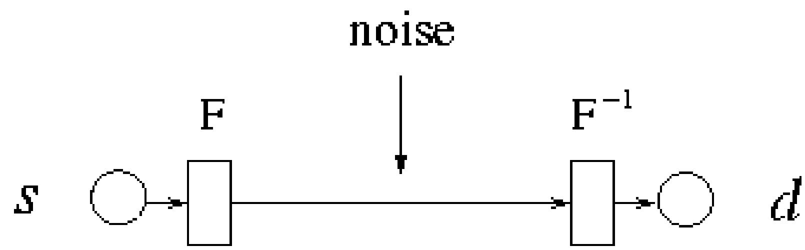
Information Transmission under Noise



Uncertainty introduced by noise:

- $\longrightarrow$ encoding/decoding: $a \mapsto w_a \mapsto w \mapsto [?]$
- $\longrightarrow$ w_a gets corrupted, i.e., becomes w
- $\longrightarrow$ if $w = w_b$, incorrectly conclude b as symbol
- $\longrightarrow$ detect w is corrupted: error detection
- $\longrightarrow$ correct w to w_a: error correction

Would like: If received code word $w = w_c$ for some symbol $c \in \Sigma$, then probability that actual symbol sent is indeed c is high.

$\longrightarrow$ $\Pr\{\text{symbol sent} = c \,|\, w = w_c\} \approx 1$

$\longrightarrow$ noiseless channel: special case (prob = 1)

In practice, w may not match any legal code word:

$\longrightarrow$ for all $c \in \Sigma$, $w \neq w_c$

$\longrightarrow$ then what?

Fundamental limitation to reliable data transmission:

Channel capacity C: maximum achievable reliable data transmission rate (bps) over a noisy channel (dB) with bandwidth W (Hz).

Channel Coding Theorem (Shannon): Given bandwidth W, signal power P_S, noise power P_N, channel subject to white noise,

$$C \;=\; W \log \left(1 + \frac{P_S}{P_N} \right) \text{ bps.}$$

P_S/P_N: signal-to-noise ratio (SNR)

$\longrightarrow$ upper bound achieved by using longer codes

$\longrightarrow$ detailed set-up/conditions omitted

Increasingly important for modern day networking:

- Power control (e.g., pocket PCs)

  $\longrightarrow$ trade-off w.r.t. battery power

  $\longrightarrow$ trade-off w.r.t. multi-user interference

  $\longrightarrow$ signal-to-interference ratio (SIR)

- Recent trend: software radio

  $\longrightarrow$ hardware-to-software migration

  $\longrightarrow$ configurable

Signal-to-noise ratio (SNR) is expressed as

$$\text{dB} \;=\; 10\log_{10}(P_S/P_N).$$

Example: Assuming a decibel level of 30, what is the channel capacity of a telephone line?

Answer: First, $W = 3000$ Hz, $P_S/P_N = 1000$. Using Channel Coding Theorem,

$$C \;=\; 3000\log 1001 \;\approx\; 30 \text{ kbps}.$$

$\longrightarrow$ compare against 28.8 kbps modems

$\longrightarrow$ what about 56 kbps modems?

$\longrightarrow$ DSL lines?

Digital vs. Analog Transmission

Two forms of *transmission*:

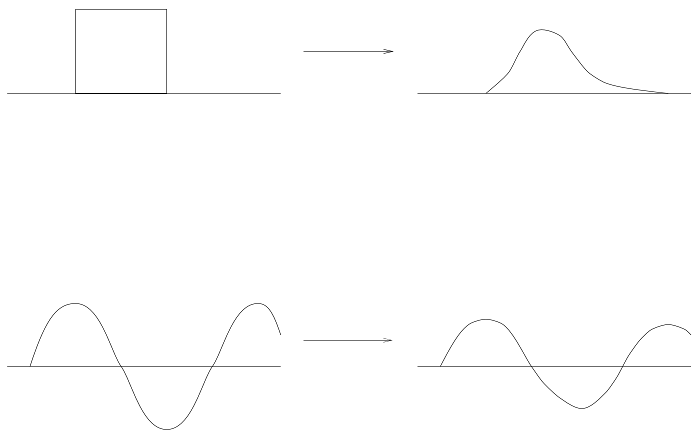
- digital transmission: data transmission using square waves
- analog transmission: data transmission using all other waves

Four possibilities to consider:

- analog data via analog transmission
  → "as is" (e.g., radio)
- analog data via digital transmission
  → sampling (e.g., voice, audio, video)
- digital data via analog transmission
  → broadband & wireless ("high-speed networks")
- digital data via digital transmission
  → baseband (e.g., Ethernet)

Why consider digital transmission?

