Physical and Data Link Layers

- Physical link characteristics, modulation and transmission
- Data link layer: framing and addressing, media access control

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The Physical Layer

- Physical layer enables communication – transmission of raw bitstream
  - 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?

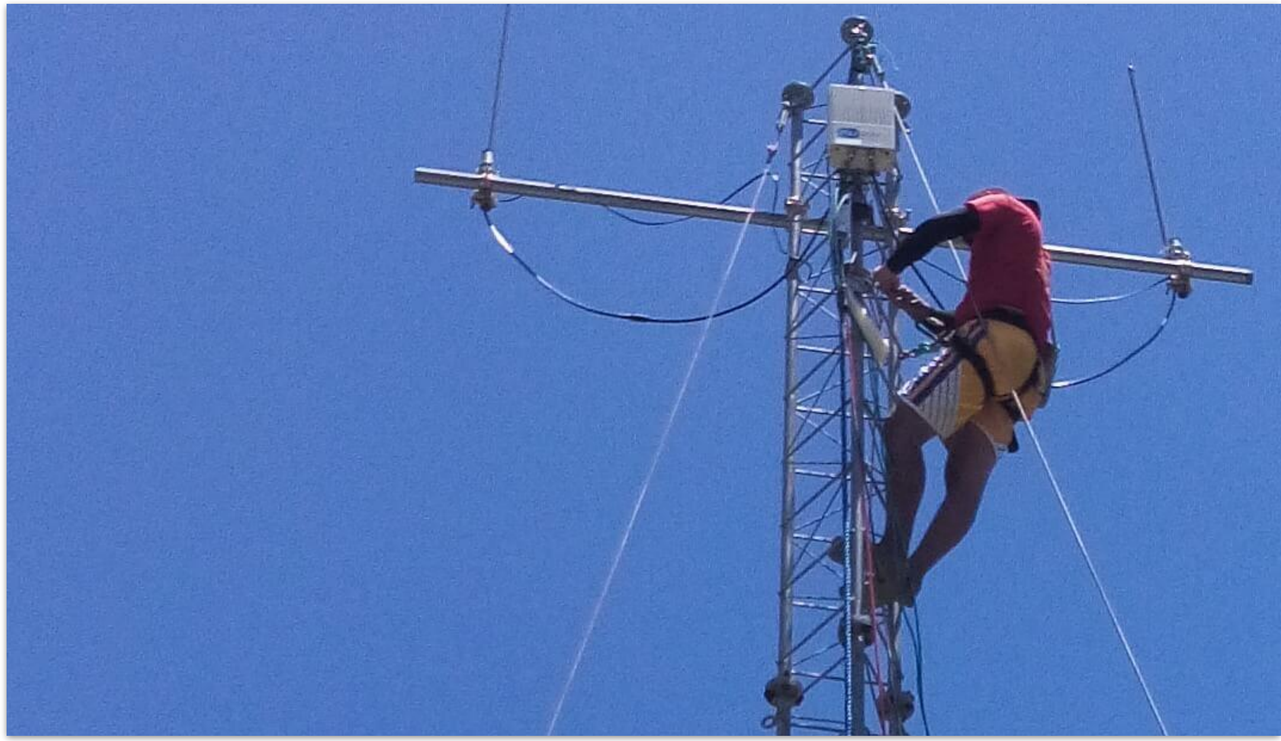

Image: Maria Theresa Perez, “Community Cellular Networks in the Philippines: Experiences from the VBTS project”, Presentation to IRTF GAIA RG, November 2019, https://www.ietf.org/proceedings/106/slides/slides-106-gaia-up-vbts-philippines-00

