University of Glasgow

Physical Layer

Networked Systems (H)
Lecture 3

Lecture Outline

- Physical layer concepts
- Wired links
- Wireless links
- Channel capacity

The Physical Layer

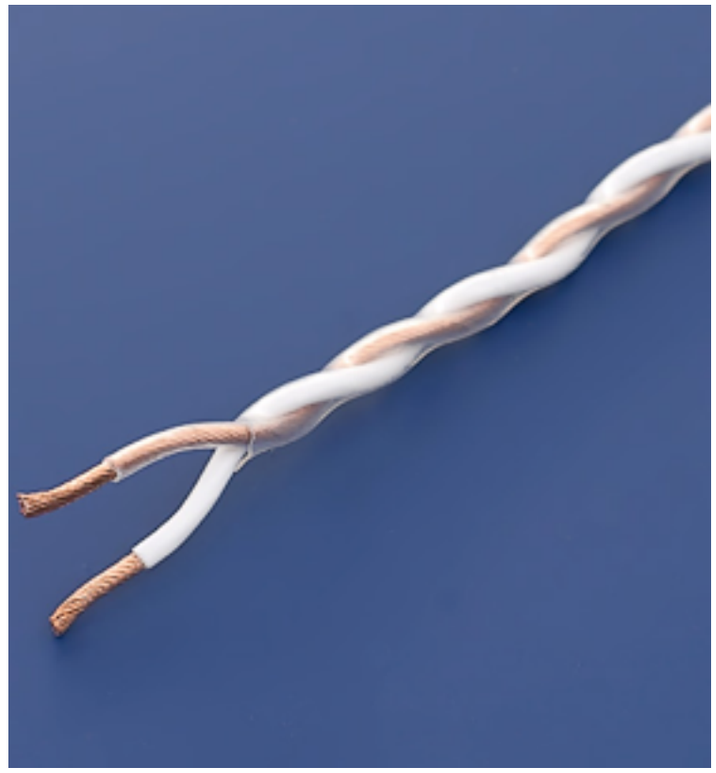
- The physical layer is concerned with transmission of raw data bits
  - What type of cable or wireless link do you use?
  - How to encode bits onto that channel?
    - Baseband encoding
    - Carrier modulation
  - What is the capacity of the channel?

Wired Links

- Physical characteristics of cable or optical fibre:
  - Size and shape of the plugs
  - Maximum cable/fibre length
  - Type of cable: electrical voltage, current, modulation
  - Type of fibre: single- or multi-mode, optical clarity, colour, power output, and modulation of the laser

Unshielded Twisted Pair

- Electrical cable using two wires twisted together in a spiral
  - Each pair is unidirectional: signal and ground
  - Twists reduce interference and noise pickup: more twists → less noise



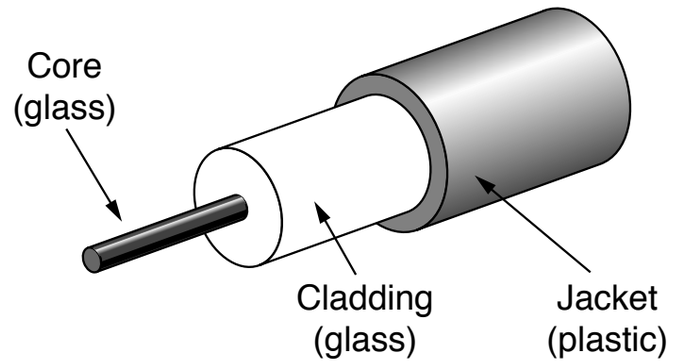
- Cable lengths of several miles possible at low data rates; ~100 metres at high rates
- Susceptibility to noise increases with cable length

