Data Link Layer

- **Function:**
  - Send blocks of data (frames) between physical devices
  - Regulate access to the physical media
- **Key challenge:**
  - How to delineate frames?
  - How to detect errors?
  - How to perform media access control (MAC)?
  - How to recover from and avoid collisions?
Outline

Media Access Control

- 802.3 Ethernet
- 802.11 Wifi
What is Media Access?

- Ethernet and Wifi are both multi-access technologies
  - Broadcast medium, shared by many hosts
  - Simultaneous transmissions cause collisions
    - This destroys the data
What is Media Access?

- Ethernet and Wifi are both multi-access technologies
  - Broadcast medium, shared by many hosts
  - Simultaneous transmissions cause collisions
    - This destroys the data
- Media Access Control (MAC) protocols are required
  - Rules on how to share the medium
  - Strategies for detecting, avoiding, and recovering from collisions
Strategies for Media Access

- Channel partitioning
  - Divide the resource into small pieces
  - Allocate each piece to one host
  - Example: Time Division Multi-Access (TDMA) cellular
  - Example: Frequency Division Multi-Access (FDMA) cellular
Strategies for Media Access

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  - Allow collisions, but use strategies to recover
  - Examples: Ethernet, Wifi
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Contestation MAC Goals

- Share the medium
  - Two hosts sending at the same time collide, thus causing interference
  - If no host sends, channel is idle
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Contestion MAC Goals

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- High utilization
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- Simple, distributed algorithm
  - Multiple hosts that cannot directly coordinate
  - No fancy (complicated) token-passing schemes
Contention Protocol Evolution

- ALOHA
  - Developed in the 70’s for packet radio networks
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- Slotted ALOHA
  - Start transmissions only at fixed time slots
  - Significantly fewer collisions than ALOHA
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Contestion Protocol Evolution

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- Carrier Sense Multiple Access (CSMA)
  - Start transmission only if the channel is idle

- CSMA / Collision Detection (CSMA/CD)
  - Stop ongoing transmission if collision is detected
ALOHA

- **Topology**: radio broadcast with multiple stations
- **Protocol**:
  - Stations transmit data immediately
  - Receivers ACK all packets
  - No ACK = collision, wait a random time then retransmit
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- Simple, but radical concept
- Previous attempts all divided the channel
  - TDMA, FDMA, etc.
- Optimized for the common case: few senders
Tradeoffs vs. TDMA

- In TDMA, each host must wait for its turn
  - Delay is proportional to number of hosts
- In Aloha, each host sends immediately
  - Much lower delay
  - But, much lower utilization
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\[2\times\text{Frame Width}\]

Sender A

Sender B

Time

ALOHA Frame

ALOHA Frame
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Maximum throughput is \( \sim 18\% \) of channel capacity
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  - But, much lower utilization.

![Graph showing tradeoffs between TDMA and Aloha.](image)

- Maximum throughput is approximately 18% of channel capacity.
Slotted ALOHA

- Protocol
  - Same as ALOHA, except time is divided into slots
  - Hosts may only transmit at the beginning of a slot
  - Thus, frames either collide completely, or not at all
  - 37% throughput vs. 18% for ALOHA
  - But, hosts must have synchronized clocks
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### 802.3 Ethernet

<table>
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<tr>
<th>Bytes</th>
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<th>1</th>
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<th>0-46</th>
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<td>SF</td>
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<td>Dest.</td>
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<td>Checksum</td>
<td></td>
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</tbody>
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802.3 Ethernet

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- Terminator
- Tee Connector
- 10Base2
- Hub
- Repeater
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Hubs and repeaters are layer-1 devices, i.e. physical only.
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- 10BaseT and 100BaseT
- T stands for Twisted Pair

Hubs and repeaters are layer-1 devices, i.e., physical only.
CSMA/CD

- Carrier sense multiple access with collision detection
- Key insight: wired protocol allows us to sense the medium
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Carrier sense multiple access with collision detection

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5. If collision, abort immediately
   - Why keep sending if the frame is already corrupted?
6. Perform exponential backoff then retransmit
CSMA/CD Collisions

- Collisions can occur

Spatial Layout of Hosts

A B C D

Time
CSMA/CD Collisions

- Collisions can occur
Collisions can occur
CSMA/CD Collisions

- Collisions can occur
- Collisions are quickly detected and aborted
CSMA/CD Collisions

- Collisions can occur
- Collisions are quickly detected and aborted
- Note the role of distance, propagation delay, and frame length

Spatial Layout of Hosts

Detect Collision and Abort
Exponential Backoff

- When a sender detects a collision, send “jam signal”
  - Make sure all hosts are aware of collision
  - Jam signal is 32 bits long (plus header overhead)
- Exponential backoff operates in multiples of 512 bits
  - Select $k \in [0, 2^n - 1]$, where $n =$ number of collisions
  - Wait $k \times 51.2\mu s$ before retransmission
  - $n$ is capped at 10, frame dropped after 16 collisions
- Backoff time is divided into contention slots
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Remember this number
Minimum Packet Sizes
Minimum Packet Sizes

- Why is the minimum packet size 64 bytes?
  - To give hosts enough time to detect collisions
- What is the relationship between packet size and cable length?