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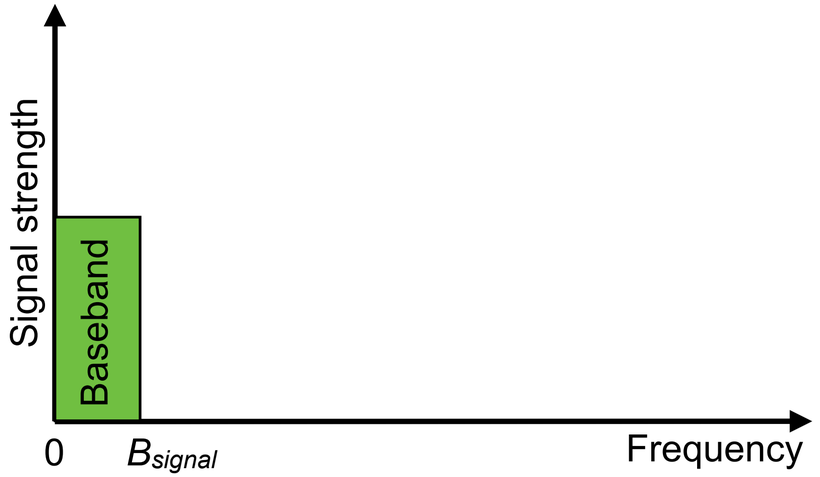
Encoding Data onto Wired Channels



- Signal usually directly encoded onto the channel, by varying some property of the channel, and occupies **baseband** region

- The maximum bitrate of a channel is described by Nyquist's theorem: $R_{max} \leq 2B \log_2 V$
  - B = bandwidth of the channel
  - V = number of discrete values per symbol
- Maximum data rate only reached with a noise-free channel



Source: IEEE

Harry Nyquist (1889-1976)

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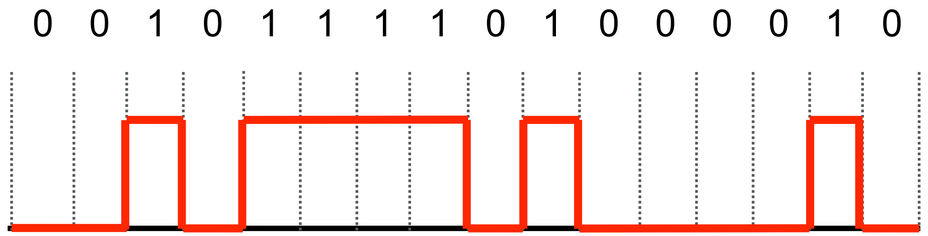
Baseband Data Encoding

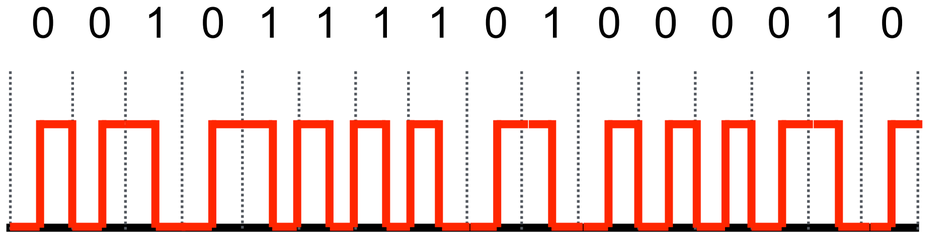
Non-return to zero (NRZ) encoding:



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

No variation in waveform if long runs of same value sent – easy to miscount number of bits

Manchester encoding:



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

Doubles bandwidth needed, since transition on every bit, but avoids miscount

- Signal encoded onto the channel by varying channel characteristics – voltage applied to an electrical cable, intensity of laser in optical fibre

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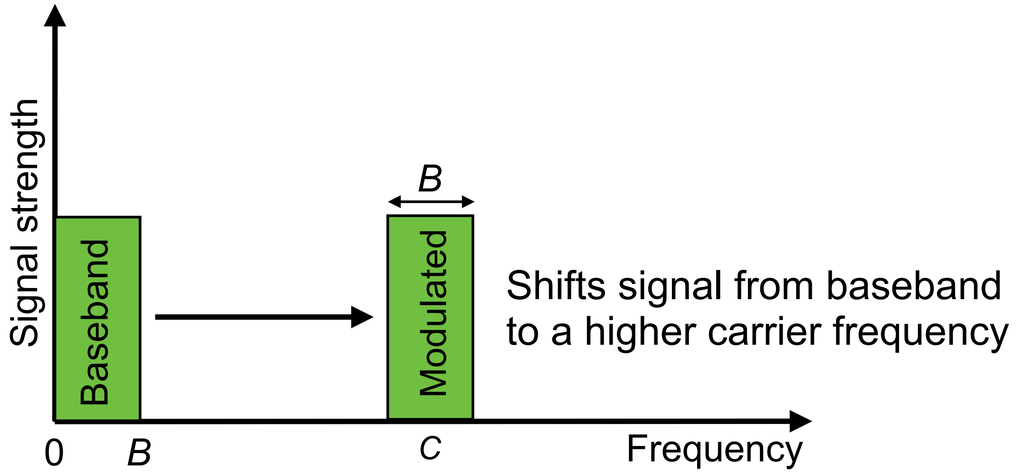
Encoding Data onto Wireless Channels