- Extremely widely deployed:
  - Ethernet cables
  - Telephone lines

Optical Fibre



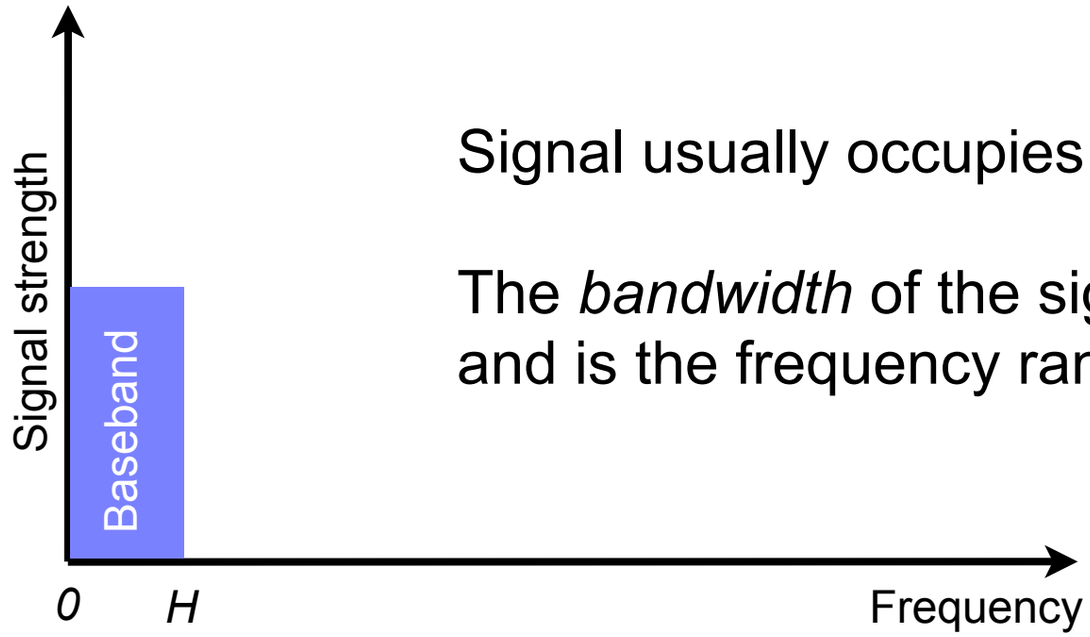
- Glass core and cladding, contained in plastic jacket for protection
  - Somewhat fragile: glass can crack if bent sharply
  - Unidirectional data: transmission laser at one end; photodetector at the other
    - Laser light trapped in fibre by total internal reflection
- Very low noise, since electromagnetic interference does not affect light
- Very high capacity: 10s of Gbps over 100s of miles
- Very cheap to manufacture
- Requires relatively expensive lasers to operate



