Chapter 5: The Data Link Layer

Our goals:
- understand principles behind data link layer services:
  - error detection, correction
  - sharing a broadcast channel: multiple access
  - link layer addressing
  - reliable data transfer, flow control: done!
- instantiation and implementation of various link layer technologies

Overview:
- link layer services
- error detection, correction
- multiple access protocols and LANs
- link layer addressing, ARP
- specific link layer technologies:
  - Ethernet
  - hubs, bridges, switches
  - ATM

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Chapter 5 outline

- 5.1 Introduction and services
- 5.2 Error detection and correction
- 5.3 Multiple access protocols
- 5.4 LAN addresses and ARP
- 5.5 Ethernet
- 5.6 Hubs, bridges, and switches
- 5.7 PPP
- 5.8 Link Virtualization: ATM and MPLS
Link Layer: setting the context
Link Layer: setting the context

- two physically connected devices:
  - host-router, router-router, host-host
- unit of data: frame
Link Layer: setting the context

Some terminology:
- hosts and routers are nodes (bridges and switches too)
- communication channels that connect adjacent nodes along communication path are links
  - wired links
  - wireless links
  - LANs
- 2-PDU is a frame, encapsulates datagram

**data-link layer** has responsibility of transferring datagram from one node to adjacent node over a link
Link layer: context

- Datagram transferred by different link protocols over different links:
  - e.g., Ethernet on first link, frame relay on intermediate links, 802.11 on last link
- Each link protocol provides different services
  - e.g., may or may not provide rdt over link

transportation analogy
- trip from Princeton to Lausanne
  - limo: Princeton to JFK
  - plane: JFK to Geneva
  - train: Geneva to Lausanne
- tourist = datagram
- transport segment = communication link
- transportation mode = link layer protocol
- travel agent = routing algorithm
Link Layer Services

- Framing, link access:
  - encapsulate datagram into frame, adding header, trailer
  - channel access if shared medium
  - 'physical addresses' used in frame headers to identify source, dest
    - different from IP address!

- Reliable delivery between adjacent nodes
  - we learned how to do this already (chapter 3)!
  - seldom used on low bit error link (fiber, some twisted pair)
  - wireless links: high error rates
    - Q: why both link-level and end-end reliability?
Link Layer Services (more)

- **Flow Control:**
  - pacing between adjacent sending and receiving nodes

- **Error Detection:**
  - errors caused by signal attenuation, noise.
  - receiver detects presence of errors:
    - signals sender for retransmission or drops frame

- **Error Correction:**
  - receiver identifies *and corrects* bit error(s) without resorting to retransmission

- **Half-duplex and full-duplex**
  - with half duplex, nodes at both ends of link can transmit, but not at same time
Adaptors Communicating

- link layer implemented in "adaptor" (aka NIC)
  - Ethernet card, PCMCIA card, 802.11 card
  - typically includes: RAM, DSP chips, host bus interface, and link interface

- sending side:
  - encapsulates datagram in a frame
  - adds error checking bits, rdt, flow control, etc.

- receiving side
  - looks for errors, rdt, flow control, etc
  - extracts datagram, passes to rcving node

- adapter is semi-autonomous

- link & physical layers
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Error Detection

EDC = Error Detection and Correction bits (redundancy)
D  = Data protected by error checking, may include header fields

• Error detection not 100% reliable!
  • protocol may miss some errors, but rarely
  • larger EDC field yields better detection and correction
Parity Checking

Single Bit Parity:
Detect single bit errors

Two Dimensional Bit Parity:
Detect and correct single bit errors

<table>
<thead>
<tr>
<th>d data bits</th>
<th>Parity bit</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 1 1 1 0 0 0 1 1 0 1 0 1 0 1 1</td>
<td>1</td>
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</tbody>
</table>

\[
\begin{array}{cccccccc}
\text{d}_{1,1} & \ldots & \text{d}_{1,j} \\
\text{d}_{2,1} & \ldots & \text{d}_{2,j} \\
\ldots & \ldots & \ldots & \ldots \\
\text{d}_{i,1} & \ldots & \text{d}_{i,j} \\
\text{d}_{i+1,1} & \ldots & \text{d}_{i+1,j} \\
\end{array}
\]

\[
\begin{array}{cccccccc}
\text{row parity} & \Rightarrow & \text{column parity} \\
\text{d}_{1, j+1} & \text{d}_{2, j+1} & \ldots & \text{d}_{i, j+1} & \text{d}_{i+1, j+1} \\
\end{array}
\]

101011 101011
111100 111100
011101 011101
001010 001010

no errors

Correctable single bit error

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Internet checksum

**Goal:** detect “errors” (e.g., flipped bits) in transmitted segment (note: used at transport layer only)

**Sender:**
- treat segment contents as sequence of 16-bit integers
- checksum: addition (1's complement sum) of segment contents
- sender puts checksum value into UDP checksum field

**Receiver:**
- compute checksum of received segment
- check if computed checksum equals checksum field value:
  - NO - error detected
  - YES - no error detected. But maybe errors nonetheless?
Checksumming: Cyclic Redundancy Check

