Computer Networks 101

- A network is a "group of computers and associated devices that are connected by communication facilities."

- Types of networks:
  - Local Area Network (LAN): laboratory/office-scale
  - Metropolitan Area Network (MAN): city-scale
  - Wide Area Network (WAN): world-wide (Internet -> "collection of networks")
Examples

- **Ethernet:**
  - popular, relatively inexpensive, easy-to-install LAN architecture
  - uses the CSMA/CD media access control
  - data transmission normally occurs at 100 Mbps (10Mbps in the early forms and 10Gbps in the most recent forms)
  - partially described in the IEEE 802.3 specification
- **Wi-Fi:**
  - popular wireless LAN architecture
  - uses a modified version of the CSMA/CA protocol
  - partially described in the IEEE 802.11 specification

ISO/OSI Model

- The International Standards Organization (ISO) Open Systems Interconnect (OSI) is a standard set of rules describing the transfer of data between each layer in a network operating system. Each layer has a specific function (i.e., the physical layer deals with the electrical and cable specifications).

**ISO/OSI Model**

- **Physical Layer**
  - Physical/electrical characteristics
  - Cable type, length, connectors, voltage level, signal durations, ...
  - Binary data (bits) as electrical or optical signals.

- **Data Link Layer**
  - Defines when/how medium will be accessed for transmission
  - Units typically called “frames”; error detection/correction; divided into sublayers including: **MAC** = Medium Access Control (MAC address 6f:00:2b:23:1f:32)

- **Network Layer**
  - **IP** = Internet Protocol
  - Addressing and routing (IP address 147.94.123.15)
ISO/OSI Model

- **Transport Layer**
  - **UDP** (User Datagram Protocol)
  - **TCP** (Transmission Control Protocol)
    - Addressing ("ports"), error correction, flow control, congestion control

- **Session Layer**
  - Management of "sessions"

- **Presentation Layer**
  - Data translation, formatting, encryption, compression

- **Application Layer**
  - Interface between user applications and lower network services

What is IP, TCP, UDP?

- **Internet Protocol (IP):**
  - Take your message and slap a "header" on it ("packet")
  - What's in a header?
    - Sender address: 112.44.44.23
    - Receiver address: 147.12.68.211
    - Routers use it to figure out what to do with it (see next slide for routers)
  - What does IP do:
    - mostly addressing
    - used by routers

Internet + Routers

- **Router**: links parts of a larger network together
  - **Routing using tables**
    - "129.74" belongs to University of Notre Dame
  - **How is the table built?**
    - Routers talk to each other to exchange what they know about the world using **ICMP = Internet Control Message Protocol**
  - **Why only remember parts of a network?**
    - 32-bit address consists of network address and computer addresses
    - Class A, B, C networks: 8/16/24 bits for network/next for computers
      - Example: C network (127.45.20.21)
        - 127.45.20 is network address
        - 21 is computer address (out of 255 computers)
  - **Routing is based on independent packets** (compare phone call vs. USPS)
UDP = User Datagram Protocol

- Slap on another header
- Adds more addressing: "ports"
  - IP address tell you which computer
  - Ports tell you which application on that computer
  - Example: a web server "listens" to requests on port 80
  - HTTP: HyperText Transfer Protocol
    - :80: optional
  - Unreliable!
    - Packets can get lost; packets can arrive out of order

TCP = Transmission Control Protocol

- Reliable protocol
- Adds ports (just like UDP), but also provides:
  - In-order delivery of packets (using sequence numbers)
  - Reliable delivery: using acknowledgment (ACK) packets
  - Flow control:
    - control of traffic between sender and receiver
    - Explicit "advertised window" in ACK: packet (how many more bytes)
  - Congestion control:
    - control of traffic flow into the network
    - Implicit: watch ACKs -> missing ACKs = router overload

UDP vs TCP

- TCP:
  - typical choice of most applications
  - do not want to lose data, out-of-order arrival, etc.
  - email, web traffic, financial transactions, etc.

- UDP:
  - can be "faster"
    - no flow/congestion control "slowing down" traffic
    - no retransmissions
    - good for "real-time" traffic
    - out-of-order arrival can also "reorder" at application level
    - loss of data: can be acceptable
    - missing frames in video/audio stream
Medium Access Control (MAC)

• Responsible for deciding **when & how to transmit frames** over a network (“channel access problem”)
  • Ethernet bus: computers connect to the same wire, i.e., two computers could “talk” at the same time: collision!
  • MAC protocol is very important for “quality” of communications (successful transmissions, reliable transmissions, high throughput, low latency, fairness, …)

Simultaneous Transmissions

• Simple strategy:
  • Ignore ongoing communications and just transmit anytime:
    • large number of collisions
    • low throughput.