Source: Tanenbaum, Copyright © 1996, Prentice-Hall

Wired Data Transmission

- Signal usually directly encoded onto the channel



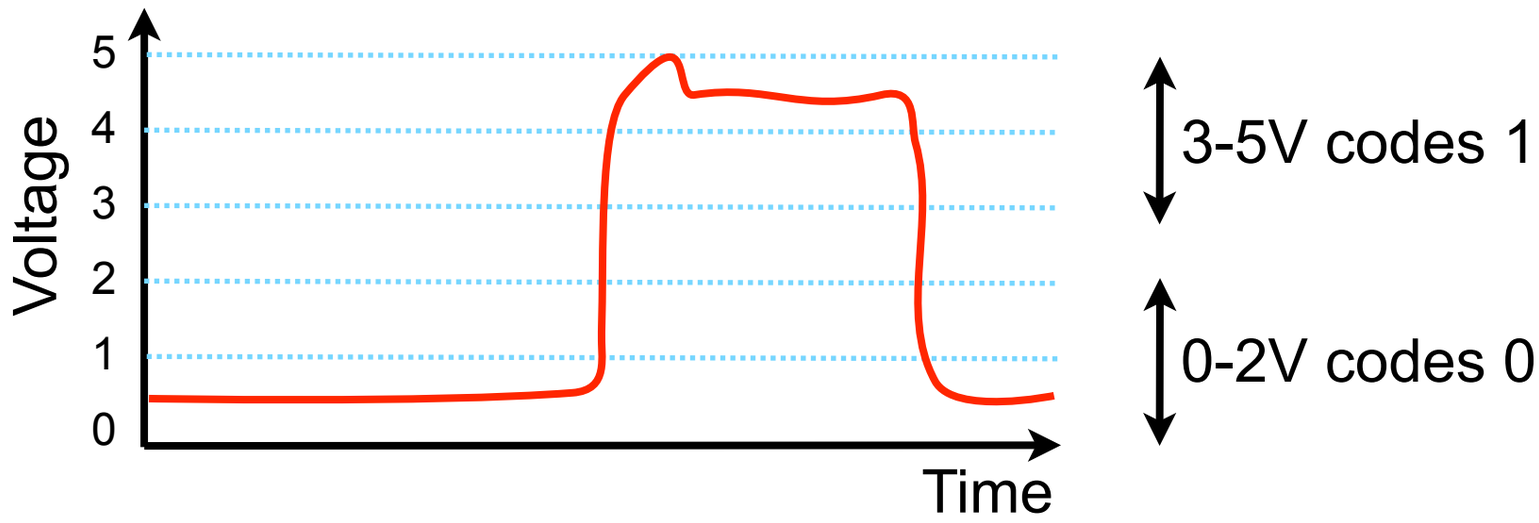
Signal usually occupies baseband region

The *bandwidth* of the signal is denoted *H*, and is the frequency range used

- Encoding performed by varying the voltage in an electrical cable, or the intensity of light in an optical fibre
- Many encoding schemes exist: NRZ, NRZI, Manchester, 4B/5B, etc.

Non-Return to Zero Encoding

- Encode a 1 as a high signal, a 0 as a low signal

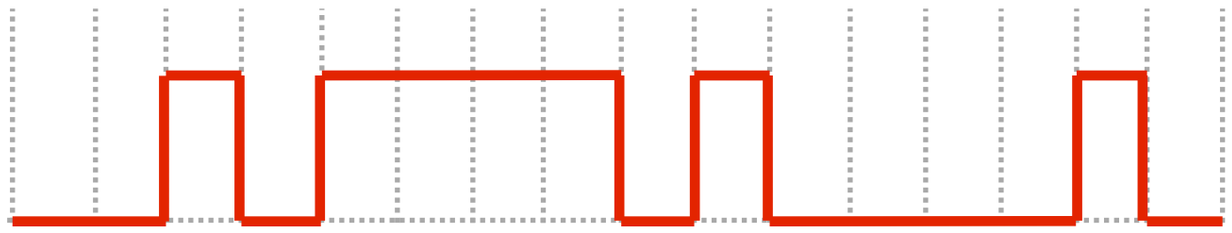


Non-Return to Zero Encoding

- Encode a 1 as a high signal, a 0 as a low signal

Bits: 0 0 1 0 1 1 1 1 0 1 0 0 0 0 1 0

NRZ:



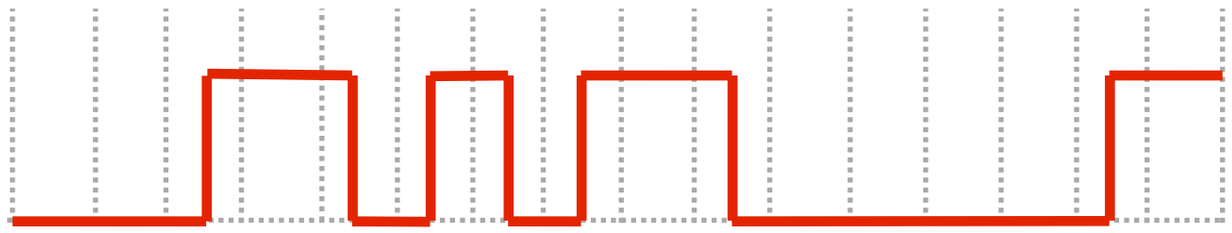
- Limitations with runs of consecutive same bit:
  - Baseline wander
  - Clock recovery

NRZ Inverted Encoding

- Encode a 1 as a change in signal value, a 0 as a constant signal

Bits: 0 0 1 0 1 1 1 1 0 1 0 0 0 0 1 0

NRZI:

