRZI)

□ 1 → make transition, 0 → remain the same
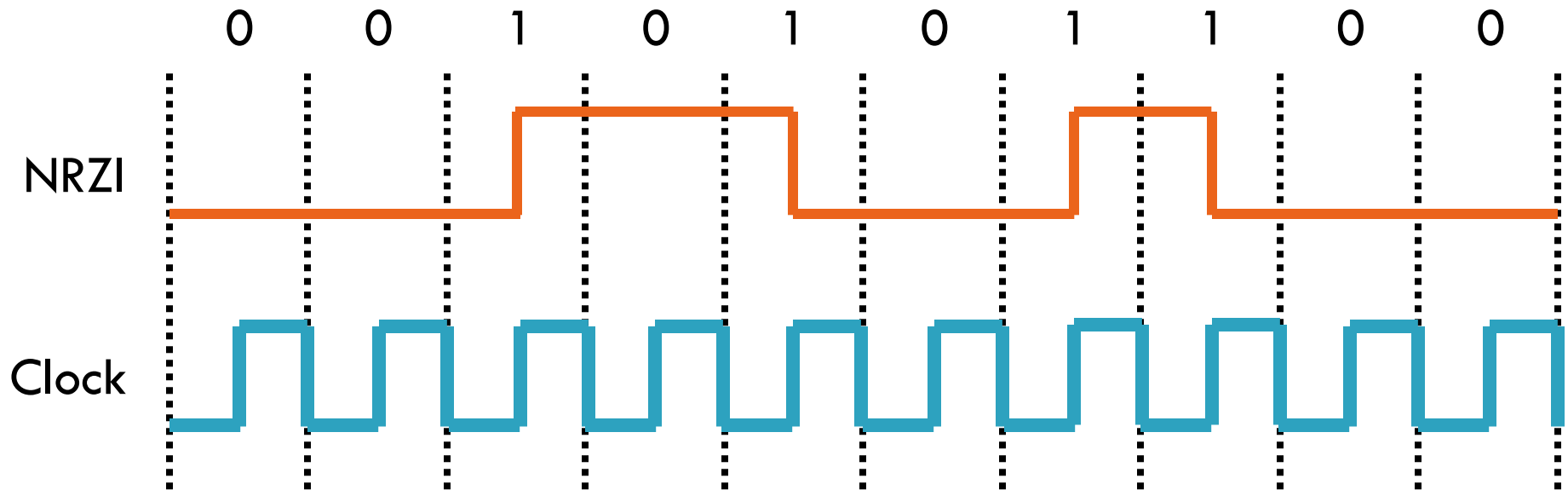
□ Solves the problem for sequences of 1s, but not 0s

Ethernet examples:
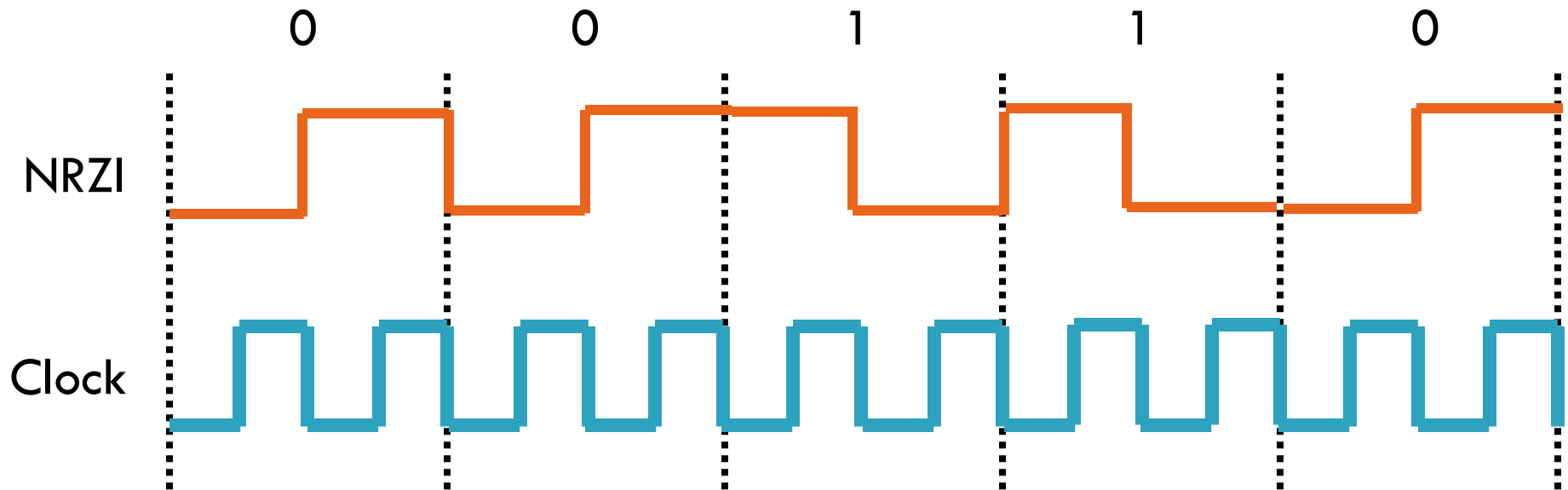10BASE-TX
100BASE-TX

Manchester – used by 10BASE-TX

- 1 → high-to-low, 0 → low-to-high

| 0 | 0 | 1 | 1 | 0 |

NRZI

Clock

- Good: Solves clock skew (every bit is a transition)
- Bad: Halves throughput (two clock cycles per bit)

