The Link Layer

Michael Brodskiy
Professor: E. Bernal Mor

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- Link Layer: Introduction
  - Terminology
    - Hosts, routers → nodes
    - Communication channels that connect adjacent nodes along communication path → links
      - Wired links
      - Wireless links
    - Over a given link, the transmitting node encapsulates the network-layer packet in a link-layer frame
  - Link layer has responsibility of transferring network-layer packets from one node to a physically adjacent node over a link
- Link Layer: Context
  - Packets transferred by different link protocols over different links
    - WiFi on first link
    - Ethernet on next link
    - Etcetera
  - Each link protocol provides different services
- Link Layer Services
  - Framing
    - Encapsulate packet into frame, adding header and maybe trailer
    - Addressing: "MAC" addresses used in frame headers to identify transmitter/receiver node → different from IP Address
  - Link access

    * Medium access control (MAC) protocol specifies the rules by which a frame is transmitted onto the link
  - Flow control
    * Pacing between adjacent sending and receiving nodes
  - Reliable delivery between adjacent nodes
    * We learned how to do this already (Transport layer)!
    * Seldom used on low error rate links, for example: fiber, some twisted pairs
    * Commonly used on high error rate links, like wireless ones
  - Error control
    * Errors caused by signal attenuation, noise
    * Error detection: receiver detects presence of errors
      · Ask sender for retransmission or drops frame
    * Error correction: receiver identifies and corrects bit error(s) without resorting to retransmission

- Half-Duplex and Full-Duplex Links
  - Unidirectional links (Simplex Links)
    * Communication occurs in one direction only
  - Bidirectional links
    * Half-Duplex Link — Communication occurs in both directions, but not at same time
    * Full-Duplex Link — Communication occurs in both directions at same time

- Where is the Link Layer Implemented?
  - For the most part, link layer is implemented on a chip called the network adapter, aka a Network Interface Card (NIC)
    * The NIC implements Link and Physical layers
    * *E.g.* Ethernet card, WiFi card or chip
  - NIC attaches into node's system buses
  - Link layer is implemented as a combination of hardware and software
    * Hardware: NIC implements most of the functions
    * Software: activating hardware controller, responds to controller interrupts, etc.

- Error Control
  - EDC $\rightarrow$ Error Detection/Correction bits (redundant bits)

- D → Data protected by error control, may include header fields
- Error control is not 100% reliable
  - Error control technique may miss some errors; we want to keep the probability of missing the errors small
  - Larger EDC field yields better detection and correction
  - Error correction needs more redundant bits than error detection for same number of errors
- Parity Checking
  - Single bit parity: detect single bit errors
    - Even parity: set parity bit so there is an even number of 1's
    - Odd parity: set parity bit so there is an odd number of 1's
  - Two-dimensional bit parity: detect and correct single bit errors
    - Even parity: no errors
- Cyclic Redundancy Check (CRC)
  - D: d data bits (given)
  - G: generator, bit pattern of $r+1$ bits where MSB must be 1 → transmitter and receiver agree on G (given)
  - R: r CRC bits, redundant bits
  - Transmitter: choose R, such that $\langle D, R \rangle$ is exactly divisible by G (modulo-2 arithmetic) → $D \cdot 2^r \mathrm{XOR} R = nG$
  - Receiver: knows G and divides $\langle D, R \rangle$ by G → non-zero remainder: error detected!
    - Can detect all burst errors less than $r+1$ bits
  - More powerful error-detection technique: widely used in practice (Ethernet, WiFi)

- Types of Links
  - Point-to=point link: a single sender at one end on a link and a single receive at the other end of the link
    - PPP (Point-to-Point Protocol), switched Ethernet, etc.
  - Broadcast (shared medium) link: Multiple transmitting and receiving nodes all connected to the same, single shared broadcast link
    - Need to handle multiple access problem (classic Ethernet, 4G/5G, WiFi, etc.)
- Multiple Access Problem
  - Multiple access problem: how to coordinate the access of multiple transmitting and receiving nodes to a single, shared broadcast channel

- Two or more simultaneous transmissions by nodes → interference
  * Collision: if a node receives two or more signals at the same time (collision happens in the receiver)
- MAC (Medium Access Control) Protocol
  * Distributed algorithm that coordinates the frame transmissions of many nodes into the broadcast channel
  * Determines how nodes share channel and when nodes can transmit
  * Communication about channel sharing must use channel itself!
  * No out-of-band channel for coordination

- An Ideal MAC Protocol
  - Given: broadcast channel of rate R bps
  - Desirable Characteristics:
    1. When one node wants to transmit, it can send at rate R
    2. When M nodes want to transmit, each can send an average rate R/M
    3. Fully Decentralized
       * No special node to coordinate transmissions
       * No synchronizations of clocks, slots
    4. Simple

- MAC Protocols Taxonomy
  - Three Broad Classes:
    1. Channel Partitioning
       * Divide channel into smaller "pieces" (time slots, frequency, code)
       * Collision free: allocate piece of node for exclusive use to avoid collisions
    2. Random Access
       * Channel not divided, allow collisions
       * "Recover" from collisions
    3. Turn-Taking
       * Nodes take turns: tightly coordinate shared access to avoid collisions

