Data-link Layer II
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Link Layer

5.1 Introduction and services
5.2 Error detection and correction
5.3 Multiple access protocols
5.4 Link-Layer Addressing
5.5 Ethernet
5.6 Hubs and switches
Network Addresses Revisited

• Transport-layer address:
  - 16-bit port number
  - Find correct application within a host

• Network-layer address:
  - 32-bit (IPv4) or 128-bit (IPv6)
  - Find correct subnet & host on the Internet

• MAC (or LAN, or physical, or Ethernet) address:
  - 48 bit number burned in the adapter ROM
  - Find correct interface within a subnet
LAN Addresses

Each adapter in a LAN must have a unique LAN address.

Broadcast address = FF-FF-FF-FF-FF-FF-FF

- 1A-2F-BB-76-09-AD
- 71-65-F7-2B-08-53
- 58-23-D7-FA-20-B0
- 0C-C4-11-6F-E3-98

= adapter
LAN Addresses

- MAC address allocation administered by IEEE
  - $660 for 36-bit prefix, $1595 for 28-bit; $2655 for 24-bit
- Manufacturer buys portion of MAC address space (to assure uniqueness)
- Analogy:
  - MAC address: like Social Security Number
  - IP address: like postal address
- Flat MAC addresses achieve portability
  - Can move NIC from one LAN to another
- Hierarchical IP addresses NOT portable
  - IP depends on subnet to which node is attached

Question: how to determine MAC address of a host knowing its IP address?

- Each IP node (host, router) on LAN has an ARP table
  - Contains IP/MAC address mappings for known LAN nodes
    < IP address; MAC address; TTL>

- TTL (Time To Live): time after which address mapping will be forgotten (typically 20 min)
ARP Protocol: Same LAN/Subnet

• X wants to send datagram to Y, but doesn’t know Y’s MAC address yet
  – X broadcasts ARP query packet, containing Y’s IP address
  – All machines on LAN process ARP query
• Y receives ARP packet, replies to X with its MAC address
  – Frame sent to X’s MAC address (unicast)

• X caches (saves) IP-to-MAC address pair in its ARP table until this information becomes outdated
  – Soft state: information times out (goes away) unless refreshed

• ARP is “plug-and-play”
  – Nodes create their ARP tables without intervention from net administrator
Routing to Another LAN

- Walkthrough: send datagram from X to Y via R
  - Suppose 1) X knows Y’s IP address; and 2) X knows its default router R (111.111.111.110)
### ARP Example

C:\>arp -a

<table>
<thead>
<tr>
<th>Internet Address</th>
<th>Physical Address</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>128.194.135.65</td>
<td>00-0c-f1-ad-9b-d9</td>
<td>dynamic</td>
</tr>
<tr>
<td>128.194.135.72</td>
<td>00-0c-f1-ad-9b-d9</td>
<td>dynamic</td>
</tr>
<tr>
<td>128.194.135.73</td>
<td>00-e0-18-91-68-9c</td>
<td>dynamic</td>
</tr>
<tr>
<td>128.194.135.74</td>
<td>00-08-74-ce-97-60</td>
<td>dynamic</td>
</tr>
<tr>
<td>128.194.135.76</td>
<td>00-04-23-ab-be-50</td>
<td>dynamic</td>
</tr>
<tr>
<td>128.194.135.81</td>
<td>00-04-23-ab-bc-7a</td>
<td>dynamic</td>
</tr>
<tr>
<td>128.194.135.92</td>
<td>00-0c-f1-ad-9b-d9</td>
<td>dynamic</td>
</tr>
</tbody>
</table>

- Why do 3 hosts in bold have the same MAC?
- Which hosts have NICs from the same manufacturer?
**DHCP**

- DHCP (Dynamic Host Configuration Protocol, 1993)
  - Assigns IP address, netmask, DNS server, default router, and other parameters to end-hosts
- DHCP runs over UDP (ports 67-68), using MAC-layer broadcasts to find available servers
  - Discovery ➔ Offer ➔ Request ➔ Lease (4 packets exchanged)
  - Client may receive multiple offers, must choose one
  - Leased IPs carry some TTL (expiration time)
  - Routers and switches may implement DHCP
- Routers may be configured to forward broadcast DHCP packets between subnets
  - One DHCP server may cover multiple LANs
DHCP Example