4-bit/5-bit (100 Mbps Ethernet)

□ Observation: NRZI works as long as no sequences of 0

□ Idea: encode all 4-bit sequences as 5-bit sequences with no

8-bit / 10-bit used in Gigabit Ethernet

4-bit	5-bit	4-bit	5-bit
0000	11110	1000	10010
0001	01001	1001	10011
0010	10100	1010	10110
0011	10101	1011	10111
0100	01010	1100	11010
0101	01011	1101	11011
0110	01110	1110	11100
0111	01111	1111	11101

□ Tradeoff: efficiency drops to 80%

Signal transmission

Baseband VS broadband transmission

- *baseband*
 - Baseband transmission directly puts the digital symbol sequences onto the wire
  - At different levels of current, voltage, … essentially, direct current (DC) is used for signaling
  - Baseband transmission suffers from the problems discussed above
    - Limited bandwidth reshapes the signal at receiver
    - Attenuation and distortion depend on frequency and baseband transmissions have many different frequencies because of their wide Fourier spectrum

- *broadband*
  - Idea: get rid of the wide spectrum needed for DC transmission
  - Use a sine wave as a carrier for the symbols to be transmitted
    - Typically, the sine wave has high frequency
    - But only a single frequency!
    - Pure sine waves has no information, so its shape has to be influenced according to the symbols to be transmitted
  - The carrier has to be modulated by the symbols (widening the spectrum)
    - Three parameters that can be influenced Amplitude, Frequency, Phase
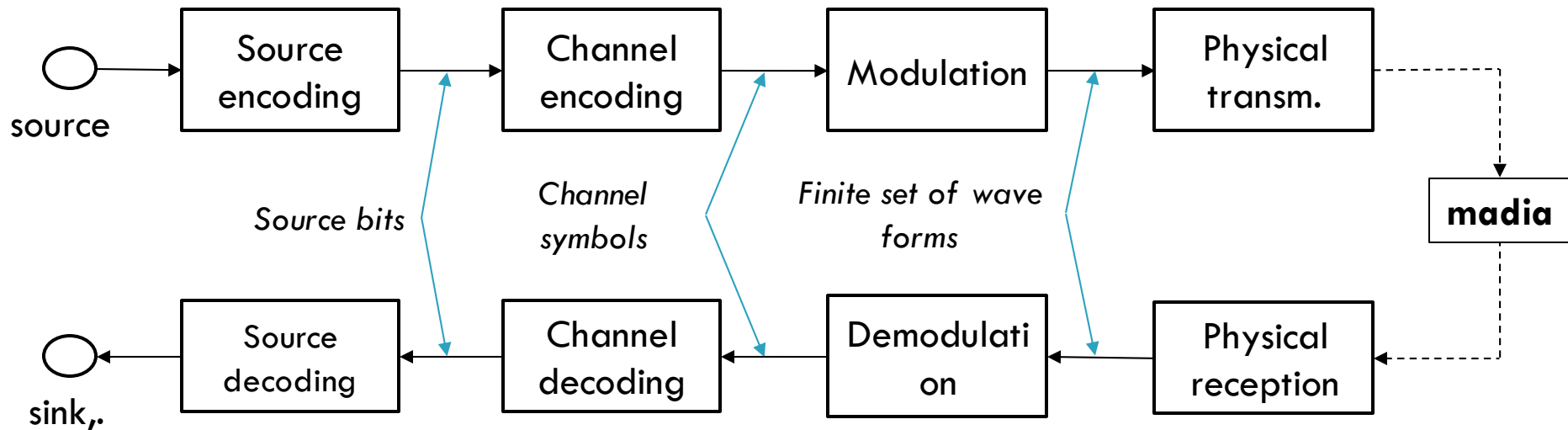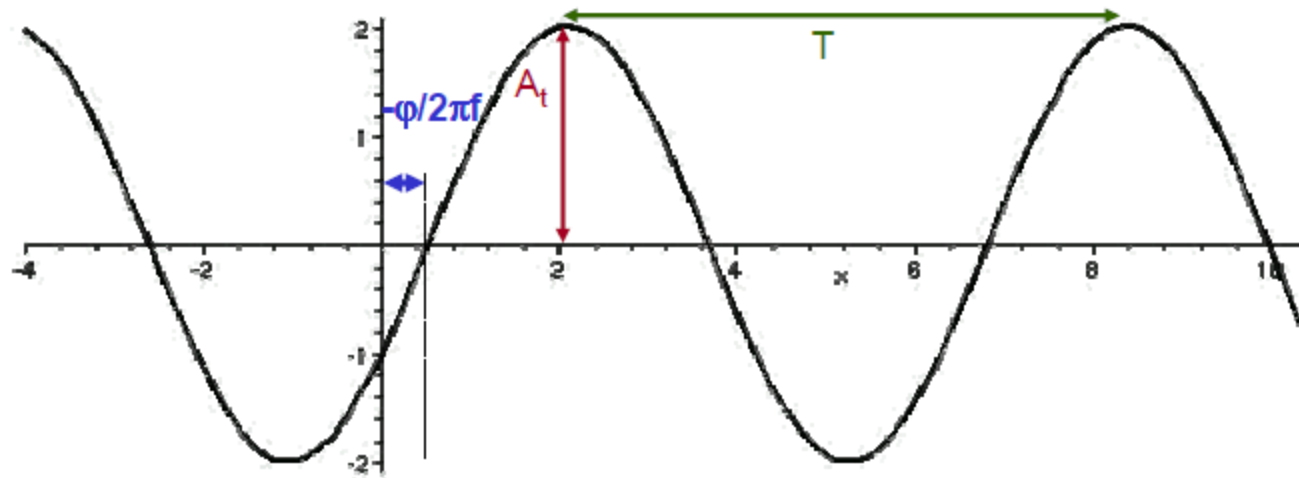
Digital baseband transmission