- Carrier wave applied to channel at frequency, *C*; signal modulated onto the carrier
- Bandwidth unchanged, but shifted to range centred on the carrier frequency

- Wireless links use carrier modulation, rather than baseband transmission
- Allows multiple signals on a channel, modulated onto carriers of different frequency
  - Compare: FM or AM radio stations
  - Can be used on wired links – this is how ADSL and voice telephones share a phone line
- Performance affected by carrier frequency, transmission power, modulation scheme, type of antenna, etc.

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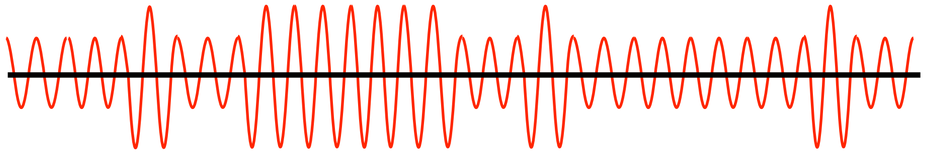
Amplitude, Frequency, Phase Modulation

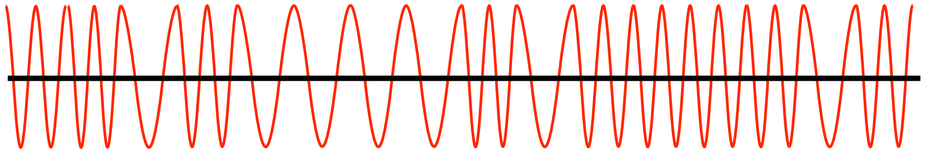
Raw signal:



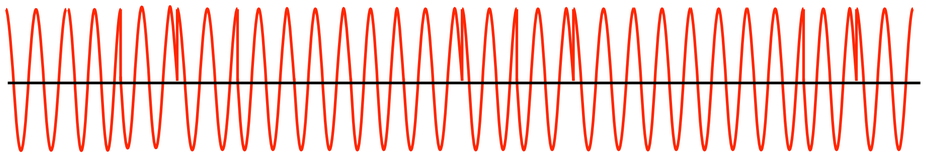
Amplitude modulation:



Frequency modulation:



Phase modulation:



Complex modulations are possible: Gigabit Ethernet uses amplitude modulation with five different amplitudes

Modulation schemes are often combined: for example, dial-up modems vary phase and amplitude → **quadrature amplitude modulation** with 12 phase shift values at two different amplitudes

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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
- Example: 802.11b Wi-Fi uses spread spectrum using several frequencies centred at either 2.4 GHz or 5 GHz



Source: Wikipedia/Public Domain

Hedy Lamarr (1914-2000)

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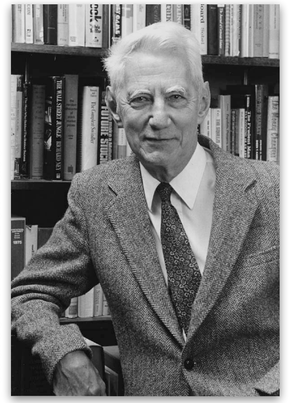
Physical Link Characteristics and Limitations

- Real-world network links are imperfect, and subject to **noise**
  - Electrical or radio interference, imperfections in optical fibre
- The Shannon-Hartley theorem predicts the maximum data rate of a channel subject to noise: $R_{max} = B \log_2 (1 + {}^{S}/_{N})$
  - B = bandwidth of the channel
  - S = signal strength
  - N = noise strength
  - Assuming Gaussian noise: interference affects all frequencies equally
- Physical limit on maximum transmission rate
  - *B* and *N* depend on properties of the channel
  - *S* depends on transmission power → trade battery life for performance