C:\> ipconfig /all
Ethernet adapter Wireless Network Connection 6:
Connection-specific DNS Suffix . : tamu.edu

Wireless Adapter #4
- Physical Address . . . . . . . . . : 00-11-95-6A-96-8A
- Dhcp Enabled. . . . . . . . . . . : Yes
- Autoconfiguration Enabled . . . . : Yes
- IP Address. . . . . . . . . . . . : 10.32.39.138
- Subnet Mask . . . . . . . . . . . : 255.255.254.0
- Default Gateway . . . . . . . . . : 10.32.38.1
- DHCP Server . . . . . . . . . . . : 10.32.38.1
- DNS Servers . . . . . . . . . . . : 128.194.254.3
  128.194.254.2
  128.194.254.1

- Lease Obtained. . . . . . . . . . : Tuesday, November 21, 2023 3:22:13 PM
- Lease Expires . . . . . . . . . . . : Tuesday, November 21, 2023 4:22:13 PM
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Ethernet

• Dominant wired LAN technology
  - Inspired by ALOHAnet, based on Robert Metcalfe’s PhD thesis in 1973
  - Xerox patented in 1976, first standardized in 1980
  - In the early 1980s, competed with Token Ring (IBM) and Token Bus (GM), eventually overpowering both

• Ethernet data rates
  - Experimental: 2.94 Mbps (1973)
  - 10Base5 thick coax [IEEE 802.3]: 10 Mbps (1983)
  - Fast Ethernet [IEEE 802.3u]: 100 Mbps (1995)
  - Gigabit Ethernet (GE) [IEEE 802.3ab]: 1 Gbps (1999)
  - 10 GE [802.3ae]: 10 Gbps (2003 fiber, 2006 twisted pair)
  - 40/100 GE [IEEE 802.3ba]: 2010-2015
Ethernet Frame Structure

• Sending adapter encapsulates IP datagram (or other network-layer protocol packet) in Ethernet frame

<table>
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<tr>
<th>preamble</th>
<th>dest MAC</th>
<th>src MAC</th>
<th>type</th>
<th>data</th>
<th>CRC</th>
<th>gap</th>
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• 8-byte preamble (physical layer):
  - 7 bytes 10101010 followed by one byte 10101011, synchronizes receiver-sender clock rates

• 6-byte MAC addresses:
  - If adapter receives frame with a matching or broadcast address, it passes data to the network layer
  - Otherwise, adapter discards frame
## Ethernet Frame Structure

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- **2-byte protocol type:**
  - Indicates the higher-layer protocol
  - Examples are IPv4 (0x800), IPv6 (0x86DD), ARP (0x806), Wake-On-LAN (0x842), AppleTalk, Novell IPX, MPLS

- **32-bit CRC checksum:**
  - Checked at receiver, if error is detected, frame is dropped

- **Minimum payload 46 bytes, inter-frame gap 12 bytes**
  - Frames shorter than minimum are interpreted as collisions
  - Resulting smallest frame time is $8+14+46+4+12 = 84$ bytes
  - 1 Gbps max rate is $1.488\text{M pps}$ (packets per second)
**Ethernet CSMA/CD**

- No slots
- Adapter doesn’t transmit if it senses that some other adapter is transmitting, that is, *carrier sense* (CS)
- Transmitting adapter aborts when it senses that another adapter is transmitting, that is, *collision detection* (CD)
- Before attempting a retransmission, adapter waits a random time, that is, *random access*
- **Connectionless:** no handshaking between sending and receiving adapter
- **Unreliable:** receiving adapter doesn’t send ACKs or NAKs to sending adapter
**Ethernet’s CSMA/CD**

- **Bit time** = $1 / \text{speed}$
  - 100 nanosec for 10 Mbps Ethernet
  - 1 nanosec for GE
  - 100 picosec for 10 GE