![Diagram showing the relationship between A and B with Propagation Delay (d).]
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![Diagram of network with two hosts A and B connected by cable with propagation delay $d$.]
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- 10 Mbps Ethernet
- Packet and cable lengths change for faster Ethernet standards

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Cable Length Examples

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- What if you changed min packet size to 1024 bytes and bandwidth to 1 Gbps?
  - 1024 meters
Exponential Backoff, Revisited

- Remember the 512 bit backoff timer?
- Minimum Ethernet packet size is also 512 bits
  - 64 bytes * 8 = 512 bits
- Coincidence? Of course not.
  - If the backoff time was < 512 bits, a sender who waits and another who sends immediately can still collide
Maximum Packet Size

- **Maximum Transmission Unit (MTU):** 1500 bytes

- **Pros:**
  - Bit errors in long packets incur significant recovery penalty

- **Cons:**
  - More bytes wasted on header information
  - Higher per packet processing overhead

- Datacenters shifting towards Jumbo Frames
  - 9000 bytes per packet
Long Live Ethernet

- Today’s Ethernet is switched
  - More on this later

- 1Gbit and 10Gbit Ethernet now common
  - 100Gbit on the way
  - Uses same old packet header
  - Full duplex (send and receive at the same time)
  - Auto negotiating (backwards compatibility)
  - Can also carry power
Outline

- Framing
- Error Checking and Reliability
- Media Access Control
  - 802.3 Ethernet
  - 802.11 Wifi
802.3 vs. Wireless

- Ethernet has one shared collision domain
  - All hosts on a LAN can observe all transmissions
- Wireless radios have small range compared to overall system
  - Collisions are local
  - Collision are at the receiver, not the sender
  - Carrier sense (CS in CSMA) plays a different role
- 802.11 uses CSMA/CA not CSMA/CD
  - Collision avoidance, rather than collision detection
Hidden Terminal Problem

- Radios on the same network cannot always hear each other
Hidden Terminal Problem

- Radios on the same network cannot always hear each other.
Hidden Terminal Problem

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Diagram:
- Three nodes: A, B, C
- Node B transmitting to node A
- Node C receiving node A's transmission
- Collision indicated by red speech bubble
Hidden Terminal Problem

- Radios on the same network cannot always hear each other.

A cannot hear C

Collision!

C cannot hear A
Hidden Terminal Problem

- Radios on the same network cannot always hear each other

- Hidden terminals mean that sender-side collision detection is useless
Exposed Terminal Problem

- Carrier sensing is problematic in wireless
Exposed Terminal Problem

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Exposed Terminal Problem

- Carrier sensing is problematic in wireless

A
B
C
D

No collision

No collision
Exposed Terminal Problem

- Carrier sensing is problematic in wireless
Exposed Terminal Problem

- Carrier sensing is problematic in wireless networks.

Carrier sense detects a busy channel

A B C D
Exposed Terminal Problem

- Carrier sensing is problematic in wireless carrier sense detects a busy channel

- Carrier sense can erroneously reduce utilization
Reachability in Wireless

- High level problem:
  - Reachability in wireless is not transitive
  - Just because A can reach B, and B can reach C, doesn’t mean A can reach C
**MACA**

- **Multiple Access with Collision Avoidance**
- Developed in 1990

Diagram:

- Host in Sender’s Range
- Sender
- Receiver
- Host in Receiver’s Range
MACA

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Host in Sender's Range

Sense the channel

Host in Receiver's Range
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Diagram:
- Host in Sender’s Range
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- Receiver
- Host in Receiver’s Range

- Sense the channel
- Soft-reserve the channel

Routing:
- RTS

MACA

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**Diagram:**
- Host in Sender's Range
- Host in Receiver's Range
- Sender
- Receiver
- RTS
- CTS

- **Sender**
  - Sense the channel

- **Receiver**
  - The receiver is busy

- Soft-reserve the channel
Multiple Access with Collision Avoidance

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- Soft-reserve the channel
- RTS but no CTS = clear to send

