Topic 3b: The Data Link Layer

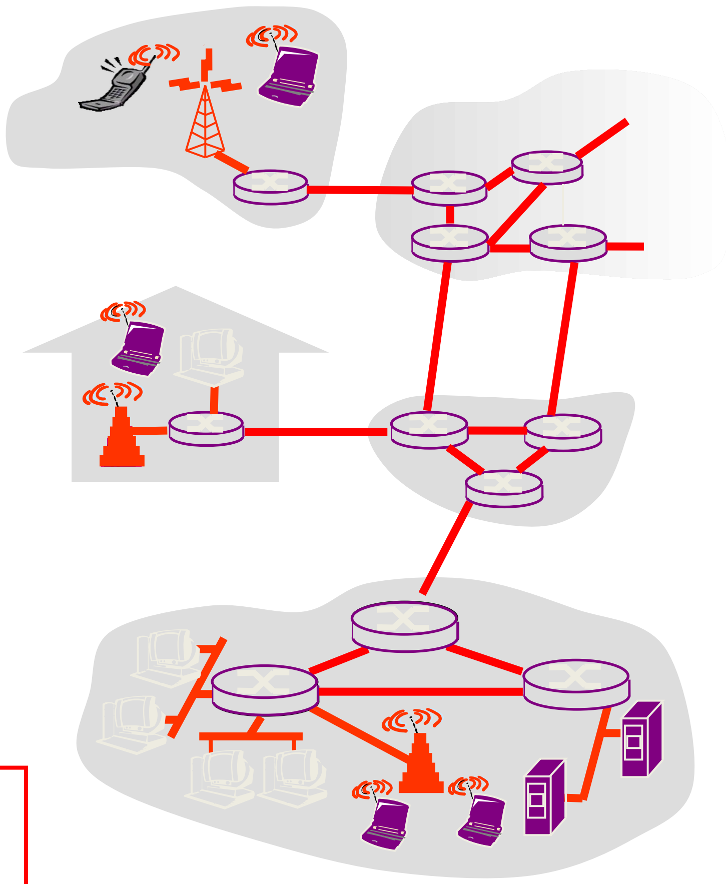
Our goals:

- Understand principles behind data link layer services:
  (these are methods & mechanisms in your networking toolbox)
  - error detection, correction
  - sharing a broadcast channel: multiple access
  - link layer addressing
  - reliable data transfer, flow control
- Instantiation and implementation of various link layer technologies
  - Wired Ethernet (aka 802.3)
  - Wireless Ethernet (aka 802.11 WiFi)
- Algorithms
  - Binary Exponential Back-off
  - Spanning Tree (Dijkstra)
- General knowledge
  - Random numbers are important and hard

Link Layer (L2): Introduction

Terminology reminder:

- hosts and routers are **nodes**
- communication channels that connect adjacent nodes along communication path are **links**
  - wired links
  - wireless links
  - LANs
- layer-2 packet is a **frame**; it encapsulates a datagram.



data-link layer has responsibility of transferring datagram from one node to adjacent peer over a link.

Link Layer (Channel) Services - 1/2

- *framing, physical addressing:*
  - encapsulate datagram into frame, adding header, trailer
  - control channel access if shared medium
  - "MAC" addresses used in frame headers to identify source, destination
    - This is **not** an IP address!

- *reliable delivery between adjacent nodes*
  - we revisit this later in the Transport Topic
  - seldom used on low bit-error link (fiber, some twisted pair)
  - commonly used on wireless links: high error rates