Common to both: problem of *attenuation*.



- decrease in signal strength as a function of distance
- increase in attenuation as a function of frequency

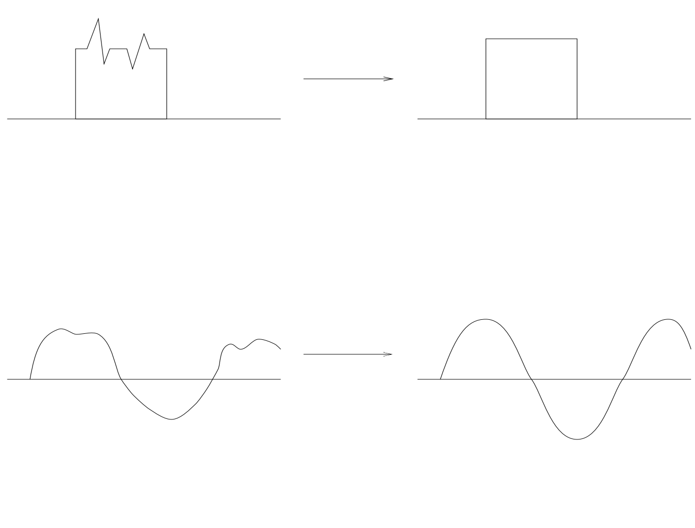
Rejuvenation of signal via amplifiers (analog) and repeaters (digital).

Delay distortion: different frequency components travel at different speeds.

Most problematic: effect of noise

$\longrightarrow$ thermal, interference, ...

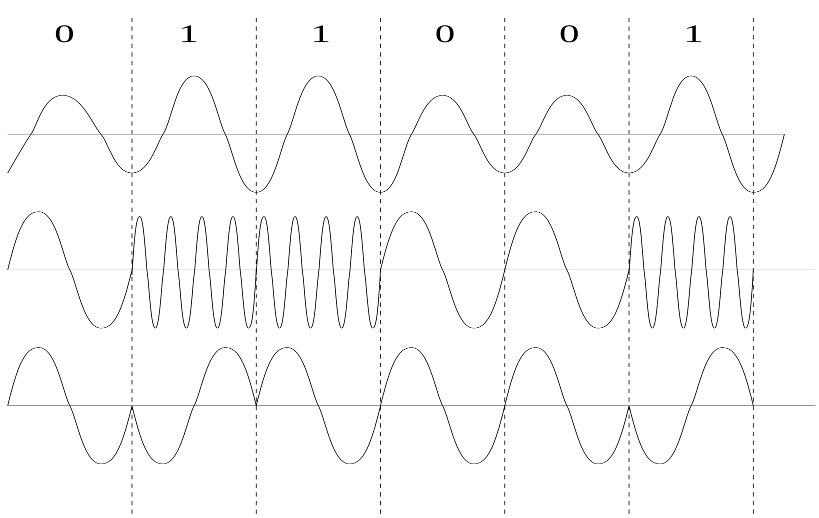
- Analog: Amplification also amplifies noise—filtering out just noise, in general, is a complex problem.
- Digital: Repeater just generates a new square wave; more resilient against ambiguitity.



Analog Transmission of Digital Data

Three pieces of information to manipulate: amplitude, frequency, phase.

- Amplitude modulation (AM): encode bits using amplitude levels.
- Frequency modulation (FM): encode bits using frequency differences.
- Phase modulation (PM): encode bits using phase shifts.



FM radio uses . . . FM!

AM radio uses . . . AM!

iPod & radio experiment uses . . . ?

Why is FM radio clearer ("high fidelity") than AM radio?

Broadband uses . . . ?

Baud Rate vs. Bit Rate

Baud rate: Unit of time within which carrier wave can be altered for AM, FM, or PM.

