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
- LAN (wired or wireless)
  - 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
- 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• X caches (saves) IP-to-MAC address pair in its ARP table until this information becomes outdated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 has a default router R
### ARP Example

```
C:\>arp -a
Interface: 128.194.135.66

<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
Description . . . . . . . . . . . . : DWL-G650M Super G MIMO
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, 2006 3:22:13 PM
Lease Expires . . . . . . . . : Tuesday, November 21, 2006 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
**Ethernet Frame Structure**

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

<table>
<thead>
<tr>
<th>preamble</th>
<th>dest MAC</th>
<th>src MAC</th>
<th>type</th>
<th>data</th>
<th>CRC</th>
<th>gap</th>
</tr>
</thead>
</table>

- **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

- 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 1.488M 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 / 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, ..., 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
  - Increased max distance between nodes
  - But individual collision domains became one large collision domain
- Additional limitations
  - No management functionality
  - All ports had to be same speed
- Similar to daisy-chaining, but with all connections in one place
Switches

- **Link layer device**
  - Stores and forwards Ethernet frames
  - Examines frame header and *selectively* forwards frame based on MAC dest address
  - When frame is to be forwarded on segment, uses CSMA/CD to access segment

- **Transparent**
  - Hosts are unaware of presence of switches

- **Plug-and-play, self-learning**
  - Switches do not need to be configured
Forwarding

• 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