Source: AT&TT Bell Labs

Claude Shannon
(1916-2001)



Source: Wikipedia

Ralph Hartley
(1888-1970)

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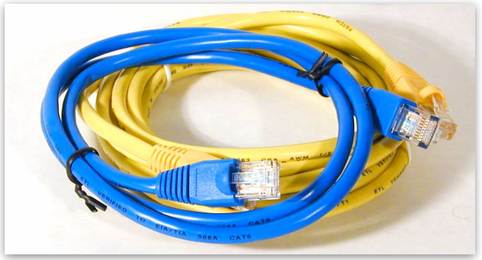
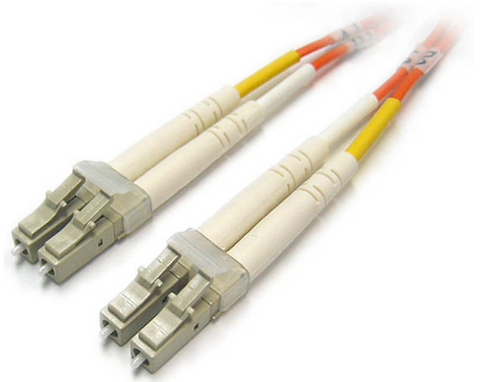
The Data Link Layer

- Physical layer enables communication
- Data link layer provides framing, addressing, media access control
  - Structure the bitstream into meaningful frames of data
  - Detect and correct transmission errors
  - Identify devices
  - Arbitrate access to the channel







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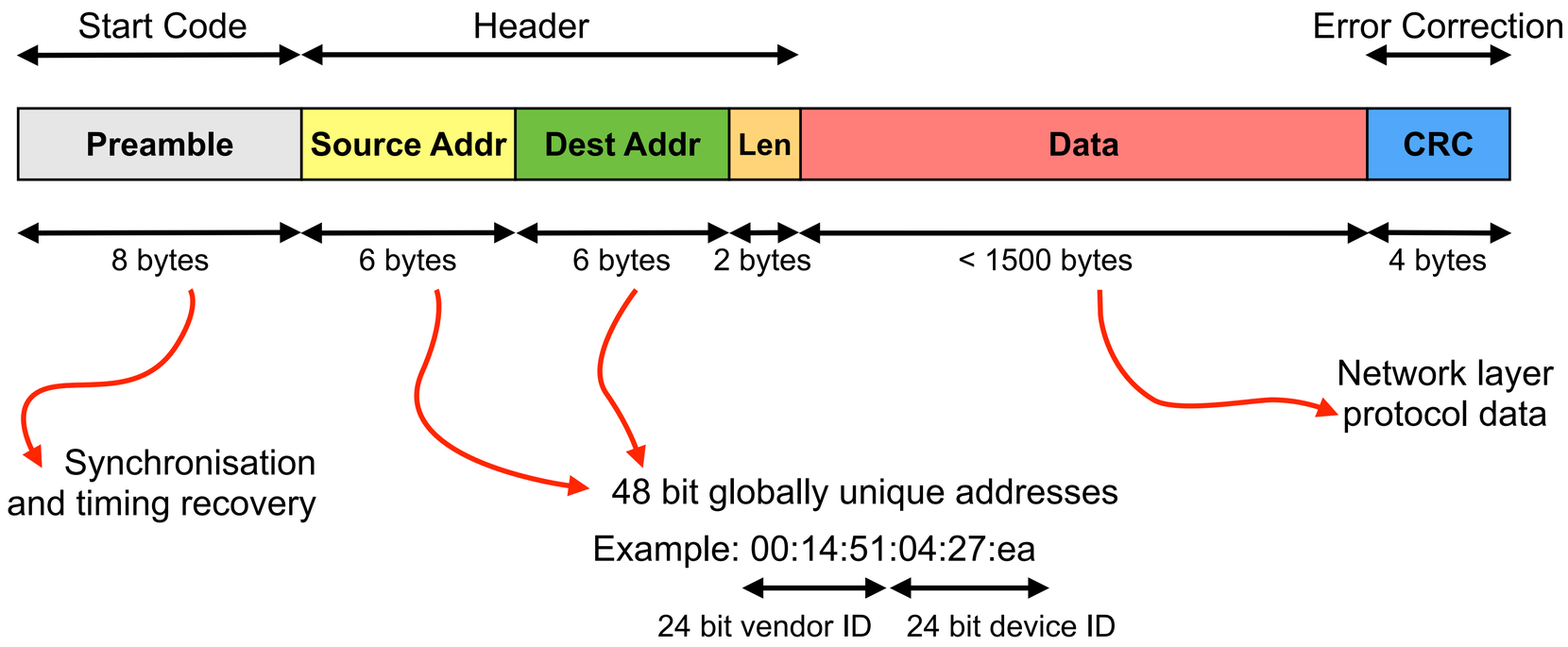
Framing and Addressing