$\longrightarrow$ signalling rate

$\longrightarrow$ e.g., clock

Not synonymous with bit rate: e.g., AM with 8 levels, PM with 8 phases

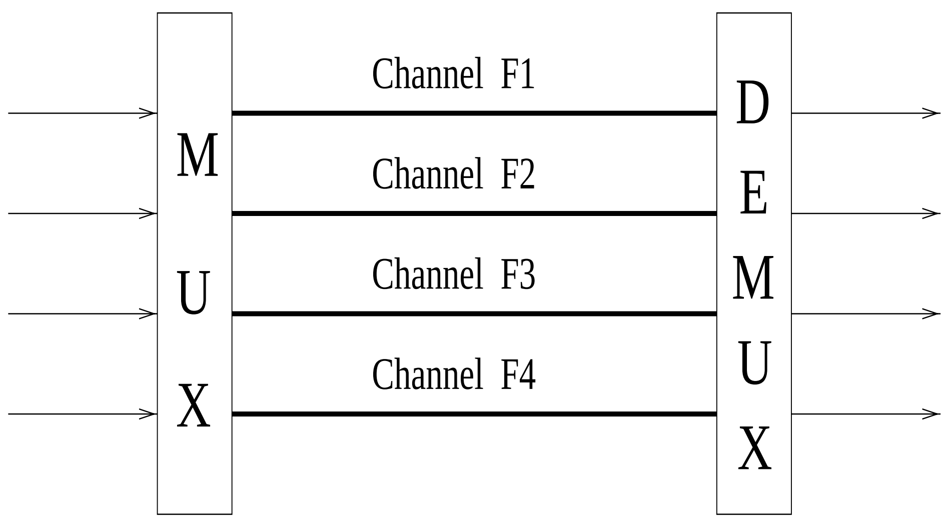
$\longrightarrow$ bit rate (bps) $= 3 \times$ baud rate

... less than one bit per baud?

Broadband vs. Baseband

Presence or absence of carrier wave: allows many channels to co-exist at the same time

$\longrightarrow$ frequency division multiplexing (FDM)



Ex.: AM radio (535 kHz–1705 kHz)

$\longrightarrow$ tuning to specific frequency: Fourier transform

$\longrightarrow$ coefficient (magnitude) carries bit information

Ex.: FM radio

$\longrightarrow$ 88 MHz–108 MHz

$\longrightarrow$ 200 kHz slices

$\longrightarrow$ how does it work?

$\longrightarrow$ better or worse than AM?

Ex.: Digital radio

$\longrightarrow$ digital audio radio service

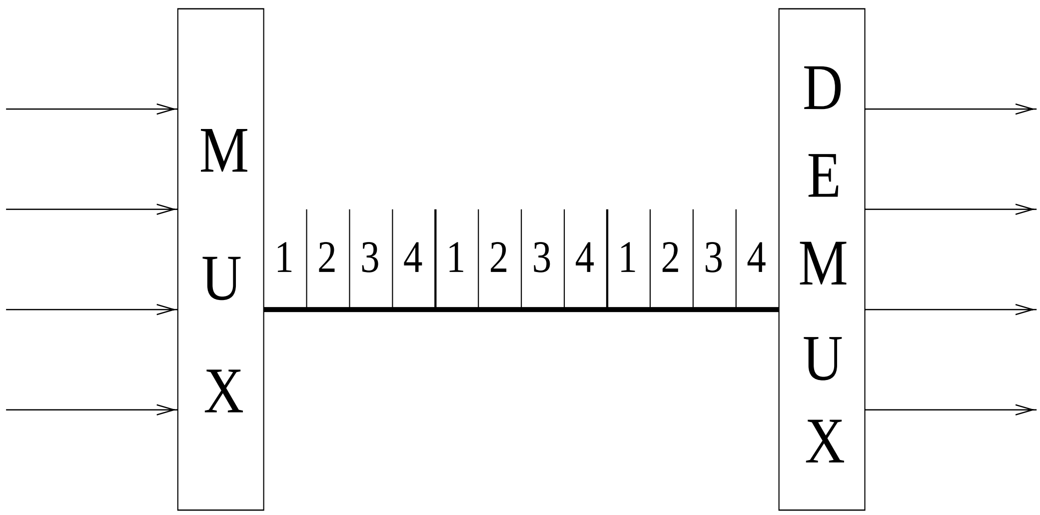
$\longrightarrow$ GEO satellites (a.k.a. satellite radio)

$\longrightarrow$ uses 2.3 GHz spectrum (a.k.a. S-band)

$\longrightarrow$ e.g., XM, Sirius

In the absence of carrier wave, can still use multiplexing:

⟶ time-division multiplexing (TDM)