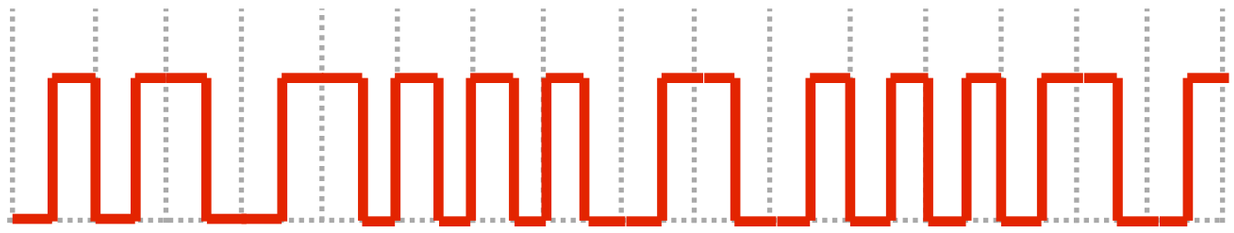


- Solves problems with runs of consecutive 1s, does nothing for runs of consecutive 0s

Manchester Encoding

- Encode a 1 as a high-low signal transition, a 0 as a low-high signal transition

  Bits: 0 0 1 0 1 1 1 1 0 1 0 0 0 0 1 0

  Manchester: 

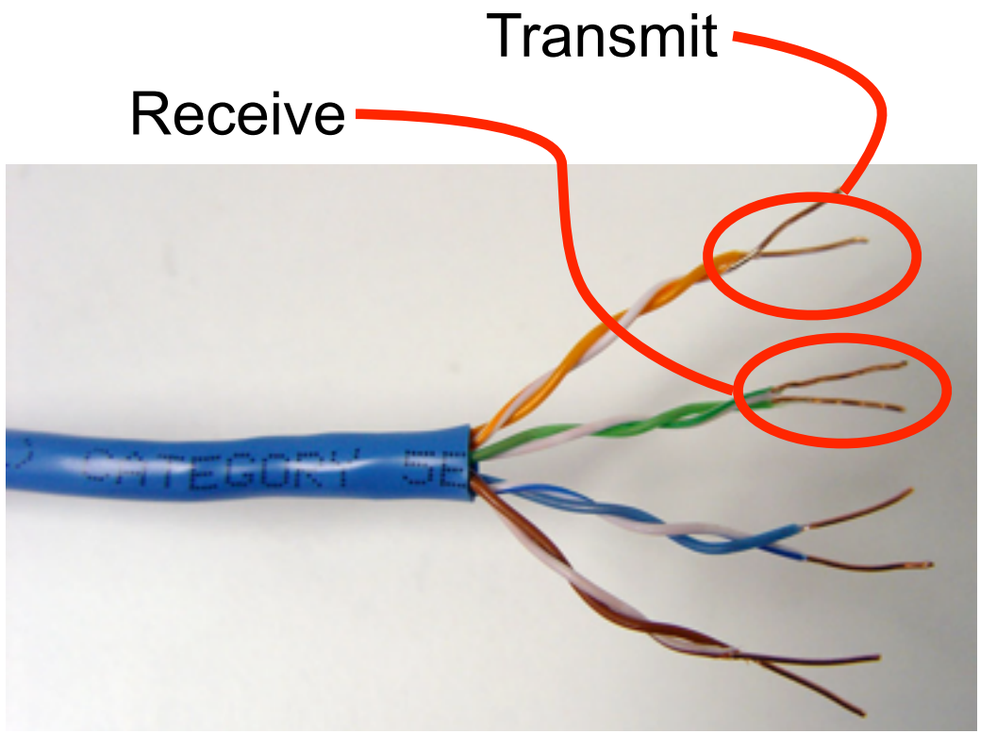
- Doubles the bandwidth needed, but avoids the problems with NRZ encoding