- view data bits, $D$, as coefficients of polynomial
- choose $r+1$ bit pattern (generator), $G$
- goal: choose $r$ CRC bits, $R$, such that
  - $<D,R>$ exactly divisible \((\text{polynomial division})\) by $G$ (modulo 2)
  - receiver knows $G$, divides $<D,R>$ by $G$. If non-zero remainder: error detected!
  - can detect all burst errors less than $r+1$ bits
- widely used in practice (ATM, HDCL)

\[
\begin{array}{c}
\text{d bits} \quad \text{r bits} \\
\hline
D: \text{data bits to be sent} \quad R: \text{CRC bits}
\end{array}
\]

\[D \times 2^r \text{ XOR } R\]

\text{bit pattern}
- Bits in word are coefficients of polynomial
  \[ D = 101110 \text{ then } D(x) = x^5 + x^3 + x^2 + x \]

- Arithmetic on coefficients is mod 2
  \[ (x+1)^2 = x^2 + 1 \]
  In particular \[ P(x) + P(x) = 0 \]

- \( R(x) \) is the remainder of \( P(x) \) divided by \( G(x) \) if
  \[ P(x) = A(x) \cdot G(x) + R(x) \text{ where } \deg(R) < \deg(G) \]

- \( G(x) \) divides \( P(x) + R(x) \) since
  \[ P(x) + R(x) = A(x) \cdot G(x) + R(x) + R(x) = A(x) \cdot G(x) \]

- \( 2^r \cdot D \) corresponds to \( x^r \cdot D(x) \)

- Given \( D \) and \( G \),
  - CRC finds \( R(x) \), remainder when \( x^r \cdot D(x) \) is divided by \( G(x) \).
  - \( R \) is word corresponding to \( R(x) \).
  - CRC is \( D \cdot 2^r \) XOR \( R \)
**Example (r=3)**

\[
\begin{align*}
D &= 101110 & D(x) &= x^5 + x^3 + x^2 + x \\
G &= 1001 & G(x) &= x^3 + 1 \\
2^rD &= 101110000 & x^3 \cdot D(x) &= x^8 + x^6 + x^5 + x^4 \\
\end{align*}
\]

\[
x^3 \cdot D(x) = G(x) \cdot (x^5 + x^3 + x + 1) + (x+1)
\]

So \( R(x) = x+1 \) and \( R = 011 \)

**CRC will transmit**

\[
D \cdot 2^r \ XOR \ R = 101110011
\]
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Media Access Control (MAC) Protocols

Two types of “links“:

- **point-to-point**
  - PPP for dial-up access
  - point-to-point link between Ethernet switch and host

- **broadcast** (shared wire or medium)
  - traditional Ethernet
  - upstream HFC
  - 802.11 wireless LAN
**Media Access Control (MAC) protocols**

- single shared communication channel
- two or more simultaneous transmissions by nodes: interference
  - only one node can send **successfully** at a time
- **multiple access protocol:**
  - distributed algorithm that determines how stations share channel, i.e., determine when station can transmit
  - communication about channel sharing must use channel itself!
  - what to look for in multiple access protocols:
    - synchronous or asynchronous
    - information needed about other stations
    - robustness (e.g., to channel errors)
    - performance
Ideal Multiple Access Protocol

Broadcast channel of rate $R$ bps
1. When one node wants to transmit, it can send at rate $R$.
2. When $M$ nodes want to transmit, each can send at average rate $R/M$
3. Fully decentralized:
   - no special node to coordinate transmissions
   - no synchronization of clocks, slots
4. Simple
MAC Protocols: a taxonomy

Three broad classes:

- **Channel Partitioning**  
  - TDMA, FDMA, CDMA (in wireless)
  - divide channel into smaller “pieces” (time slots, frequency)
  - allocate piece to node for exclusive use

- **Random Access**  
  - ALOHA, CSMA, CSMA/CD, CSMA/CA
  - allow collisions
  - “recover” from collisions

- **“Taking turns”**  
  - Polling, Token passing
  - tightly coordinate shared access to avoid collisions

**Goal:** efficient, fair, simple, decentralized
Channel Partitioning MAC protocols: TDMA

**TDMA**: time division multiple access

- access to channel in "rounds"
- each station gets fixed length slot (length = pkt trans time) in each round
- unused slots go idle
- example: 6-station LAN, 1,3,4 have pkt, slots 2,5,6 idle
Channel Partitioning MAC protocols: FDMA

FDMA: frequency division multiple access

- channel spectrum divided into frequency bands
- each station assigned fixed frequency band
- unused transmission time in frequency bands go idle
- example: 6-station LAN, 1,3,4 have pkt, frequency bands 2,5,6 idle
Random Access Protocols

- When node has packet to send
  - transmit at full channel data rate $R$.
  - no *a priori* coordination among nodes
- two or more transmitting nodes $\rightarrow$ “collision”,
- random access MAC protocol specifies:
  - how to detect collisions
  - how to recover from collisions (e.g., via delayed retransmissions)
- Examples of random access MAC protocols:
  - slotted ALOHA
  - ALOHA
  - CSMA, CSMA/CD, CSMA/CA
Slotted Aloha

- Time is divided into equal size slots (= pkt trans. time)
- Node with new arriving pkt: transmit at beginning of next slot
- If collision: retransmit pkt in future slots with probability $p$, until successful.