- Sense the channel
- The receiver is busy
**MACA**

- **Multiple Access with Collision Avoidance**
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![Diagram of MACA protocol](chart.png)
Collisions in MACA

What if sender does not receive CTS or ACK?
- Assume collision
- Enter exponential backoff mode
802.11b

- 802.11
  - Uses CSMA/CA, not MACA
- 802.11b
  - Introduced in 1999
  - Uses the unlicensed 2.4 Ghz band
    - Same band as cordless phones, microwave ovens
  - Complementary code keying (CCK) modulation scheme
  - 5.5 and 11 Mbps data rates
    - Practical throughput with TCP is only 5.9 Mbps
  - 11 channels (in the US). Only 1, 6, and 11 are orthogonal
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802.11a/g

- **802.11a**
  - Uses the 5 Ghz band
  - 6, 9, 12, 18, 24, 36, 48, 54 Mbps
  - Switches from CCK to Orthogonal Frequency Division Multiplexing (OFDM)
    - Each frequency is orthogonal

- **802.11g**
  - Introduced in 2003
  - Uses OFDM to improve performance (54 Mbps)
  - Backwards compatible with 802.11b
    - Warning: b devices cause g networks to fall back to CCK
802.11n/ac

- **802.11n**
  - Introduced in 2009
  - Multiple Input Multiple Output (MIMO)
    - Multiple send and receive antennas per device (up to four)
    - Data stream is multiplexed across all antennas
  - Maximum 600 Mbps transfer rate (in a 4x4 configuration)
  - 300 Mbps is more common (2x2 configuration)

- **802.11ac**
  - Final approval in Feb 2014
  - 8x8 MIMO in the 5 GHz band, 500 Mbps – 1 GBps rates
MACA-style RTS/CTS is optional

Distributed Coordination Function (DCF) based on...

- Inter Frame Spacing (IFS)
  - DIFS – low priority, normal data packets
  - PIFS – medium priority, used with Point Coordination Function (PCF)
  - SIFS – high priority, control packets (RTS, CTS, ACK, etc.)

- Contention interval: random wait time
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Sense the channel

Sender

Channel Busy

Time
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  - SIFS – high priority, control packets (RTS, CTS, ACK, etc.)

- Contention interval: random wait time
MACA-style RTS/CTS is optional

Distributed Coordination Function (DCF) based on...
- Inter Frame Spacing (IFS)
  - DIFS – low priority, normal data packets
  - PIFS – medium priority, used with Point Coordination Function (PCF)
  - SIFS – high priority, control packets (RTS, CTS, ACK, etc.)
- Contention interval: random wait time
802.11 DCF Example

Sender 1

Channel Busy

Sender 2

Sender 3

Time
802.11 DCF Example

Sender 1

Sense the channel

Channel Busy

Sender 2

Sender 3

Time
802.11 DCF Example

Channel Busy

Sender 1

Sender 2

Sender 3

Time

SIFS

PIFS

DIFS
802.11 DCF Example

Sender 1

Channel Busy

Sender 2

Sender 3
802.11 DCF Example

Sender 1

Channel Busy

Sender 2

SIFS

PIFS

Contention

Sender 3

DIFS

Time

Sense the channel
802.11 DCF Example

- **Sender 1**: Channel Busy, SIFS, Transmit Data
- **Sender 2**: Contention
- **Sender 3**: DIFS

Time line shows the sequence of events with SIFS, PIFS, DIFS, and Transmit Data.
802.11 DCF Example

Sender 1
Channel Busy

Sender 2
Channel Busy

Sender 3

Time

SIFS
PIFS
DIFS

Transmit Data

Contention
802.11 DCF Example

Sender 1

Channel Busy

Sender 2

Channel Busy

Sender 3

Channel Busy

SIFS

PIFS

DIFS

Transmit Data

Contention

Time

Ssense the channel

Ssense the channel
802.11 DCF Example

Time

Sender 1
Channel Busy

Sender 2

Sender 3

SIFS
PIFS
DIFS

Transmit Data

Contention

Channel Busy
We’ve only scratched the surface of 802.11

- Association – how do clients connect to access points?
  - Scanning
  - What about roaming?

- Variable sending rates to combat noisy channels

- Infrastructure vs. ad-hoc vs. point-to-point
  - Mesh networks and mesh routing

- Power saving optimizations
  - How do you sleep and also guarantee no lost messages?

- Security and encryption (WEP, WAP, 802.11x)

This is why there are courses on wireless networking