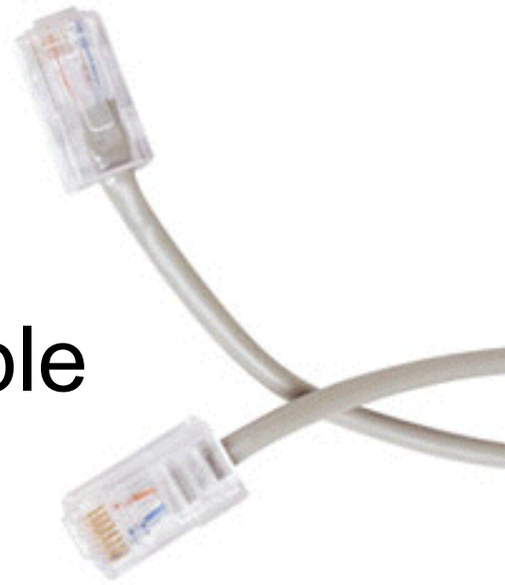
4B/5B Encoding

4-Bit Data Symbol	5-Bit Encoding
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

- Manchester encoding inefficient – only 50% of link capacity used
- Alternative – insert extra bits to break up sequences of same bit
  - Each 4 bit data symbol is changed to a 5 bit code for transmission; reversed at receiver
  - Transmit 5 bit codes using NRZI encoding
  - 80% of link capacity used for data

Example: Ethernet





4 twisted pairs per cable

3 twists per inch

24 gauge (~0.5mm) copper

100m maximum cable length

Baseband data with Manchester coding at 10 Mbps, or 4B/5B coding at 100 Mbps

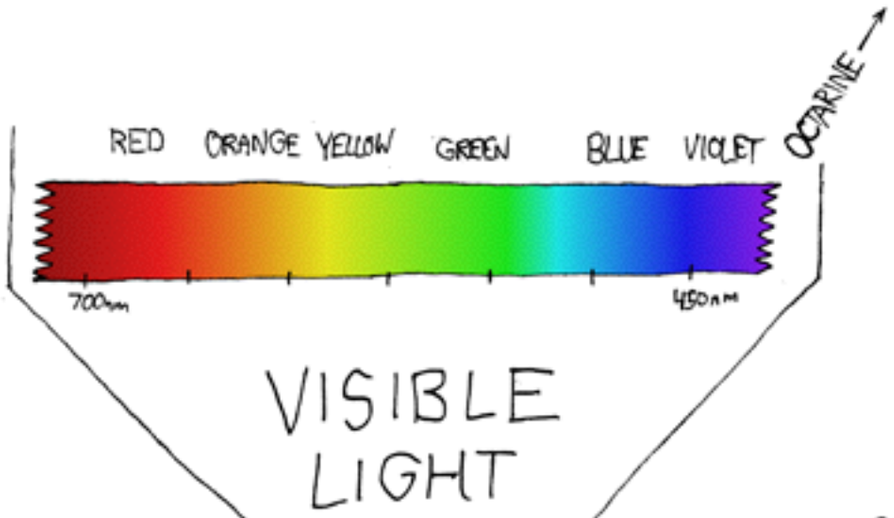
Wireless Links

- Wireless links use carrier modulation, rather than baseband transmission
- Performance affected by:
  - Carrier frequency
  - Transmission power
  - Modulation scheme
  - Type of antenna, etc.

Source: http://xkcd.com/273/

THE ELECTROMAGNETIC SPECTRUM

THESE WAVES TRAVEL THROUGH THE ELECTROMAGNETIC FIELD. THEY WERE FORMERLY CARRIED BY THE AETHER, WHICH WAS DECOMMISSIONED IN 1897 DUE TO BUDGET CUTS.