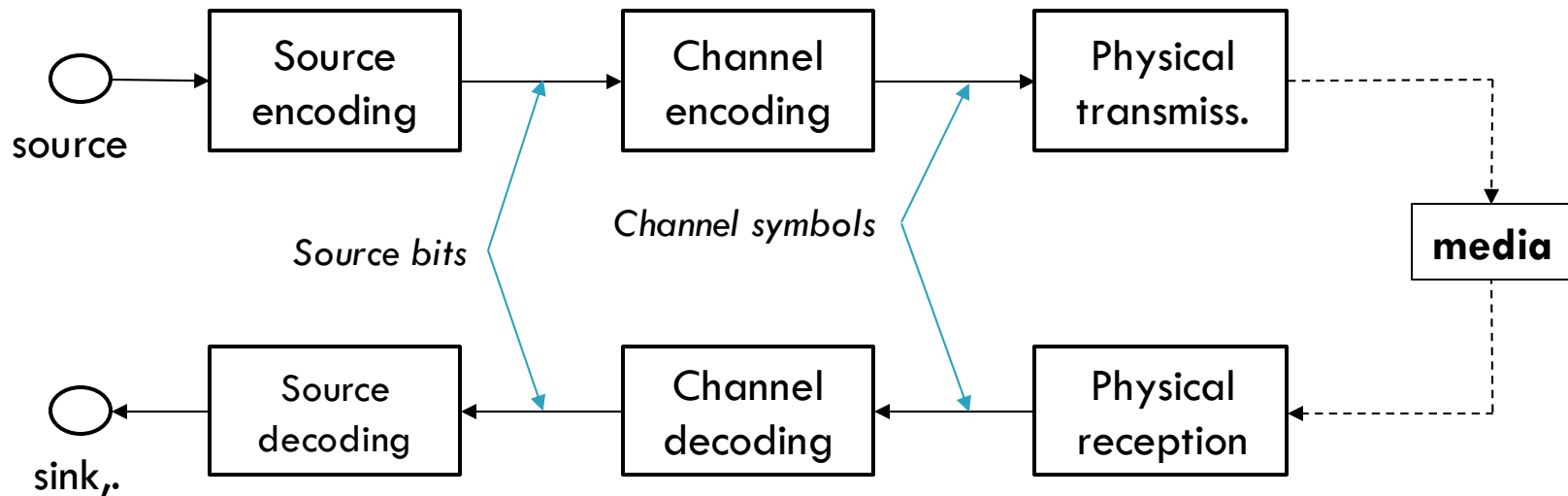
- Bring source information in digital form
  - E.g., sample and quantize an analog voice signal, represent text as ASCII
- Source encode: Remove redundant or irrelevant data
  - E.g., lossy compression (MP3, MPEG 4); lossless compression (Huffmann coding, runlength coding)
- Channel encode: Map source bits to channel symbols
  - Potentially several bits per symbol
  - May add redundancy bits to protect against errors
  - Tailored to channel characteristics
- Physical transmit: Turn the channel symbols into physical signals
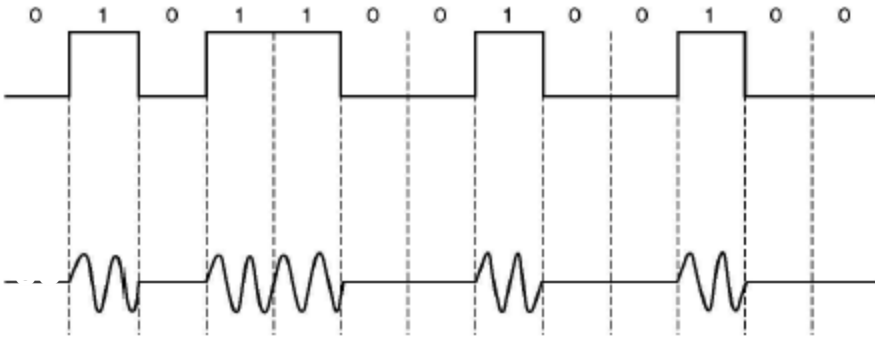- At receiver: Reverse all these steps

Digital broadband transmission

```
          ┌──────────┐    ┌──────────┐    ┌──────────┐    ┌──────────┐
  source──▶│  Source  │───▶│ Channel  │───▶│Modulation│───▶│ Physical │ ⋯┐
   ○       │ encoding │    │ encoding │    │          │    │ transm.  │  │
 source    └──────────┘    └──────────┘    └──────────┘    └──────────┘  │
                                                                         ▼
         Source bits    Channel        Finite set of wave             ┌──────┐
                        symbols            forms                       │madia │
                                                                       └──────┘
          ┌──────────┐    ┌──────────┐    ┌──────────┐    ┌──────────┐  │
   ○◀─────│  Source  │◀───│ Channel  │◀───│Demodulati│◀───│ Physical │ ◀┘
 sink,.   │ decoding │    │ decoding │    │   on     │    │reception │
          └──────────┘    └──────────┘    └──────────┘    └──────────┘
```