“Smarter” Approach

• Listen before you talk!
  • **Carrier Sense Multiple Access (CSMA)**
    • “Sense” (listen) carrier (“is anyone else talking right now?”)
    • If “busy”: wait; if “idle”: transmit

Can collisions still occur?
Collisions in CSMA

- Collisions still do occur:
  - Non-zero propagation delays
  - Partial collision: entire packet lost

CSMA/CD

- CD = Collision Detection.
- How? Keep listening to channel while transmitting!
- If transmitted signal and sensed signal differ:
  - Collision detected
  - Abort transmission
  - Jam channel: send random bit sequence to "inform" other computers that a collision has occurred

CSMA/CD

- Assumption: the received and transmitted signal are identical (non-dispersive)
- Assumption: receiver "sees" the same signals as transmitters on channel
- Problem: both not true in wireless networks!
- Transmitter does not know what the receiver "sees" and therefore does not know if transmission was successful
Wireless Transmissions

Collision Detection

- Signal received depends on “signal to interference plus noise ratio” (SINR = P/(I+N)).

Hidden Terminal/Exposed Terminal

- Hidden terminal: C does not hear A (and A cannot hear C), but it can interfere with A at B.
  - Node SHOULD NOT transmit!
- Exposed terminal: X hears A and wants to transmit to Y. It cannot interfere with A at B.
  - Node SHOULD transmit!
IEEE 802.11 (CSMA/CA)

CA = Collision Avoidance

RTS = Request To Send
CTS = Clear To Send

Further Reducing Collisions

- Wait random amount of time before transmitting!
- Choose a random number $R = \text{rand}(0, CW_{\text{min}})$
- Each node counts down $R$
  - Continue carrier sensing while counting down
  - Once carrier busy, freeze countdown
- Whoever reaches ZERO transmits RTS
  - Neighbors freeze countdown, decode RTS
  - RTS contains $(\text{CTS} + \text{DATA} + \text{ACK})$ duration = $T_{\text{comm}}$
  - Neighbors set NAV = $T_{\text{comm}}$
  - Remains silent for NAV time
Further Reducing Collisions
- Receiver replies with CTS
  - Also contains (DATA + ACK) duration
  - Neighbors update NAV again
- Tx sends DATA, Rx acknowledges with ACK
  - After ACK, everyone initiates remaining countdown
  - Tx chooses new $R = \text{rand}(0, CW_{\text{min}})$
- If RTS or DATA collides (i.e., no CTS/ACK returns)
  - Indicates collision
  - Tx chooses new random $R_1 = \text{rand}(0, 2CW_{\text{min}})$
  - Exponential Backoff $R_i = \text{rand}(0, 2^i \times CW_{\text{min}})$
  - Once successful transmission, reset to $\text{rand}(0, CW_{\text{min}})$

Recap
- CSMA/CD: works good in wired networks; but doesn't work in wireless networks
- CMSA/CA ("collision avoidance"): goal is to reduce the occurrences of collisions instead of detecting and handling them

Next Up: Wireless Communications
- Fundamental aspects of wireless networks and radio communications
Frequencies for Communication

- **VLF = Very Low Frequency**
- **LF = Low Frequency**
- **MF = Medium Frequency**
- **HF = High Frequency**
- **VHF = Very High Frequency**

- **UHF = Ultra High Frequency**
- **SHF = Super High Frequency**
- **EHF = Extra High Frequency**
- **HF = High Frequency**
- **UV = Ultraviolet Light**

**Frequency and wave length**

\[ \lambda = \frac{c}{f} \]

- \( \lambda \): wave length, \( c \): speed of light \( \approx 3 \times 10^8 \) m/s, \( f \): frequency

**Frequencies for Mobile Communication**

- **Low Frequencies**:
  - low data rates
  - travel long distances
  - follow Earth's surface
  - penetrate objects and water (submarine communication)

- **High Frequencies**:
  - high data rates
  - short distances
  - straight lines
  - cannot penetrate objects ("Line of Sight" or LOS)

**Frequencies and Regulations**

- ITU-R holds auctions for new frequencies, manages frequency bands worldwide (WRC, World Radio Conferences)