- digital transmission of analog data

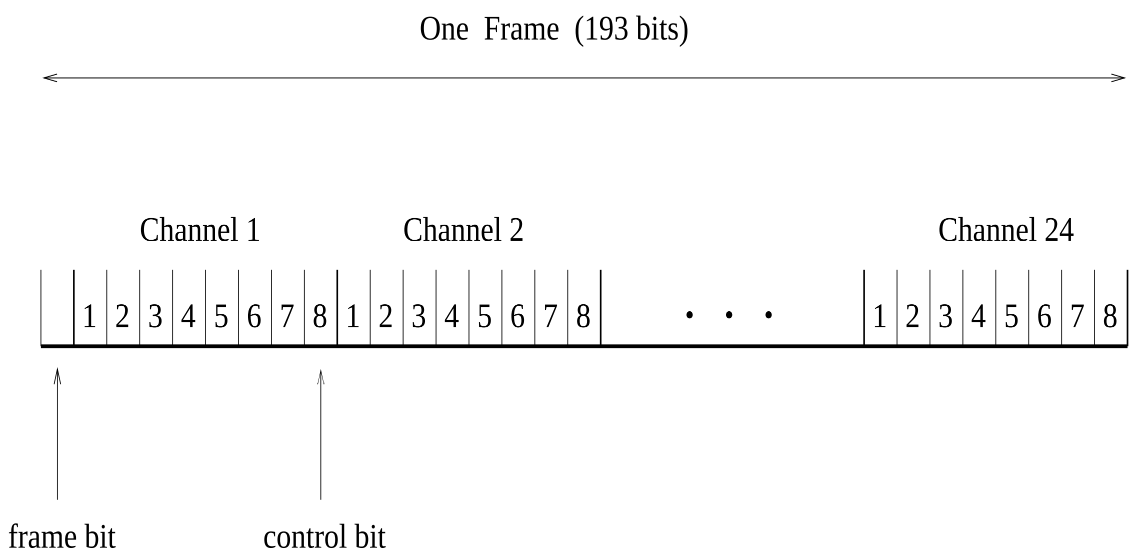
  → first digitize

  → PCM (e.g., PC sound cards), modem

- digital transmission of digital data

  → e.g., telephony backbone network

Example: T1 carrier (1.544 Mbps)



- 24 simultaneous users
- 7 bit quantization

Assuming 4 kHz telephone channel bandwidth, Sampling Theorem dictates 8000 samples per second.

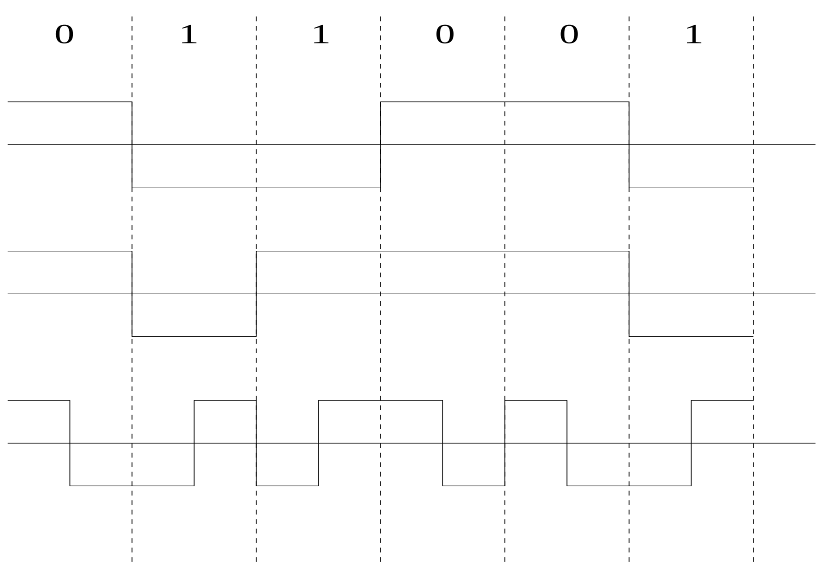
$\longrightarrow$ 125 μsec inter-sample interval

Bandwidth $= 8000 \times 193 = 1.544$ Mbps

Digital transmission of digital data

Direct encoding of square waves using voltage differentials; e.g., -15V–+15V for RS-232-C.

- NRZ-L (non-return to zero, level)
- NRZI (NRZ invert on ones)
- Manchester (biphase or self-clocking codes)



$\longrightarrow$ baud rate vs. bit rate of Manchester?

Trade-offs:

- NRZ codes—long sequences of 0's (or 1's) causes synchronization problem; need extra control line (clock) or sensitive signalling equipment.
- Manchester codes—synchronization achieved through self-clocking; however, achieves only 50% efficiency vis-à-vis NRZ codes.

4B/5B code

Encode 4 bits of data using 5 bit code where the code word has at most one leading 0 and two trailing 0's.

0000 $\leftrightarrow$ 11110, 0001 $\leftrightarrow$ 01001, etc.

$\longrightarrow$ at most three consecutive 0's

$\longrightarrow$ efficiency: 80%

Multiplexing techniques:

- TDM
- FDM
- mixture (FDM + TDM); e.g., TDMA
- CDMA (code division multiple access) or spread spectrum

  $\rightarrow$ wireless communication

  $\rightarrow$ competing scheme with TDMA