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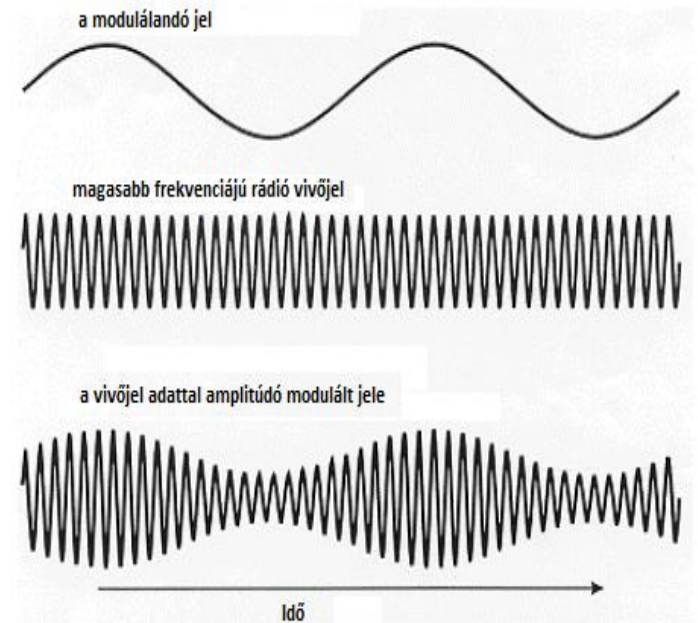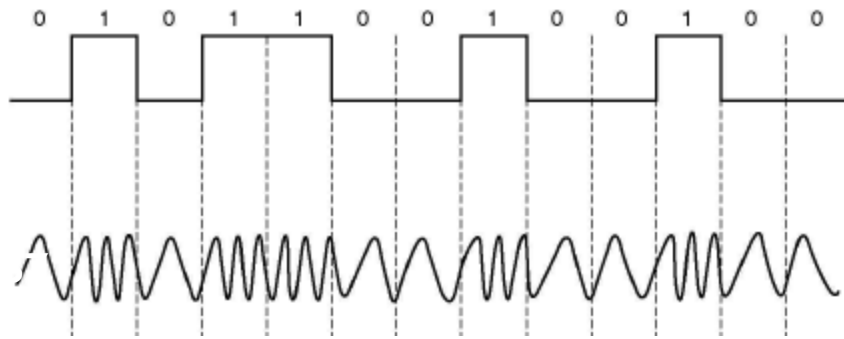The top shows a digital signal with bits: 0 1 0 1 1 0 0 1 0 0 1 0 0 and below it the amplitude-keyed waveform.

- The time-varying *s(t)* signal is encoded into the amlitude of the sine wave (carrier):

$$f_A(t) = s(t) * \sin(2\pi f t + \varphi)$$

  - *Analog signal*: amplitude modulation

  - *Digital signal*: amplitude keying or on/off keying
    (s(t) takes discrete values)

a modulálandó jel

magasabb frekvenciájú rádió vivõjel

a vivõjel adattal amplitúdó modulált jele

Idő

The time-varying s(t) signal is encoded into the frequency of the sine wave:

$$f_F(t) = a * \sin(2\pi s(t)t + \varphi)$$

- *analog signal*: frequency modulation
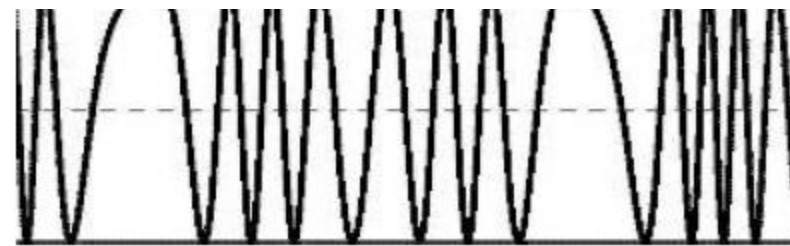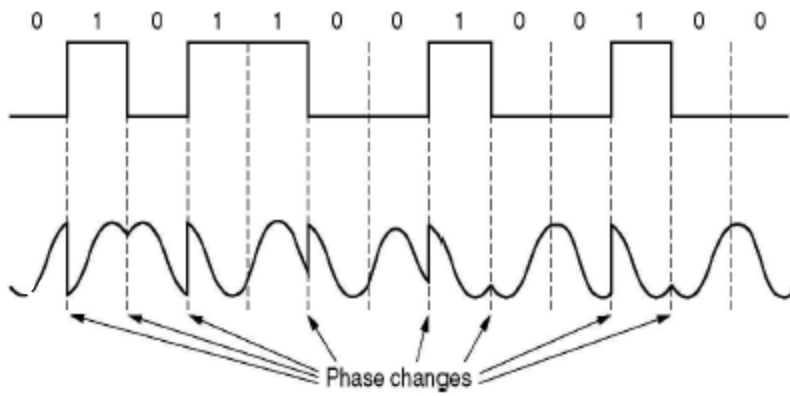
- *Digital signal*: frequency-shift keying
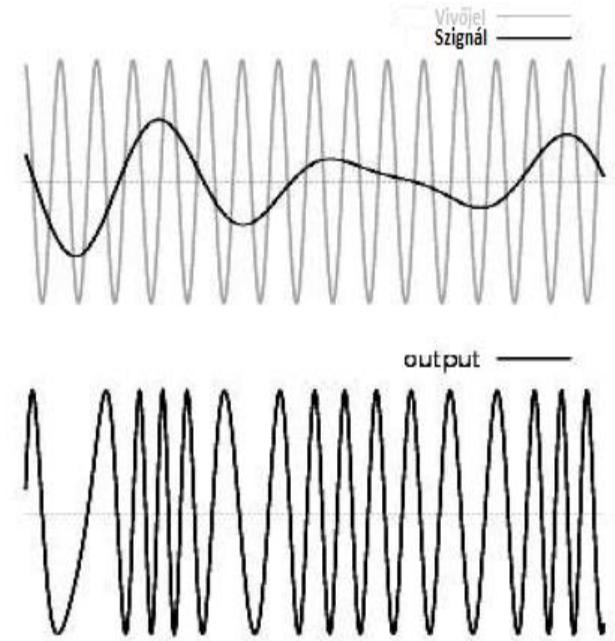
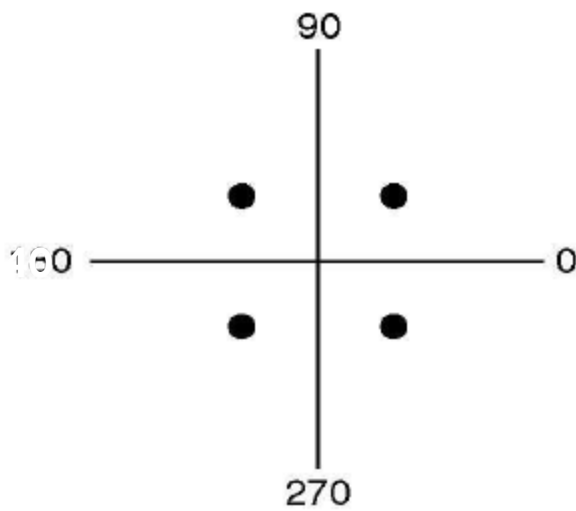# Illustration - AM & FM for analog signals