Success (S), Collision (C), Empty (E) slots
**Slotted ALOHA**

**Assumptions**
- all frames same size
- time is divided into equal size slots, time to transmit 1 frame
- nodes start to transmit frames only at beginning of slots
- nodes are synchronized
- if 2 or more nodes transmit in slot, all nodes detect collision

**Operation**
- when node obtains fresh frame, it transmits in next slot
- no collision, node can send new frame in next slot
- if collision, node retransmits frame in each subsequent slot with prob. p until success
**Slotted ALOHA**

### Pros
- Single active node can continuously transmit at full rate of channel
- Highly decentralized: only slots in nodes need to be in sync
- Simple

### Cons
- Collisions, wasting slots
- Idle slots
- Nodes may be able to detect collision in less than time to transmit packet

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Slotted Aloha efficiency

**Efficiency** is the long-run fraction of successful slots when there's many nodes, each with many frames to send.

- Suppose N nodes with many frames to send, each transmits in slot with probability \( p \)
- prob that 1st node has success in a slot = \( p(1-p)^{N-1} \)
- prob that any node has a success = \( Np(1-p)^{N-1} \)

- For max efficiency with N nodes, 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 \( 1/e = 0.37 \)

*At best:* channel used for useful transmissions 37% of time!
Pure (unslotted) ALOHA

- unslotted Aloha: simpler, no synchronization
- when frame first arrives
  - transmit immediately
- collision probability increases:
  - frame sent at $t_0$ collides with other frames sent in $[t_0-1, t_0+1]$
Pure Aloha efficiency

\[ P(\text{success by given node}) = P(\text{node transmits}) \cdot \]
\[ P(\text{no other node transmits in } [t_{0-1}, t_0]) \cdot \]
\[ P(\text{no other node transmits in } [t_0, t_0+1]) \]
\[ = p \cdot (1-p)^{N-1} \cdot (1-p)^{N-1} \]
\[ = p \cdot (1-p)^{2(N-1)} \]

... choosing optimum \( p \) and then letting \( n \to \infty \) ...

Even worse! \[ = \frac{1}{2e} = .18 \]
CSMA: (Carrier Sense Multiple Access)

- **CSMA**: Listen before transmitting
  - This is *Carrier Sensing*
  - If someone else is already transmitting then back off (wait) until channel is free
    
    Wait how long?

- If collision is detected during transmission then must retransmit the frame.
  
  When is it retransmitted?
CSMA: (Carrier Sense Multiple Access)

- **1-Persistent CSMA**
  - If channel sensed idle: transmit entire pkt
  - If channel sensed busy, wait until channel becomes idle and then transmit right away.
  - If collision occurs wait *random* time and then restart process

- **Non-persistent CSMA**: (for nonslotted channels)
  - If channel sensed idle: transmit entire pkt
  - If channel sensed busy, wait *random* time before trying again.
  - If collision occurs wait *random* time and then restart process

- **P-Persistent CSMA**: (for slotted channels)
  - If channel sensed idle then, with probability $p$, transmit in current slot. With probability $q=1-p$, wait until next slot and try again (with probability $p$)
  - If channel sensed busy wait until next slot and try again
  - If collision occurs, wait *random* time and then restart process
**CSMA collisions**

**collisions can occur:**
propagation delay means two nodes may not hear each other’s transmission

**collision:**
entire packet transmission time wasted

**note:**
role of distance and propagation delay in determining collision prob.
CSMA/CD (Collision Detection)

**CSMA/CD:** carrier sensing, deferral as in CSMA

- collisions *detected* within short time
- colliding transmissions aborted, reducing channel wastage

- collision detection:
  - easy in wired LANs: measure signal strengths, compare transmitted, received signals
  - difficult in wireless LANs: receiver shut off while transmitting

- human analogy: the polite conversationalist
CSMA/CD collision detection

Collision detect/abort time

$A, B, C, D$

$t_0, t_1$
“Taking Turns” MAC protocols

Channel partitioning MAC protocols:
- Share channel efficiently and fairly at high load.
- Inefficient at low load: delay in channel access, 1/N bandwidth allocated even if only 1 active node!

Random access MAC protocols:
- Efficient at low load: single node can fully utilize channel.
- High load: collision overhead.

“Taking turns” protocols:
- Look for best of both worlds!
"Taking Turns" MAC protocols

Polling:
- master node "invites" slave nodes to transmit in turn
- concerns:
  - polling overhead
  - latency
  - single point of failure (master)

Token passing:
- control token passed from one node to next sequentially.
- token message
- concerns:
  - token overhead
  - latency
  - single point of failure (token)
Summary of MAC protocols

- What do you do with a shared media?
  - Channel Partitioning, by time, frequency or code
    - Time Division, Code Division, Frequency Division
  - Random partitioning (dynamic),
    - ALOHA, S-ALOHA, CSMA, CSMA/CD
    - carrier sensing: easy in some technologies (wire), hard in others (wireless)
    - CSMA/CD used in Ethernet
  - Taking Turns
    - polling from a central site, token passing
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LAN technologies

Data link layer so far:
- services, error detection/correction, multiple access

Next: LAN technologies
- addressing
- Ethernet
- hubs, bridges, switches
- 802.11
- PPP
- ATM
LAN Addresses and ARP

32-bit IP address:
- network-layer address
- used to get datagram to destination IP network (recall IP network definition)