Link Layer (Channel) Services – 2/2

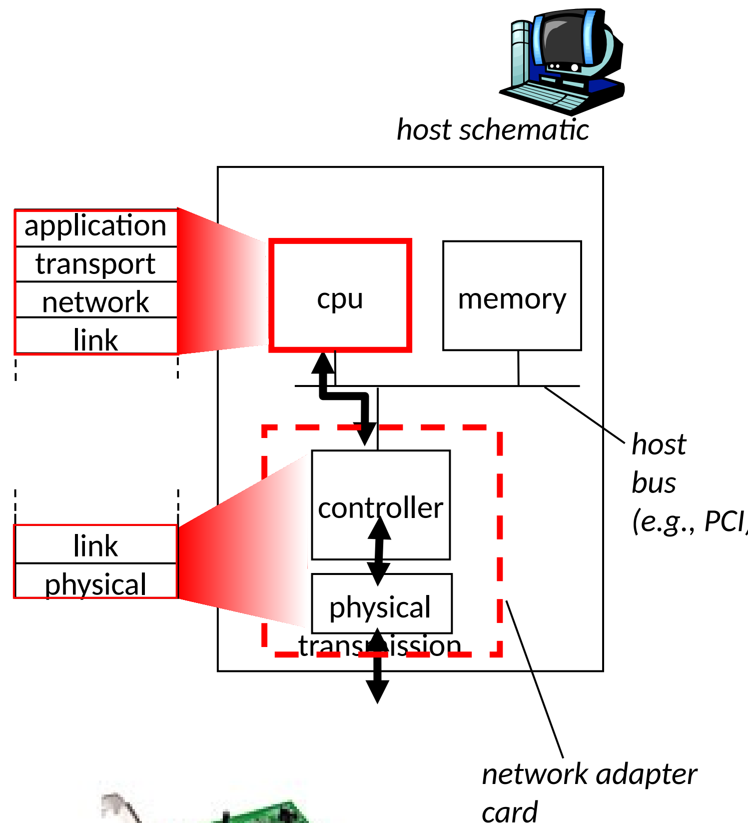
- *flow control:*
  - pacing between adjacent sending and receiving nodes

- *error control:*
  - *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

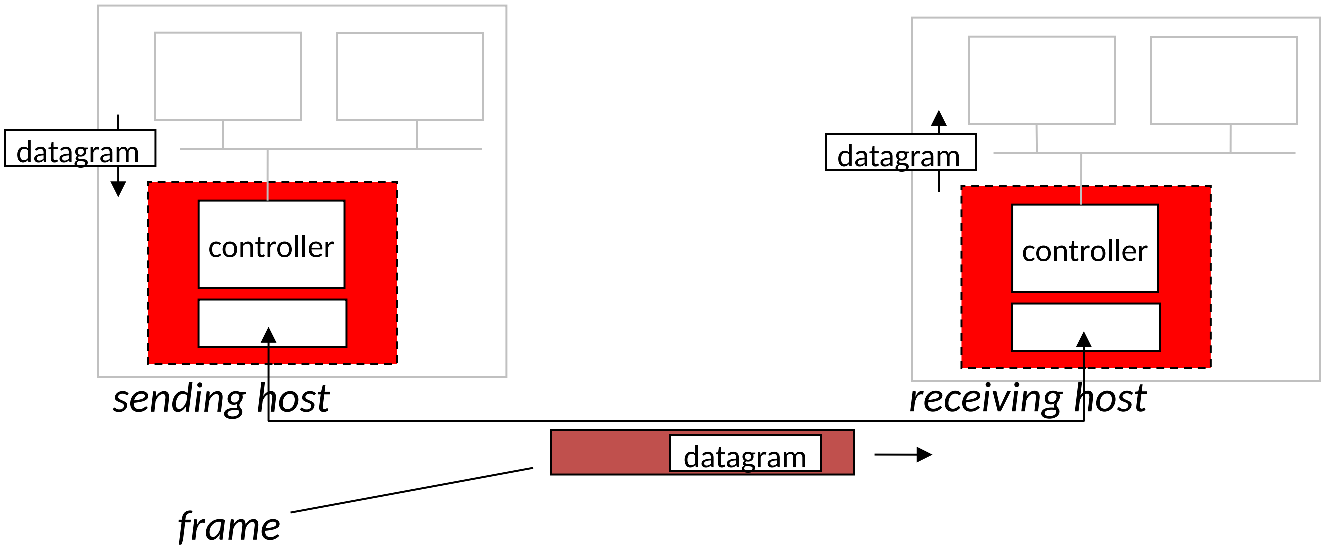
- *access control: half-duplex and full-duplex*
  - with half-duplex, nodes at both ends of link can transmit, but not at same time.

Where is the link layer implemented?

- in each and every host
- link layer implemented in "adaptor" (aka *network interface card* NIC)
  - Ethernet card, 802.11 i/face or on motherboard.
  - implements link and physical layers.
- attaches to host's system bus or sometimes USB.
- combination of hardware, software, firmware.



Adaptors Communicating



- sending side:
  - encapsulates datagram in frame
  - adds error checking and control bits for reliability, flow control, etc…
  - encodes data for the physical layer and sends.
- receiving side
  - decodes data from the physical layer
  - looks for errors, implements reliability, flow control, etc
  - extracts datagram
  - passes to upper layer.