0　1　0　1　1　0　0　1　0　0　1　0　0
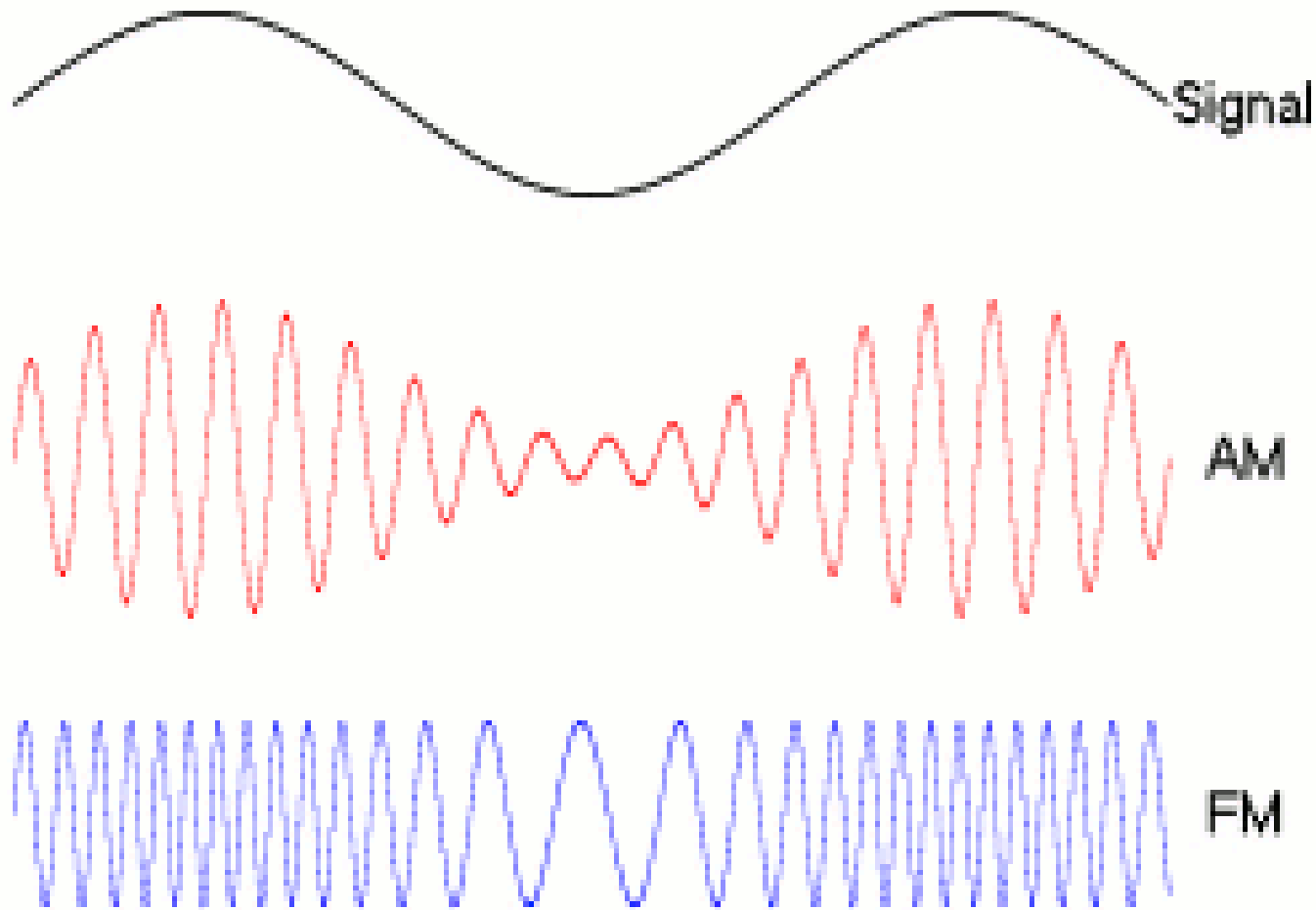
Phase changes

he phase of

$s(t))$

ulation (not
really used)

- *Digital signal*: phase-shift keying
  (discrete set of phase changes)

lues

ally quite well distinguish phase shifts

- 4 symbols/values: $\frac{\pi}{4}, \frac{3\pi}{4}, \frac{5\pi}{4}, \frac{7\pi}{4}$
- Result: Data rate is twice the symbol rate
- Technique is called Quadrature Phase Shift Keying (QPSK)

Amlitude + Phase modulation
- Methods can be combined
- Symbols are encoded by a discrete set of amlitude, phase values

  - E.g. 16 symbols

  - Four times higher data rate than the symbol rate

  - Called as **Q**uadrature **A**mplitude **M**odulation-16
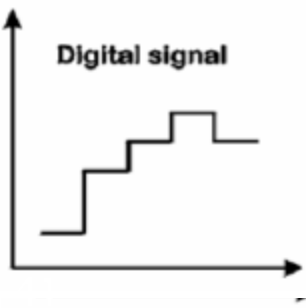
VS analog signals

- A sender has two principal options what types of signals to generate
  - It can choose from a finite set of different signals – digital transmission
  - There is an infinite set of possible signals – analog transmission
- Simplest example: Signal corresponds to current/voltage level on the wire
  - In the digital case, there are finitely many voltage levels to choose from
  - In the analog case, any voltage is legal
- More complicated example: finite/infinitely many sinus functions
  - In both cases, the resulting wave forms in the medium can well be continuous functions of time!
- Advantage of digital signals: There is a principal chance that the receiver can precisely reconstruct the transmitted signal

Static Channel Allocation

Multiplexing

- Enabling multiple signals to travel through the same media at the same time

- To this end, the channel is split into multiple smaller subchannels

- A special device (multiplexer) is needed at the sender, transmitting signals to the proper subchannel
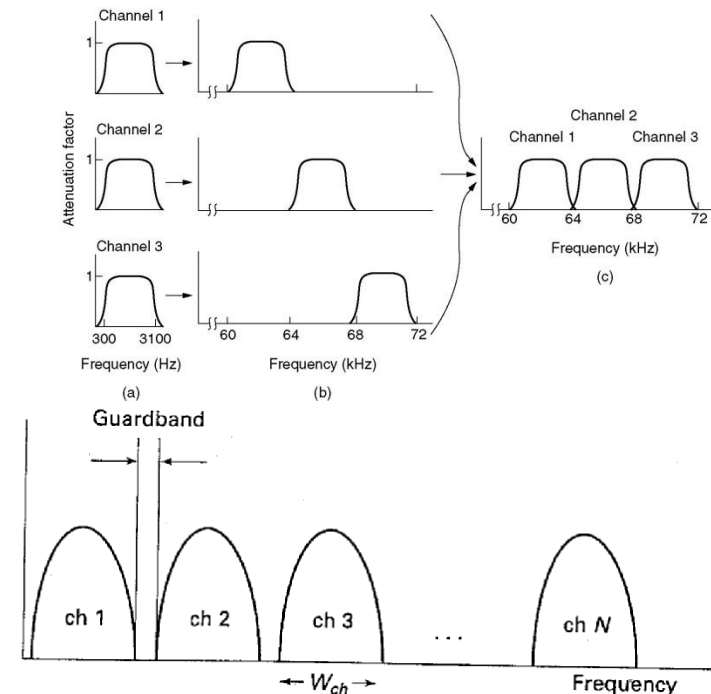
Space-Division Multiplexing