LAN (or MAC or physical or Ethernet) address:
- used to get datagram from one interface to another physically-connected interface (same network)
- 48 bit MAC address (for most LANs) burned in the adapter ROM
LAN Addresses and ARP

Each adapter on LAN has unique LAN address

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

5C-66-AB-90-75-B1

1A-23-F9-CD-06-9B

88-B2-2F-54-1A-0F

49-BD-D2-C7-56-2A

node

node

node

node

= adapter

LAN
LAN Address (more)

- **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
- **MAC flat address** $\Rightarrow$ portability
  - can move LAN card from one LAN to another
- **IP hierarchical address** NOT portable
  - depends on IP network to which node is attached
Recall earlier routing discussion

Starting at A, given IP datagram addressed to B:

- look up net. address of B, find B on same net. as A
- link layer send datagram to B inside link-layer frame

```
frame source, dest address
B's MAC addr  A's MAC addr

datagram source, dest address
A's IP addr  B's IP addr  IP payload
```

```
dataframe
```

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Question: how to determine MAC address of B knowing B’s IP address?

- Each IP node (Host, Router) on LAN has ARP table
- ARP Table: IP/MAC address mappings for some LAN nodes < IP address; MAC address; TTL>
  - TTL (Time To Live): time after which address mapping will be forgotten (typically 20 min)
**ARP protocol**

- A wants to send datagram to B, and A knows B’s IP address.
- Suppose B’s MAC address is not in A’s ARP table.
- A **broadcasts** ARP query packet, containing B’s IP address
  - Dest MAC address = FF-FF-FF-FF-FF-FF
  - all machines on LAN receive ARP query
- B receives ARP packet, replies to A with its (B’s) MAC address
  - frame sent to A’s MAC address (unicast)

- A caches (saves) IP-to-MAC address pair in its ARP table until information becomes old (times out)
  - **soft state**: information that 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 A to B via R
assume  A knows B IP address

- Two ARP tables in router R, one for each IP network (LAN)
- A creates datagram with source A, destination B
- A uses ARP to get R's MAC address for 111.111.111.110
- A creates link-layer frame with R's MAC address as dest, frame contains A-to-B IP datagram
- A's data link layer sends frame
- R's data link layer receives frame
- R removes IP datagram from Ethernet frame, sees it's destined to B
- R uses ARP to get B's physical layer address
- R creates frame containing A-to-B IP datagram sends to B
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Ethernet

“dominant” LAN technology:

- cheap $20 for 100Mbs!
- first widely used LAN technology
- Simpler, cheaper than token LANs and ATM
- Kept up with speed race: 10, 100, 1000 Mbps

Metcalfe’s Ethernet sketch
Star topology

- Bus topology popular through mid 90s
- Now star topology prevails
- Connection choices: hub or switch (more later)
Ethernet Frame Structure

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

- **Preamble:**
  - 7 bytes with pattern 10101010 followed by one byte with pattern 10101011
  - used to synchronize receiver, sender clock rates
Ethernet Frame Structure (more)

- **Addresses**: 6 bytes
  - if adapter receives frame with matching destination address, or with broadcast address (e.g., ARP packet), it passes data in frame to net-layer protocol
  - otherwise, adapter discards frame

- **Type**: indicates the higher layer protocol, mostly IP but others may be supported such as Novell IPX and AppleTalk

- **CRC**: checked at receiver, if error is detected, the frame is simply dropped
Unreliable, connectionless service

- **Connectionless:** No handshaking between sending and receiving adapter.
- **Unreliable:** receiving adapter doesn’t send acks or nacks to sending adapter
  - stream of datagrams passed to network layer can have gaps
  - gaps will be filled if app is using TCP
  - otherwise, app will see the gaps
Ethernet uses CSMA/CD

- No slots
- Adapter doesn’t transmit if it senses that some other adapter is transmitting, that is, carrier sense
- Transmitting adapter aborts when it senses that another adapter is transmitting, that is, collision detection
- Before attempting a retransmission, adapter waits a random time, that is, random access
  random time depends upon # collisions so far
Ethernet CSMA/CD algorithm

1. Adaptor gets datagram from link and creates frame

2. If adapter senses channel idle, it starts to transmit frame. If it senses channel busy, waits until channel idle and then transmits

3. If adapter transmits entire frame without detecting another transmission, the adapter is done with frame!

4. If adapter detects another transmission while transmitting, aborts and sends jam signal

5. After aborting, adapter enters exponential backoff: after the mth collision, adapter chooses a K at random from \(\{0,1,2,...,2^m-1\}\). Adapter waits \(K \times 512\) bit times and returns to Step 2
Ethernet: slotless, uses CSMA/CD

create frame from datagram
A: sense channel; if idle
    then {
        transmit frame and monitor the channel;
        If detect another transmission
            then {
                abort and send jam signal;
                update # collisions;
                delay as required by exponential backoff algorithm;
                goto A
            }
        else {done with the frame; set collisions to zero}
    }
else {wait until ongoing transmission is over and goto A}
Ethernet’s CSMA/CD (more)

See Applet

Jam Signal: make sure all other transmitters are aware of collision; 48 bits;

Exponential Backoff:

- **Goal**: adapt retransmission attempts to estimated current load
  - heavy load: random wait will be longer

- first collision: choose K from \{0,1\}; delay is K \times 512 bit transmission times
  (btt = .1 microsec for 10Mbps Ethernet; for K=1023, wait time is about 50msec)

- after second collision: choose K from \{0,1,2,3\}...