OTHER WAVES:

SLINKY WAVES

SOUND WAVES

AUDIBLE SOUND

20 KHz

20 Hz

THAT HIGH-PITCHED NOISE IN EMPTY ROOMS

THE WAVE

SHOUTING CAR DEALERSHIP COMMERCIALS

HAM RADIO

KOSHER RADIO

CIA (SECRET)

CELL PHONE CANCER RAYS

99.3 "THE FOX"

101.5 "THE BADGER"

106.3 "THE FRIGHTENED SQUIRREL"

SPACE RAYS CONTROLLING STEVE BALLMER

ALIENS

SETI

GRAVITY

24/7 NPR PLEDGE DRIVES

AM (US)

WIFI

BRAIN WAVES

SULAWESI

VHF

UHF

FHF

SUPERMAN'S HEAT VISION

JACK BLACK'S HEAT VISION

SUNLIGHT

MAIN DEATH STAR LASER

CENSORED UNDER PATRIOT ACT

POTATO

BLOGORAYS

MAIL-ORDER X-RAY GLASSES

SINISTER GOOGLE PROJECTS

POWER & TELEPHONE | RADIO & TV | MICROWAVES | TOASTERS | IR | VISIBLE LIGHT | UV | VISIBLE DARK | MILLER LIGHT | X-RAYS | GAMMA/COSMIC RAYS

λ (m) 10^{3} 10^{2} 10^{1} 10^{0} 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12} 10^{-13}

100Mm 10Mm 1Mm 100km 10km 1km 100m 10m 1m 10cm 1cm 1mm 100μm 10μm 1μm 100nm 10nm 1nm 100pm 10pm 1pm 100fm

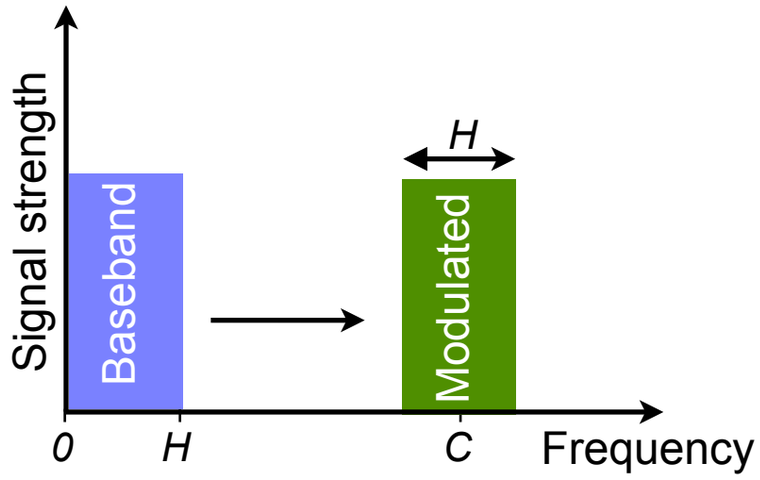
f (Hz) 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7} 10^{8} 10^{9} 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20} 10^{21} 10^{22}

1Hz 10Hz 100Hz 1KHz 10KHz 100KHz 1MHz 10MHz 100MHz 1GHz 10GHz 100GHz 1THz 10THz 100THz OTHER ENTERTAINING GREEK PREFIXES LIKE PETA- AND EXA- AND ZAPPA-

Q (Gal²/Coloumb) 17 117 π 17 42 Φ $e^{\pi}-\pi$ -2 $5!0^{50}$ 12 11^{2}

Carrier Modulation

- Carrier wave applied to channel at frequency, C
- Signal modulated onto the carrier



Shifts signal from baseband to a higher carrier frequency

- Allows multiple signals on a single channel
  - Provided carriers spaced greater than bandwidth, *H*, of the signal
  - Usually applied to wireless links, but can be used on wired links – this is how ADSL and voice telephones share a phone line

Amplitude, Frequency, Phase Modulation

Raw signal:

Amplitude modulation:

Frequency modulation:

Phase modulation:



Complex Modulations

- More complex modulation schemes allow more than one bit to be sent per baud
  - Use multiple levels of the modulated component
    - Example: gigabit Ethernet uses amplitude modulation with five levels, rather than binary signalling
  - Combine modulation schemes
    - Vary both phase and amplitude → quadrature amplitude modulation
    - Example: 9600bps modems use 12 phase shift values at two different amplitudes
  - Extremely complex combinations regularly used

Spread Spectrum Communication

- Single frequency channels prone to interference
  - Mitigate by repeatedly changing carrier frequency, many times per second: noise unlikely to affect all frequencies
  - Use a pseudo-random sequence to choose which carrier frequency is used for each time slot
  - Seed of pseudo-random number generator is shared secret between sender and receiver, ensuring security



Hedy Lamarr

- Example: 802.11b Wi-Fi uses spread spectrum using several frequencies centred ~2.4 GHz with phase modulation

Bandwidth and Channel Capacity

- The bandwidth of a channel determines the frequency range it can transport
  - Fundamental limitations based on physical properties of the channel, design of the end points, etc.
- What about digital signals?