Error Detection and Correction

Transmission media are not perfect, resulting in signal impairment:

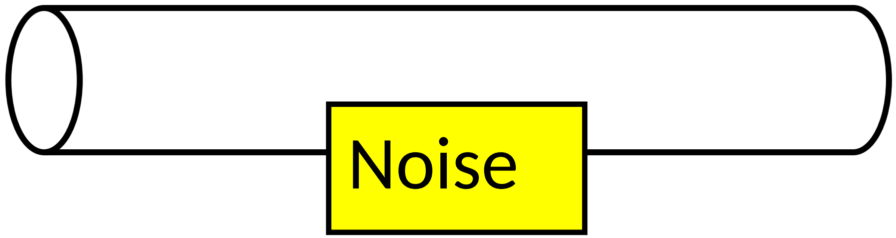
1. Attenuation
   – Loss of energy to overcome medium's resistance
2. Distortion
   – The signal changes its form or shape, caused in composite signals
3. Noise
   – Thermal noise, induced pickup noise, crosstalk, impulse noise

Interference can change the shape or timing of a signal:

0 → 1 or 1 → 0 or 'erasure'

Error Detection and Correction

How to use coding to deal with errors in data communication?



0000	0000

0001	0000

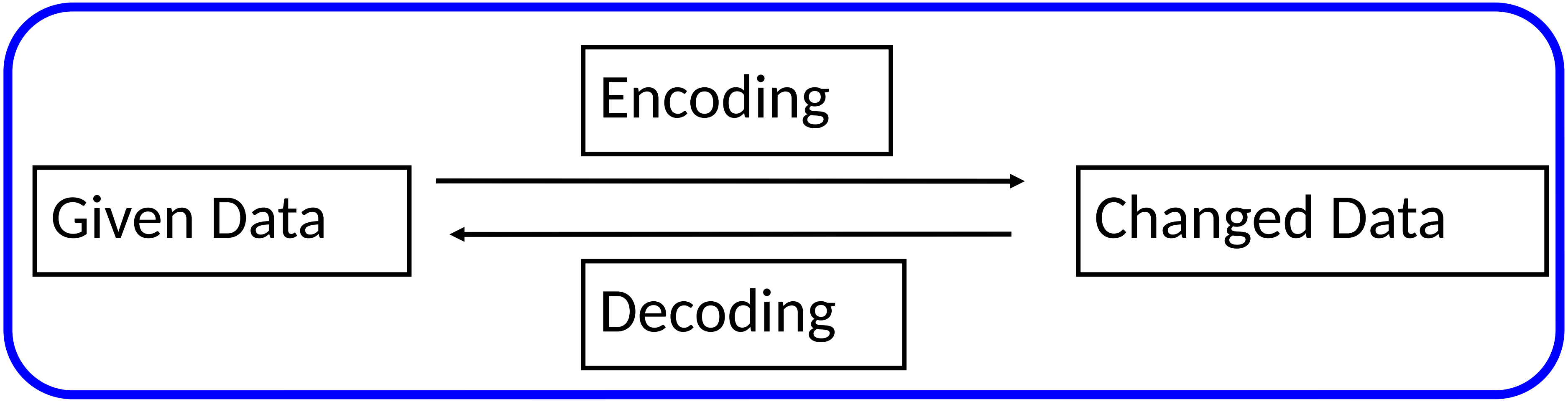
Basic Idea :