- after ten or more collisions, choose K from \{0,1,2,3,4,...,1023\}
CSMA/CD efficiency

- $T_{\text{prop}} = \text{max prop between 2 nodes in LAN}$
- $t_{\text{trans}} = \text{time to transmit max-size frame}$

\[
\text{efficiency} = \frac{1}{1 + \frac{5T_{\text{prop}}}{t_{\text{trans}}}}
\]

- Efficiency goes to 1 as $T_{\text{prop}}$ goes to 0
- Goes to 1 as $t_{\text{trans}}$ goes to infinity
- Much better than ALOHA, but still decentralized, simple, and cheap
Ethernet Technologies: 10Base2

- **10**: 10Mbps; **2**: under 200 meters max cable length
- thin coaxial cable in a bus topology

- repeaters used to connect up to 5 multiple segments
- repeater repeats bits it hears on one interface to its other interfaces: physical layer device only!
- has become a legacy technology
10BaseT and 100BaseT

- 10/100 Mbps rate; latter called “fast ethernet”
- T stands for Twisted Pair
- Nodes connect to a hub: “star topology”; 100 m max distance between nodes and hub
Hubs

Hubs are essentially physical-layer repeaters:

- bits coming from one link go out all other links
- at the same rate
- no frame buffering
- no CSMA/CD at hub: adapters detect collisions
- provides net management functionality
Gbit Ethernet

- use standard Ethernet frame format
- allows for point-to-point links and shared broadcast channels
- in shared mode, CSMA/CD is used; short distances between nodes to be efficient
- uses hubs, called here “Buffered Distributors”
- Full-Duplex at 1 Gbps for point-to-point links
- 10 Gbps now!
Token Passing: IEEE802.5 standard

- 4 Mbps
- max token holding time: 10 ms, limiting frame length

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<tr>
<th>SD</th>
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<th>FC</th>
<th>dest addr</th>
<th>src addr</th>
<th>data</th>
<th>checksum</th>
<th>ED</th>
<th>FS</th>
</tr>
</thead>
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- **SD, ED** mark start, end of packet
- **AC**: access control byte:
  - **token bit**: value 0 means token can be seized, value 1 means data follows FC
  - **priority bits**: priority of packet
  - **reservation bits**: station can write these bits to prevent stations with lower priority packet from seizing token after token becomes free
Token Passing: IEEE802.5 standard

- **FC**: frame control used for monitoring and maintenance
- **source, destination address**: 48 bit physical address, as in Ethernet
- **data**: packet from network layer
- **checksum**: CRC
- **FS**: frame status: set by dest., read by sender
  - set to indicate destination up, frame copied OK from ring
  - DLC-level ACKing
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Interconnecting LANs

Q: Why not just one big LAN?
- Limited amount of supportable traffic: on single LAN, all stations must share bandwidth
- Limited length: 802.3 specifies maximum cable length
- Large “collision domain” (can collide with many stations)
- Limited number of stations: 802.5 have token passing delays at each station
Hubs

- Physical Layer devices: essentially repeaters operating at bit levels: repeat received bits on one interface to all other interfaces
- Hubs can be arranged in a hierarchy (or multi-tier design), with backbone hub at its top
Hubs (more)

- Each connected LAN referred to as LAN segment
- Hubs do not isolate collision domains: node may collide with any node residing at any segment in LAN
- Hub Advantages:
  - simple, inexpensive device
  - Multi-tier provides graceful degradation: portions of the LAN continue to operate if one hub malfunctions
  - extends maximum distance between node pairs (100m per Hub)
Hub limitations

- single collision domain results in no increase in max throughput
  - multi-tier throughput same as single segment throughput
- individual LAN restrictions pose limits on number of nodes in same collision domain and on total allowed geographical coverage
- cannot connect different Ethernet types (e.g., 10BaseT and 100baseT)

- We now move on to switches
Switches (and bridges)

- 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
Switches: traffic isolation

- Switch installation breaks LAN into LAN segments
- switches filter packets:
  - same-LAN-segment frames not usually forwarded onto other LAN segments
  - segments become separate collision domains

![Diagram](attachment:image.png)

- LAN segment → LAN segment
- LAN (IP network)
Switches: Forwarding

How do determine to which LAN segment to forward frame?
• Looks like a routing problem...
Switches: Self learning

- A switch has a switch table
- entry in switch table:
  - (MAC Address, switch Interface, Time Stamp)
  - 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
switches: Filtering/Forwarding

When switch receives a frame:

index switch table using MAC dest 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 frame to D

- Switch receives frame from from C
  - notes in switch 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 switch table that D is on interface 2
  - because C is in table, switch forwards frame only to interface 1

- Frame received by C
Switches: Interconnection without backbone

- Not recommended for two reasons:
  - single point of failure at Computer Science hub
  - all traffic between EE and SE must path over CS segment
Switches: Backbone configuration

Recommended!
Separates world into 3 diff collision domains
Spanning Tree

- For increased reliability, desirable to have redundant, alternative paths from source to dest.
- With multiple paths, cycles result - switches may multiply and forward frame forever.
- Solution: organize switch in a spanning tree by disabling subset of interfaces.
Some switch features