Source: IEEE

Harry Nyquist, 1889-1976

- Sampling theorem: to accurately digitise an analogue signal, need *2H* samples per second
- Maximum transmission rate of a digital signal depends on channel bandwidth: $R_{max} = 2H \log_2 V$
  - R_{max} = maximum transmission rate of channel (bits per second)
  - H = bandwidth
  - V = number of discrete values per symbol
- Assumption: perfect, noise-free, channel

Noise

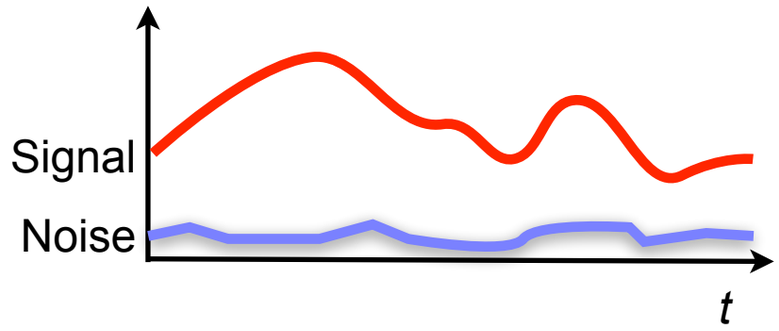
- Real world channels are subject to *noise*
- Many causes of noise:
  - Electrical interference
  - Cosmic radiation
  - Thermal noise

Different noise spectra

- Corrupts the signal: additive interference

Signal to Noise Ratio

- Can measure signal power, S, and noise floor, N, in a channel



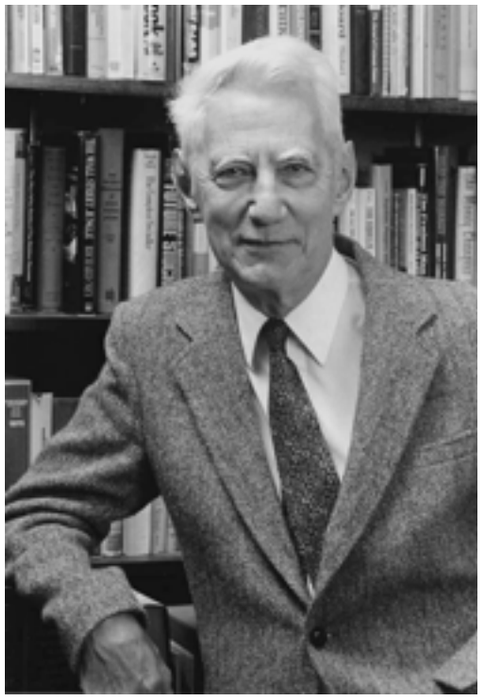
- Gives signal-to-noise ratio: S/N
  - Typically quoted in decibels (dB), not directly
  - Signal-to-noise ratio in dB = 10 $\log_{10}$ S/N

S/N	dB
2	3
10	10
100	20
1000	30

- Example: ADSL modems report S/N ~30 for good quality phone lines: signal power 1000x greater than noise