**Exponential Backoff:**
- **Goal:** adapt retransmission attempts to estimated load
  - Heavy load: random wait should be longer
- After $m$-th collision in a row
  - Choose integer $D \in [0, 2^m-1]$; then wait $512 \cdot D$ bit times before retx
- **Example:**
  - After second collision: choose $D$ from $\{0, 1, 2, 3\}$
  - After ten collisions, choose $D$ from $\{0, 1, 2, 3, 4, \ldots, 1023\}$

TCP’s exponential timer backoff during congestion is similar
Ethernet Efficiency

- \( d \) = max propagation delay between any two nodes in LAN
- \( T \) = time to transmit frame

\[
\text{efficiency} = \frac{1}{1 + 5\frac{d}{T}}
\]

- Efficiency goes to 1 as \( d \) goes to 0 (less collision probability)
- It also goes to 1 as \( T \) goes to infinity (less frequent switching between hosts)
- 1GE with 10m link and 1500 byte MTU: 98.6% utilization
  - Much better than slotted ALOHA (where efficiency is 37%), but still decentralized, simple, and cheap
Ethernet Technology

- Notation: [speed]Base[medium]
- Examples
  - 10base5 (thick coax 500m), 10base2 (thin coax 200m), 10baseT (twisted-pair/copper CAT3 with 8 wires and RJ45 connectors 100m), 1000BaseSX (short-range fiber 550m), 1000BaseLX (long-range fiber 5km)
- Now: 10GBaseT over CAT6 (55m), CAT6a (100m)
- Coax networks were daisy-chained, while copper and fiber run the star topology
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**Hubs**

- Hubs were physical-layer repeaters:
  - Bits coming from one link went out all other links
- No frame buffering
  - No CSMA/CD at hub: host adapters must detect collisions
- Backbone hubs interconnected other hubs
  - Easier to diagnose faults than daisy chains
  - But collision domain still encompassed all of the hosts
- Additional limitations
  - No management functionality
  - All ports had to be same speed
Switches

- Switches replaced hubs in the 1990s
- Link layer devices
  - Store and forward Ethernet frames
  - Examine frame header and **selectively** forward frames based on MAC dest address
  - When frame is to be forwarded on segment, use CSMA/CD to access segment
- Transparent
  - Hosts are unaware of presence of switches
- Plug-and-play, self-learning
  - Switches can function without manual configuration
• How to determine onto which LAN segment to forward frame?
  – Looks like a routing problem…
• Most LAN networks are trees and flooding is permitted, which makes the problem much simpler!
Self Learning

• A switch has a switch table
• Entry in switch table:
  - (MAC Address, Interface, TTL)
  - Stale entries in table dropped (TTL can be 60 min)
• Switch *learns* which hosts can be reached through which interfaces
  - When frame received, switch “learns” location of sender: incoming LAN segment
  - Records sender/location pair in switch table
Filtering/Forwarding

When switch receives a frame:

index switch table using destination MAC address

if entry found for destination then {
    if dest on segment from which frame arrived then drop the frame
    else forward the frame on interface indicated
} else flood

Forward on all but the interface on which the frame arrived
Switch Example

Suppose C sends a frame to D

- Switch receives frame from C
  - Notes in its table that C is on interface 1
  - Because D is not in table, switch forwards frame into interfaces 2 and 3

- Frame received by D
Switch Example

Suppose D replies back with frame to C

- Switch receives frame from D
  - Notes in the table that D is on interface 2
  - Because C is in table, switch forwards only to interface 1
- Frame received by C
Switches: Dedicated Access

- **Dedicated**: hosts have direct connection to switch
  - No collisions; full duplex
- **Switching**: A-to-D and B-to-E simultaneous, no collisions
- **Buffering**: A-to-D and C-to-D simultaneous, no collisions
- **Combinations of shared/dedicated and diverse (10/100/1000 Mbps) interfaces are possible**
**Switches vs. Routers**

- Both store-and-forward devices
  - Routers: network-layer devices
  - Switches: link-layer devices

- Modern switches can perform some IP functionality
  - This violates the end-to-end principle, but makes network administration easier