- Isolates collision domains resulting in higher total max throughput
- Limitless number of nodes and geographical coverage
- Can connect different Ethernet types
- Transparent ("plug-and-play"): no configuration necessary
Routers vs. Switches

- both store-and-forward devices
  - routers: network layer devices (examine network layer headers)
  - switches (bridges) are link layer devices
- routers maintain routing tables, implement routing algorithms
- switches maintain switch tables, implement filtering, learning and spanning tree algorithms
Routers vs. Switches

Switches + and -
+ Switch operation is simpler requiring less packet processing
+ Switch tables are self learning
- All traffic confined to spanning tree, even when alternative bandwidth is available
- Switches do not offer protection from broadcast storms
Routers vs. Switches

Routers + and -

+ arbitrary topologies can be supported, cycling is limited by TTL counters (and good routing protocols)
+ provide protection against broadcast storms
- require IP address configuration (not plug and play)
- require higher packet processing

- switches do well in small (few hundred hosts) while routers used in large networks (thousands of hosts)
More on Switches

- Switch with many interfaces
- Hosts have direct connection to switch
- No collisions; full duplex

Switching: A-to-A' and B-to-B' simultaneously, no collisions
Even More on Switches

- **cut-through switching**: frame forwarded from input to output port without awaiting for assembly of entire frame
  - slight reduction in latency
- combinations of shared/dedicated, 10/100/1000 Mbps interfaces
Institutional network

to external network

router

switch

mail server

web server

IP subnet
## Summary comparison

<table>
<thead>
<tr>
<th></th>
<th>hubs</th>
<th>routers</th>
<th>switches</th>
</tr>
</thead>
<tbody>
<tr>
<td>traffic</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>isolation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>plug &amp; play</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>optimal routing</td>
<td>no</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>cut through</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
</tr>
</tbody>
</table>

Comp 361, Spring 2005
Chapter 5 outline

- 5.1 Introduction and services
- 5.2 Error detection and correction
- 5.3 Multiple access protocols
- 5.4 LAN addresses and ARP
- 5.5 Ethernet
- 5.6 Hubs, bridges, and switches
- 5.7 PPP
- 5.8 Link Virtualization: ATM and MPLS
Point to Point Data Link Control

- one sender, one receiver, one link: easier than broadcast link:
  - no Media Access Control
  - no need for explicit MAC addressing
  - e.g., dialup link, ISDN line

- popular point-to-point DLC protocols:
  - PPP (point-to-point protocol)
  - HDLC: High level data link control (Data link used to be considered “high layer” in protocol stack!)
PPP Design Requirements [RFC 1557]

- **packet framing**: encapsulation of network-layer datagram in data link frame
  - carry network layer data of any network layer protocol (not just IP) *at same time*
  - ability to demultiplex upwards
- **bit transparency**: must carry any bit pattern in the data field
- **error detection** (no correction)
- **connection liveness**: detect, signal link failure to network layer
- **network layer address negotiation**: endpoint can learn/configure each other’s network address
PPP non-requirements

- no error correction/recovery
- no flow control
- out of order delivery OK
- no need to support multipoint links (e.g., polling)

Error recovery, flow control, data re-ordering all relegated to higher layers!
PPP Data Frame

- **Flag**: delimiter (framing)
- **Address**: does nothing (only one option)
- **Control**: does nothing; in the future possible multiple control fields
- **Protocol**: upper layer protocol to which frame delivered (e.g., PPP-LCP, IP, IPCP, etc)
**PPP Data Frame**

- **info**: upper layer data being carried
- **check**: cyclic redundancy check for error detection

```
+-------------------+-------------------+-------------------+
| 1                 | 1                 | 1                 |
| 1 or 2            | variable length   | 2 or 4            |
+-------------------+-------------------+-------------------+
| protocol          | info              | check             |
+-------------------+-------------------+-------------------+
| 01111110          | 00000011           | 01111110           |
+-------------------+-------------------+-------------------+
| flag              | control           | flag              |
| address           |                   |                   |
```
Byte Stuffing

- “data transparency” requirement: data field must be allowed to include flag pattern <01111110>
  - **Q:** is received <01111110> data or flag?

- **Sender:** adds (“stuffs”) extra < 01111110> byte after each < 01111110> *data* byte

- **Receiver:**
  - two 01111110 bytes in a row: discard first byte, continue data reception
  - single 01111110: flag byte
Byte Stuffing

flag byte pattern in data to send

flag byte pattern plus stuffed byte in transmitted data
Before exchanging network-layer data, data link peers must

- configure PPP link (max. frame length, authentication)
- learn/configure network layer information
  - for IP: carry IP Control Protocol (IPCP) msgs (protocol field: 8021) to configure/learn IP address
Chapter 5 outline

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- 5.6 Hubs, bridges, and switches
- 5.7 PPP
- 5.8 Link Virtualization: ATM and MPLS
Virtualization of networks

Virtualization of resources: a powerful abstraction in systems engineering:

- computing examples: virtual memory, virtual devices
  - Virtual machines: e.g., java
  - IBM VM os from 1960’s/70’s

- layering of abstractions: don’t sweat the details of the lower layer, only deal with lower layers abstractly
The Internet: virtualizing networks

1974: multiple unconnected nets
- ARPAnet
- data-over-cable networks
- packet satellite network (Aloha)
- packet radio network

... differing in:
- addressing conventions
- packet formats
- error recovery
- routing

"A Protocol for Packet Network Intercommunication",
V. Cerf, R. Kahn, IEEE Transactions on Communications,
The Internet: virtualizing networks

Internetwork layer (IP):
- addressing: internetwork appears as a single, uniform entity, despite underlying local network heterogeneity
- network of networks

Gateway:
- “embed internetwork packets in local packet format or extract them”
- route (at internetwork level) to next gateway
Cerf & Kahn’s Internetwork Architecture

What is virtualized?