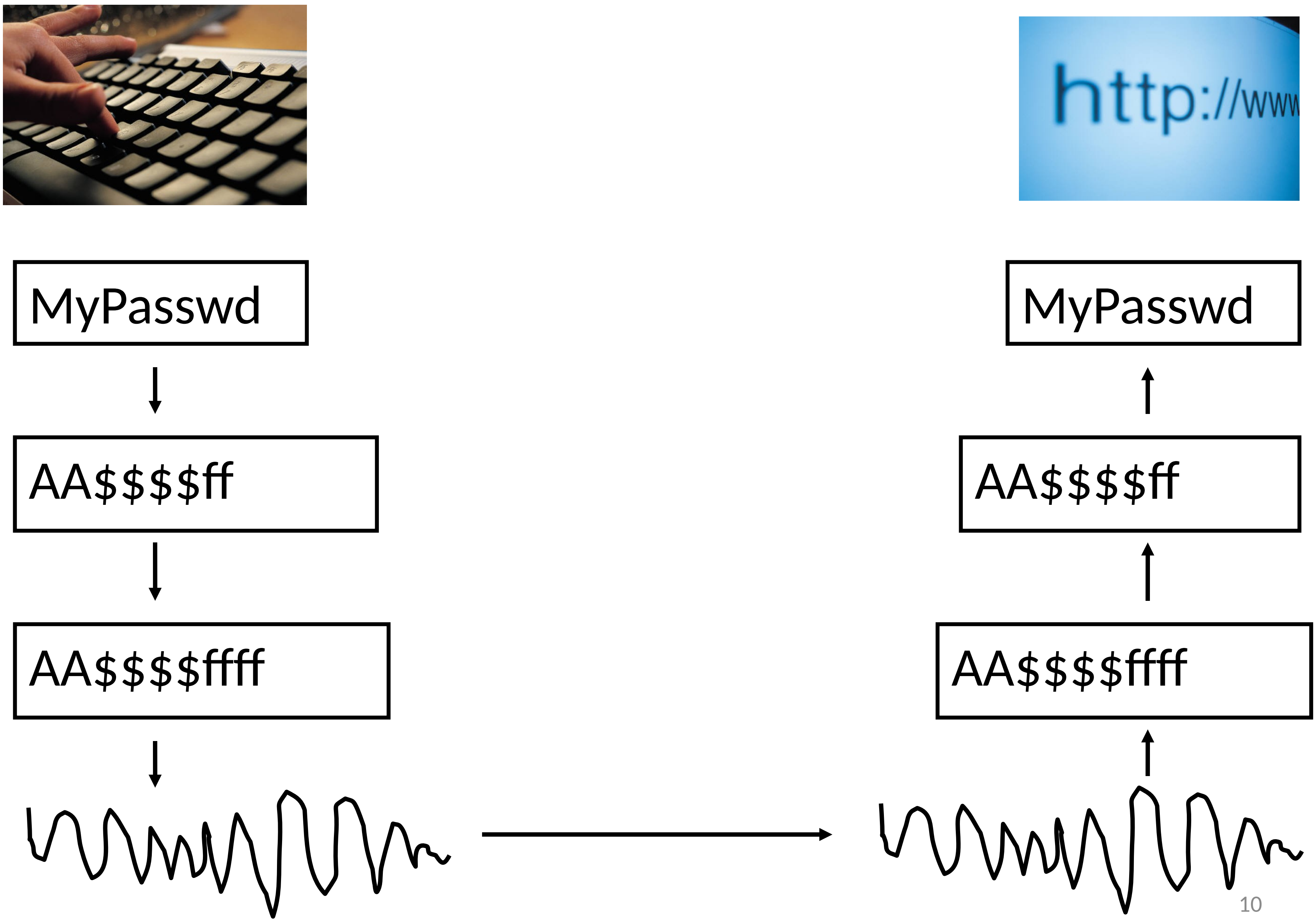
1. Add additional information (redundancy) to a message.
2. Detect an error and discard

   Or, fix an error in the received message.

Coding – a channel function

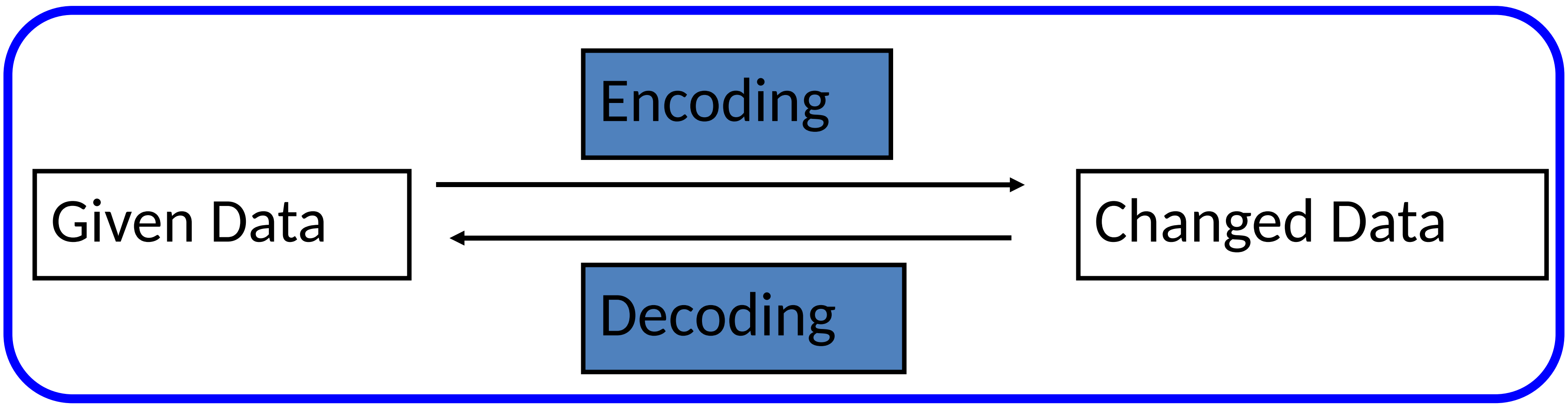
Change the representation of data.