Separate the bitstream into meaningful frames of data

Example: Ethernet frame format



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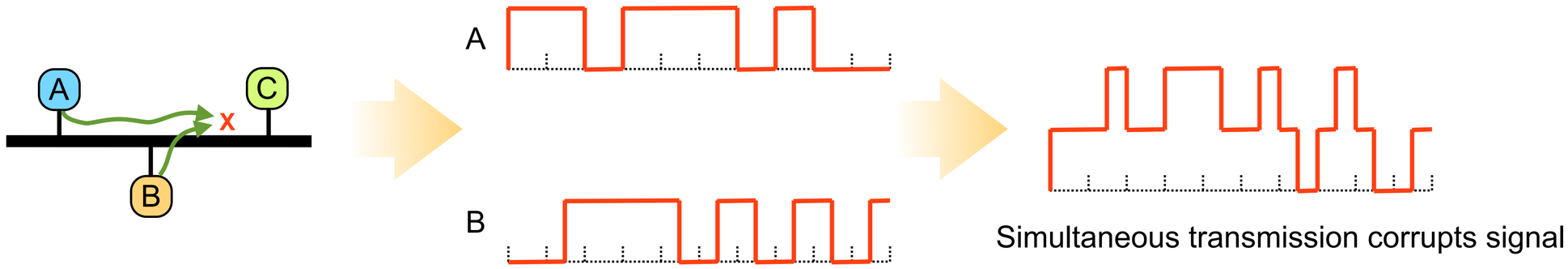
Media Access Control



Control when frames are sent, to avoid collisions

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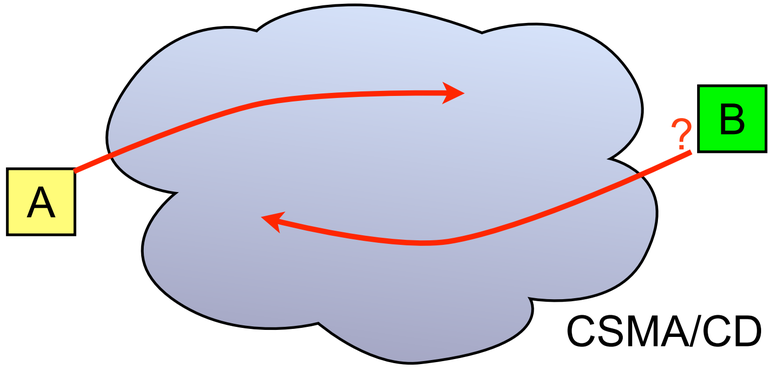
Media Access Control

- When propagation delay low, listen before sending
  - If link is idle, send data immediately
  - If another transmission is active, or if collision occurs, stop sending, wait, then retransmit
    - Wait time should be random – to avoid deterministic repeated collisions; pick a random initial back-off interval of *x* seconds ± 50%
    - Wait time should increase with number of collisions – repeated collisions signal congestion; reduce transmission rate allows network to recover; each repeated collision before success, $x \rightarrow 2x$
- Improves utilisation
  - Active transmissions not disrupted by collisions
  - Only the new sender backs-off if the channel is active
- Examples: Ethernet, Wi-Fi

Why does propagation delay matter?



CSMA/CD

A starts transmitting

B listens, hears no traffic (message from A hasn't reached it yet)

B starts transmitting

Collision occurs, as messages overlap in transit; smaller propagation delay → less likely to occur

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