- ☐ Simplest way of multiplexing

- ☐ Wired example: point-to-point wire for each subchannel

- ☐ Wireless example: Different antennas for the subchannels
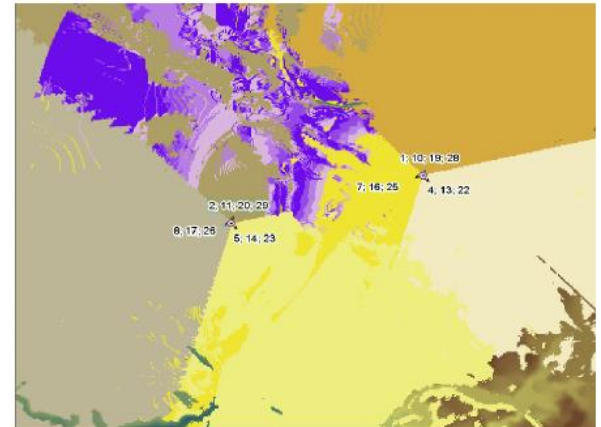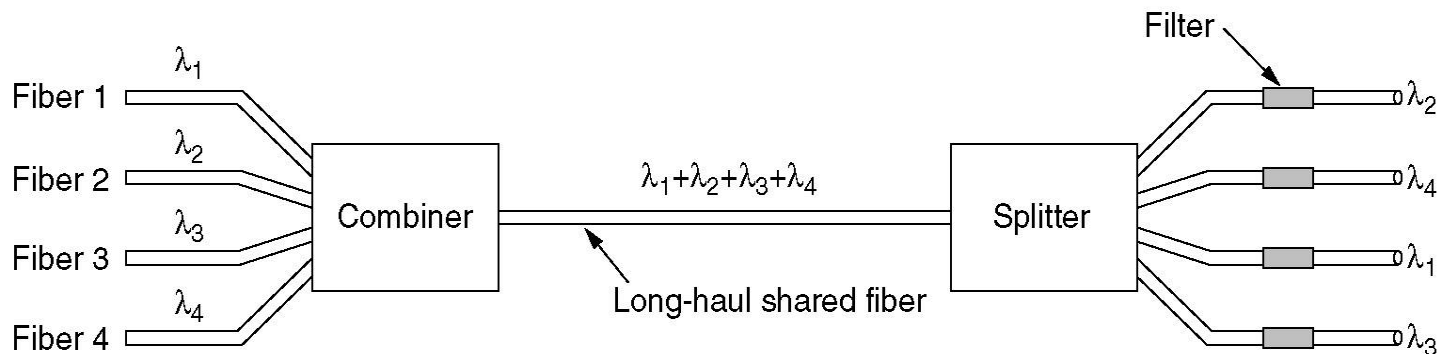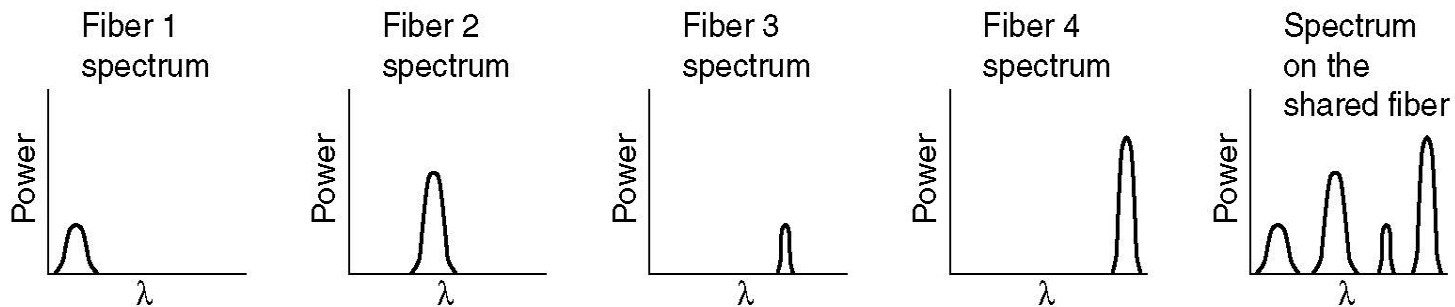
Frequency-Division Multiplexing

- Multiple signals are combined and transmitted over the channel
- Each signal is transmitted in different frequency ranges
- Typically used for analog transmission
- Multiple implementations…
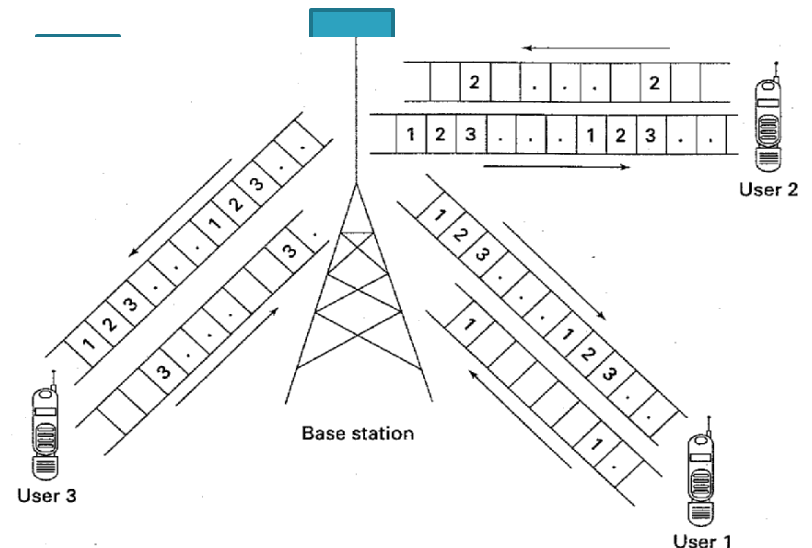
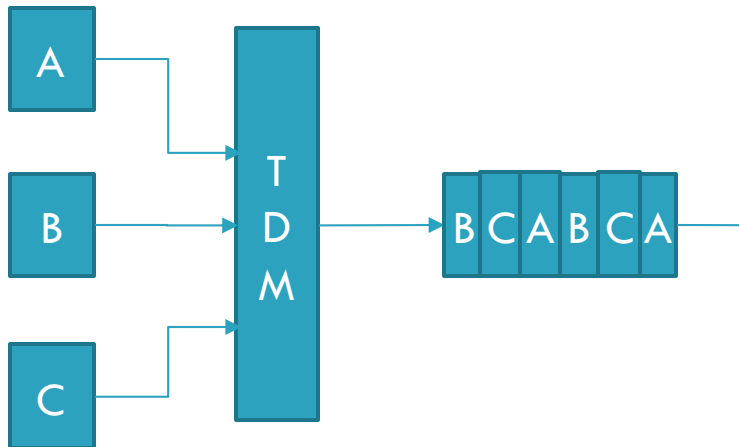# Wavelength-Division Multiplexing