- Channel Partitioning: FDMA
  - FDMA: Frequency Division Multiple Access
  - Frequency spectrum of the channel is divided into N frequency bands (each with transmission rate R/N bps)
  - Each node is assigned a fixed frequency band

  - Advantages: Avoids collisions, and divides the capacity link fairly
  - Drawback: Unused link capacity if frequency band goes idle

- Channel Partitioning: TDMA
  - TDMA: Time Division Multiple Access
  - Access to channel in "rounds" $\rightarrow$ time divided in N slots
  - Each node gets fixed time slot in each round (node average transmission rate R/N bps)
  - Advantages: it avoids collisions, and it divides the link capacity fairly
  - Drawback: unused link capacity if slots fo idle

- Random Access Protocols
  - A transmitting node always transmits at full channel rate, R bps
  - Two or more transmitting nodes create a collision
  - Random access MAC protcool specifics:
    * How to detect collisions
    * How to recover from collisions (like via delayed transmissions)

- Slotted ALOHA
  - Assumptions:
    * All frames same size
    * Time divided into equal size slots
      · Slot duration: time to transmit one frame, t_l
    * Nodes start to transmit only at the beginning of slot
    * Nodes are synchronized
    * If 2 or more nodes transmit in slot, all nodes detect collision
  - Operation:
    * When node obtains fresh frame, transmits in next slot
      · If no collision: node can send new frame in next slot
      · If collision: node retransmits frame in each subsequent slot with probability p until success

- Slotted ALOHA: Efficiency
  - Efficiency: long-run fraction of successful slots (many nodes, all with many frames to send)
  - Suppose N nodes with many frames to send, each transmits in slot with probability p

    - * Probability that a given node has success in a slot: $p(1-p)^{N-1}$
    - * Probability that any node has a success: $Np(1-p)^{N-1}$
    - * Max efficiency: find p^* that maximizes $Np(1-p)^{N-1}$
    - * For many nodes, take limit of $Np^*(1-p^*)^{N-1}$ as N goes to infinity gives:

$$\text{Max Efficiency: } \frac{1}{e} = .37$$

- Pure Aloha
  - Unslotted Aloha: simpler, no synchronization (no time slots)
  - Consider that t_f is the frame transmission time
  - When node obtains fresh frame, transmit immediately
  - Collision: retransmit with probability p immediately, repeat every t_f until the frame is transmitted
  - Collision probability increases:
    - * Frame sent at t_0 collides with other frames sent in $[t_0 - t_f, t_0 + t_f]$
- Pure Aloha Efficiency
  - Efficiency at many nodes is .18, even worse than slotted aloha
- Carrier Sense Multiple Access (CSMA)
  - CSMA: listen before transmitting
    - * If channel sensed idle: transmit entire frame
    - * If channel sensed busy: defer transmission
  - CSMA/CD: CSMA with Collision Detection
    - * Collisions detected within short time
    - * Colliding transmissions aborted, reducing channel wastage
    - * After collision, wait a random time before repeating the CSMA/CD cycle
- CSMA: Collisions
  - Collisions can still occur with carrier sensing:
    - * Propagation delay: two nodes may not heard each other's just-started transmission
    - * The longer the propagation delay from one node to another, the larger the probability that a node is not able to sense a transmission that has already begun at another node
    - * Distance and propagation delay play a crucial role in determining collisoon probability

- Collision: nodes contitute to transmit their frames
  - Entire frame transmission time wasted

- CSMA/CD
  - Collision detection
    - Wired Links: while transmitting, node monitors for the presence of signal energy coming from others nodes
      - Signal energy from other nodes detected! Abort transmission
    - Wireless links: difficult $\rightarrow$ use CSMA/CA instead
  - CSMA/CD reduces the amount of time wasted in collisions
    - Transmission aborted on collision detection

- Ethernet CSMA/CD Algorithm
  - NIC receives packet from network layer, creates frame
  - NIC senses channel:
    - If idle: start frame transmission
    - If busy: wait until channel idle, then transmit
  - If NIC transmits entire frame without collision, NIC is done with frame!
  - If NIC detects another transmission while transmitting, abort and send jam signal
  - After aborting, NIC enters binary exponential backoff:
    - After n-th collision, NIC chooses K at random from $\{0, 1, 2, \ldots, 2^n - 1\}$
    - NIC waits $K \cdot 512$ bit duration times, returns to step 2
    - More collisions: longer backoff interval

- CSMA/CD Efficiency
  - t_{prop} is the maximum propagation delay between two nodes in broadcast link
  - t_{trans} is the time to transmit maximum-size frame

$$eff = \frac{1}{1 + 5t_{prop}/t_{trans}}$$

  - Efficiency goes to 1 when either propagation goes to zero or transmission goes to infinity
  - Better performance than ALOHA: and simple and cheap