- two layers of addressing: internetwork and local network
- new layer (IP) makes everything homogeneous at internetwork layer
- underlying local network technology
  - cable
  - satellite
  - 56K telephone modem
  - today: ATM, MPLS

... “invisible” at internetwork layer. Looks like a link layer technology to IP!
ATM and MPLS

- ATM, MPLS separate networks in their own right
  - different service models, addressing, routing from Internet
- viewed by Internet as logical link connecting IP routers
  - just like dialup link is really part of separate network (telephone network)
- ATM, MPLS: of technical interest in their own right
Asynchronous Transfer Mode: ATM

- 1990's/00 standard for high-speed (155Mbps to 622 Mbps and higher) Broadband Integrated Service Digital Network architecture
- **Goal**: integrated, end-end transport of carry voice, video, data
  - meeting timing/QoS requirements of voice, video (versus Internet best-effort model)
  - “next generation” telephony: technical roots in telephone world
  - packet-switching (fixed length packets, called “cells”) using virtual circuits
ATM architecture

- **adaptation layer**: only at edge of ATM network
  - data segmentation/reassembly
  - roughly analogous to Internet transport layer
- **ATM layer**: “network” layer
  - cell switching, routing
- **physical layer**
ATM: network or link layer?

**Vision:** end-to-end transport: “ATM from desktop to desktop”
- ATM is a network technology

**Reality:** used to connect IP backbone routers
- “IP over ATM”
- ATM as switched link layer, connecting IP routers
ATM Adaptation Layer (AAL)

- ATM Adaptation Layer (AAL): "adapts" upper layers (IP or native ATM applications) to ATM layer below
- AAL present only in end systems, not in switches
- AAL layer segment (header/trailer fields, data) fragmented across multiple ATM cells
  - analogy: TCP segment in many IP packets
ATM Adaptation Layer (AAL) [more]

Different versions of AAL layers, depending on ATM service class:

- **AAL1**: for CBR (Constant Bit Rate) services, e.g. circuit emulation
- **AAL2**: for VBR (Variable Bit Rate) services, e.g., MPEG video
- **AAL5**: for data (e.g., IP datagrams)
AAL5 - Simple And Efficient AL (SEAL)

- **AAL5**: low overhead AAL used to carry IP datagrams
  - 4 byte cyclic redundancy check
  - PAD ensures payload multiple of 48 bytes
  - large AAL5 data unit to be fragmented into 48-byte ATM cells

<table>
<thead>
<tr>
<th>CPCS-PDU payload</th>
<th>PAD</th>
<th>Length</th>
<th>CRC</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-65535</td>
<td>0-47</td>
<td>2</td>
<td>4</td>
</tr>
</tbody>
</table>
**ATM Layer**

**Service:** transport cells across ATM network
- analogous to IP network layer
- very different services than IP network layer

<table>
<thead>
<tr>
<th>Network Architecture</th>
<th>Service Model</th>
<th>Guarantees?</th>
<th>Congestion feedback</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Bandwidth</td>
<td>Loss</td>
</tr>
<tr>
<td>Internet</td>
<td>best effort</td>
<td>none</td>
<td>no</td>
</tr>
<tr>
<td>ATM</td>
<td>CBR</td>
<td>constant rate</td>
<td>yes</td>
</tr>
<tr>
<td>ATM</td>
<td>VBR</td>
<td>guaranteed rate</td>
<td>yes</td>
</tr>
<tr>
<td>ATM</td>
<td>ABR</td>
<td>guaranteed minimum</td>
<td>no</td>
</tr>
<tr>
<td>ATM</td>
<td>UBR</td>
<td>none</td>
<td>no</td>
</tr>
</tbody>
</table>
ATM Layer: Virtual Circuits

- **VC transport**: cells carried on VC from source to dest
  - call setup, teardown for each call *before* data can flow
  - each packet carries VC identifier (not destination ID)
  - *every* switch on source-dest path maintain “state” for each passing connection
  - link, switch resources (bandwidth, buffers) may be *allocated* to VC: to get circuit-like perf.

- **Permanent VCs (PVCs)**
  - long lasting connections
  - typically: “permanent” route between to IP routers

- **Switched VCs (SVC)**:
  - dynamically set up on per-call basis
**ATM VCs**

- Advantages of ATM VC approach:
  - QoS performance guarantee for connection mapped to VC (bandwidth, delay, delay jitter)
- Drawbacks of ATM VC approach:
  - Inefficient support of datagram traffic
  - One PVC between each source/dest pair) does not scale (N*2 connections needed)
  - SVC introduces call setup latency, processing overhead for short lived connections
ATM Layer: ATM cell

- 5-byte ATM cell header
- 48-byte payload
  - Why?: small payload -> short cell-creation delay for digitized voice
  - halfway between 32 and 64 (compromise!)