- ☐ Used for optical cables

- ☐ IR laser rays at different wavelengths

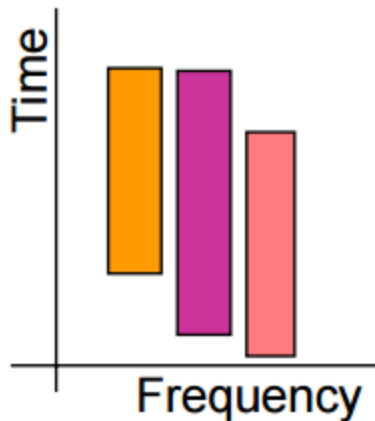# Time-Division Multiplexing

- ☐ Time is divided into not overlapping intervals
- ☐ Each time slot is assigned to a sender, exlusively.
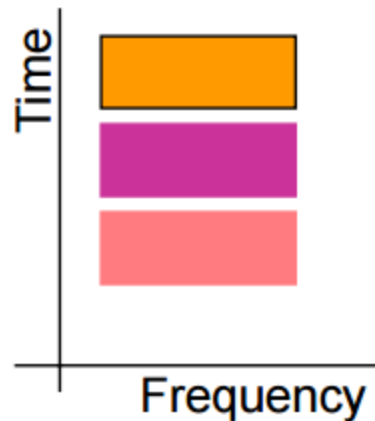- ☐ Empty slots may happen.

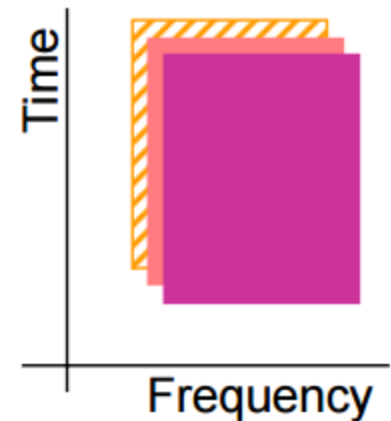# CDMA – Code Division Multiple Access

CDMA Analogy

- 10 people in a room.
  - 5 speak English, 2 speak Spanish, 2 speak Chinese, and 1 speaks Russian.
- Everyone is talking at relatively the same time over the same medium – the air.
- Who can listen to whom and why?
- Who can't you understand?
- Who can't speak to anyone else?

CDMA – Code Division Multiple Access

- Used by 3G and 4G cellular networks
- Each station can broadcast at any time in the full frequency spectrum
- The signals may interfere
  - Resulting in a linear combination of individual signals

- Algorithm
  - We assign a vector of length m to each station: v
    - Pairwise orthogonal vectors!!!
  - Each bit is encoded
    by the chip vector of the sender or it's complement: v or -v
  - If it sends bit 1, it transmits v
  - If it sends bit 0, it transmits -v

- Result is a sequence of vectors of length m
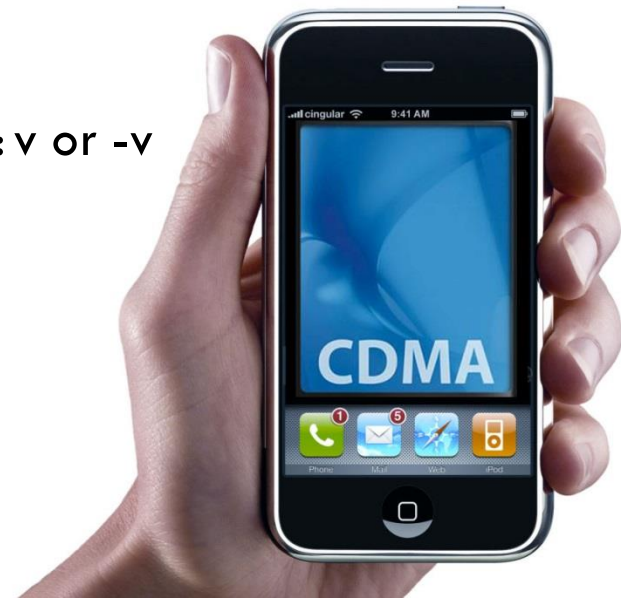
CDMA – Code Division Multiple Access

- Interference
  - A sends a,-a,a,a
  - B sends b,b,-b,-b
  - After interference we receive: a+b,-a+b,a-b,a-b ???

- How to decode?

CDMA – Code Division Multiple Access

☐ Interference
- A sends a,-a,a,a
- B sends b,b,-b,-b
- After interference we receive: a+b,-a+b,a-b,a-b ???

☐ Decoding the message of A
- Take the dot product by the sender's chip code
  - $(a+b)a > 0 \Rightarrow 1$
  - $(-a+b)a < 0 \Rightarrow 0$
  - $(a-b)a > 0 \Rightarrow 1$
  - $(a-b)a > 0 \Rightarrow 1$

If the dot product is
< 0: bit 0 was sent by A
> 0: bit 1 was sent by A
$= 0$: nothing was sent by A
the channel is not used by A

Thank you…