**Examples**

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<thead>
<tr>
<th>Europe</th>
<th>USA</th>
<th>Japan</th>
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<tbody>
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<td>850-885, 1900-1990</td>
<td>850-950</td>
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Signal propagation

- Transmission range
  - communication possible
  - low error rate
- Detection range
  - detection of the signal possible
  - no communication possible
- Interference range
  - signal may not be detected
  - signal adds to the background noise

Signal propagation

- Propagation in free space always like light (straight line)
- Receiving power proportional to 1/d² in vacuum – much more in real environments
  - (d = distance between sender and receiver)
- Path loss (attenuation)
  - Fundamental propagation behaviors:
    - ground wave (<2MHz): follow earth’s surface, long distances (submarine communication, AM radio)
    - sky wave (2-30MHz): reflected at ionosphere, around the world (int'l broadcasts, amateur radio)
    - line-of-sight (>30MHz): LOS, straight line, waves are bent by atmosphere due to refraction (mobile phones, satellite, cordless)
- Most systems we will discuss work with >100MHz: LOS (question: so how do mobile phones work then???)

Other propagation effects

- Receiving power additionally influenced by
  - fading (frequency dependent)
  - shadowing
  - reflection at large obstacles
  - refraction depending on the density of a medium
  - scattering at small obstacles
  - diffraction at edges
Real world examples

Multipath propagation
- Signal can take many different paths between sender and receiver due to reflection, scattering, diffraction
- Time dispersion: signal is dispersed over time
- Interference with "neighbor" symbols, Inter Symbol Interference (ISI)
- The signal reaches a receiver directly and phase shifted
  - Distorted signal depending on the phases of the different parts

Effects of Mobility
- Channel characteristics change over time and location
  - Signal paths change
  - Different delay variations of different signal parts
  - Different phases of signal parts
  - Quick changes in the power received (short term fading)
- Additional changes in
  - Distance to sender
  - Obstacles further away
  - Slow changes in the average power received (long term fading)
Multiplexing

- Multiplexing in 4 dimensions
  - space ($s$)
  - time ($t$)
  - frequency ($f$)
  - code ($c$)

- Goal: multiple use of a shared medium
- Important: guard spaces needed!

Frequency division multiplexing (FDM)

- Separation of the whole spectrum into smaller frequency bands
- A channel gets a certain band of the spectrum for the whole time
- Advantages
  - no dynamic coordination necessary
  - works also for analog signals
- Disadvantages
  - waste of bandwidth if the traffic is distributed unevenly
  - inflexible

Time division multiplexing (TDM)

- A channel gets the whole spectrum for a certain amount of time
- Advantages
  - only one carrier in the medium at any time
  - throughout high even for many users
- Disadvantages
  - precise synchronisation necessary
Time and Frequency Multiplex

- Combination of both methods
- A channel gets a certain frequency band for a certain amount of time
- Example: GSM
  - Advantages
    - better protection against tapping
    - protection against frequency selective interference
  - But: precise coordination required

Code Division Multiplexing (CDM)

- Each channel has unique code
- All channels use the same spectrum at the same time
- Advantages
  - bandwidth efficient
  - no coordination and synchronization necessary
  - good protection against interference and tapping
- Disadvantages
  - varying user data rates
  - more complex signal regeneration
  - Implemented using spread spectrum technology

Physical Layer: Modulation

- Digital modulation
  - digital data is translated into an analog signal
- Basic schemes
  - Amplitude Modulation (AM)
  - Frequency Modulation (FM)
  - Phase Modulation (PM)
Modulation and demodulation

Digital Modulation
- Modulation of digital signals known as Shift Keying
  - Amplitude Shift Keying (ASK):
    - very simple
    - low bandwidth requirements
    - very susceptible to interference
  - Frequency Shift Keying (FSK):
    - needs larger bandwidth
  - Phase Shift Keying (PSK):
    - more complex
    - robust against interference

Quadrature Amplitude Modulation
- Quadrature Amplitude Modulation (QAM)
  - combines amplitude and phase modulation
  - It is possible to code n bits using one symbol
  - 2^n discrete levels, n=2 identical to QPSK
  - Bit error rate increases with n, but less errors compared to comparable PSK schemes
    - Example: 16-QAM (4 bits = 1 symbol)
    - Symbols 0011 and 0001 have the same phase \( \phi \), but different amplitude.
    - Symbols 0000 and 1000 have different phase, but same amplitude.