Cell header

<table>
<thead>
<tr>
<th>VCI</th>
<th>PT</th>
<th>CLP</th>
<th>HEC</th>
</tr>
</thead>
</table>

Cell format

- 3rd bit in PT field; 1 indicates last cell (AAL-Indicate bit)

ATM Cell Payload - 48 bytes

SAR PDU
**ATM cell header**

- **VCI**: virtual channel ID
  - will *change* from link to link thru net
- **PT**: Payload type (e.g. RM cell versus data cell)
- **CLP**: Cell Loss Priority bit
  - CLP = 1 implies low priority cell, can be discarded if congestion
- **HEC**: Header Error Checksum
  - cyclic redundancy check

<table>
<thead>
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<th>VCI</th>
<th>CLP</th>
<th>PT</th>
<th>HEC</th>
</tr>
</thead>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

40 bits
ATM Physical Layer (more)

*Two* pieces (sublayers) of physical layer:
- **Transmission Convergence Sublayer (TCS):** adapts ATM layer above to PMD sublayer below
- **Physical Medium Dependent:** depends on physical medium being used

**TCS Functions:**
- Header *checksum* generation: 8 bits CRC
- Cell *delineation*
- With “unstructured” PMD sublayer, transmission of *idle cells* when no data cells to send
**ATM Physical Layer**

Physical Medium Dependent (PMD) sublayer

- **SONET/SDH**: transmission frame structure (like a container carrying bits);
  - bit synchronization;
  - bandwidth partitions (TDM);
  - several speeds: \(OC3 = 155.52\) Mbps; \(OC12 = 622.08\) Mbps; \(OC48 = 2.45\) Gbps, \(OC192 = 9.6\) Gbps

- **TI/T3**: transmission frame structure (old telephone hierarchy): 1.5 Mbps/ 45 Mbps

- **unstructured**: just cells (busy/idle)
IP-Over-ATM

Classic IP only
- 3 "networks" (e.g., LAN segments)
- MAC (802.3) and IP addresses

IP over ATM
- replace "network" (e.g., LAN segment) with ATM network
- ATM addresses, IP addresses
IP-Over-ATM

<table>
<thead>
<tr>
<th>app</th>
<th>transport</th>
</tr>
</thead>
<tbody>
<tr>
<td>IP</td>
<td>Eth</td>
</tr>
<tr>
<td>Eth</td>
<td>ATM</td>
</tr>
<tr>
<td>phy</td>
<td>phy</td>
</tr>
</tbody>
</table>

Diagram:
- Application layer
- Transport layer
- IP layer
- Ethernet layer
- ATM layer
- Physical layer

Diagram shows the flow from application to physical layers, with the addition of ATM and AAL layers in between.
Datagram Journey in IP-over-ATM Network

- **at Source Host:**
  - IP layer maps between IP, ATM dest address (using ARP)
  - passes datagram to AAL5
  - AAL5 encapsulates data, segments cells, passes to ATM layer

- **ATM network:** moves cell along VC to destination

- **at Destination Host:**
  - AAL5 reassembles cells into original datagram
  - if CRC OK, datagram is passed to IP
IP-Over-ATM

Issues:
- IP datagrams into ATM AAL5 PDUs
- from IP addresses to ATM addresses
  - just like IP addresses to 802.3 MAC addresses!
Multiprotocol label switching (MPLS)

- initial goal: speed up IP forwarding by using fixed length label (instead of IP address) to do forwarding
  - borrowing ideas from Virtual Circuit (VC) approach
  - but IP datagram still keeps IP address!

![Diagram of MPLS structure]

- PPP or Ethernet header
- MPLS header
- IP header
- remainder of link-layer frame

- label
- Exp
- S
- TTL

- 20
- 3
- 1
- 5
MPLS capable routers

- a.k.a. label-switched router
- forwards packets to outgoing interface based only on label value (don’t inspect IP address)
  - MPLS forwarding table distinct from IP forwarding tables
- signaling protocol needed to set up forwarding
  - RSVP-TE
    - forwarding possible along paths that IP alone would not allow (e.g., source-specific routing) !!
    - use MPLS for traffic engineering
- must co-exist with IP-only routers
MPLS forwarding tables

<table>
<thead>
<tr>
<th>in label</th>
<th>out label</th>
<th>dest</th>
<th>out interface</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>A</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>D</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>A</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>in label</th>
<th>out label</th>
<th>dest</th>
<th>out interface</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>6</td>
<td>A</td>
<td>1</td>
</tr>
<tr>
<td>12</td>
<td>9</td>
<td>D</td>
<td>0</td>
</tr>
</tbody>
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</thead>
<tbody>
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<td>6</td>
<td>A</td>
<td>0</td>
</tr>
</tbody>
</table>

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Chapter 5: Summary

- principles behind data link layer services:
  - error detection, correction
  - sharing a broadcast channel: multiple access
  - link layer addressing, ARP

- instantiation and implementation of various link layer technologies
  - Ethernet
  - switched LANS
  - PPP
  - virtualized networks as a link layer: ATM, MPLS