Capacity of a Noisy Channel

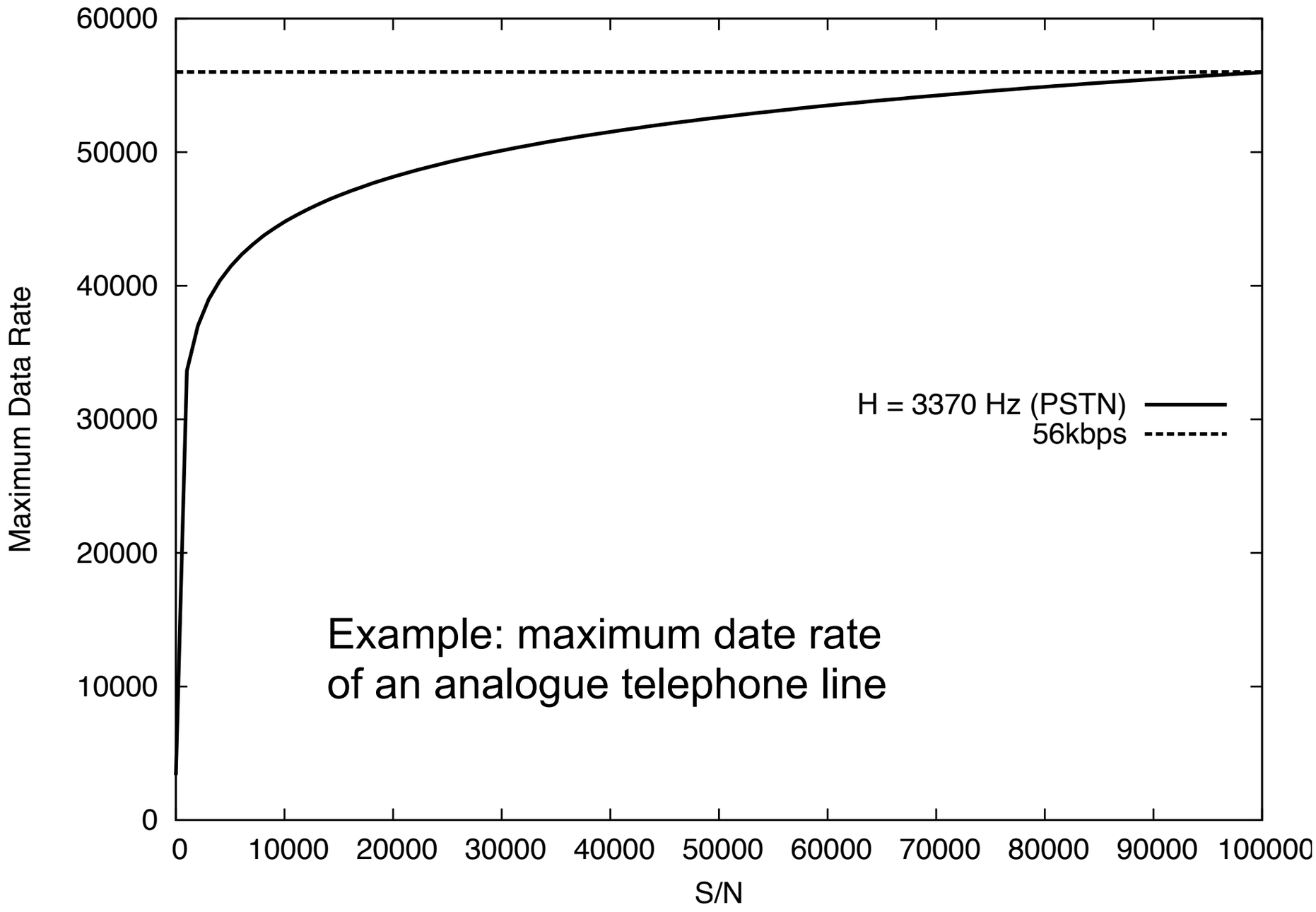
- Capacity of noisy channel depends on type of noise
  - Uniform or bursty; affecting all or some frequencies
  - Simplest to model is *Gaussian noise:* uniform noise that impacts all frequencies equally
  - Maximum transmission rate of a channel subject to Gaussian noise: $R_{max} = H \log_2(1 + S/N)$



Source: AT&TT Bell Labs

Claude Shannon, 1916-2001

Capacity of a Noisy Channel



Implications

- Physical characteristics of channel limit amount of information that can be transferred
  - Bandwidth
  - Signal to noise ratio
- These are fundamental limits: might be reached with careful engineering, *but cannot be exceeded*