http://www
MyPasswd
AA$$$$ff
AA$$$$ffff
MyPasswd
AA$$$$ff
AA$$$$ffff

Coding Examples

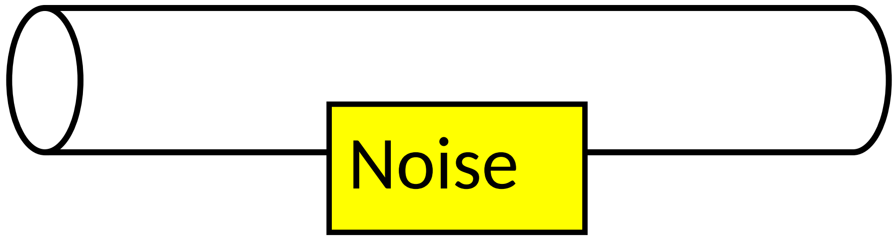
Changing the representation of data:



1. Encryption: MyPasswd <-> AA$$$$ff
2. Error Detection: AA$$$$ff <-> AA$$$$ffff
3. Compression: AA$$$$ffff <-> A2$4f4
4. Analog: A2$4f4 <-> 

Error Detection Code: Parity

Add one bit, such that the count of 1's is even.



0000	0	X	0001	0
0001	1	✓	0001	1
1001	0	✓	1111	0

Problem: This simple parity cannot detect two-bit errors.

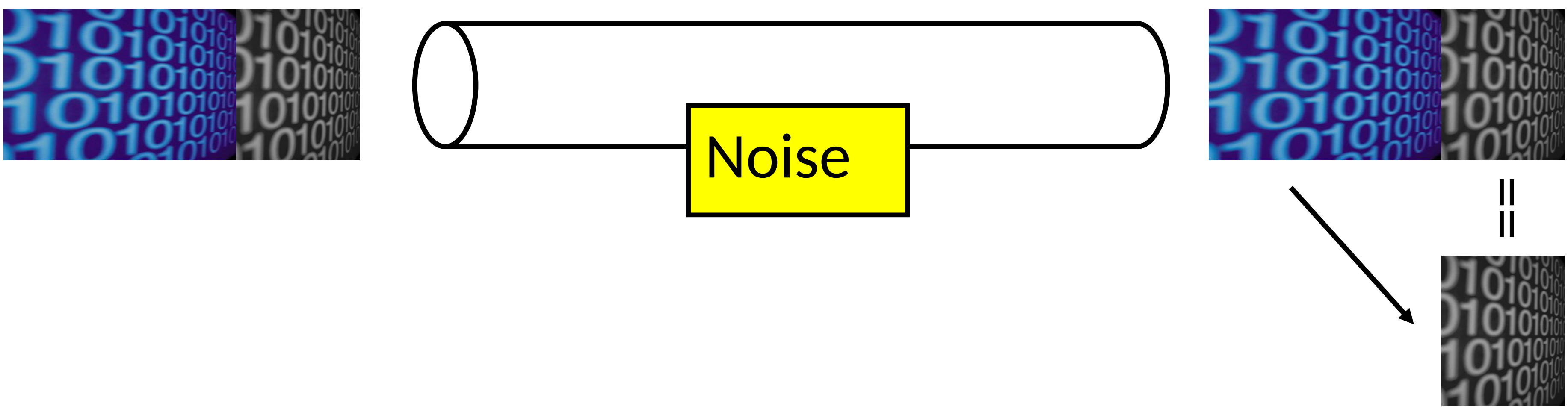
Error Detection Code

Sender:

```
Y = generateCheckBit(X);
send(X.Y);
```

Receiver:

```
receive(X1.Y1);
Y2=generateCheckBit(X1);
if (Y1 != Y2) ERROR;
else NOERROR
```



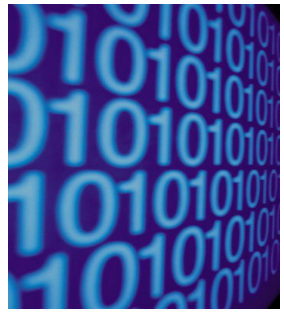
Error Detection Code: CRC

- Cyclic Redundancy Check (CRC) of length L based on P and R (pre-agreed constants).
- R is less than 2^L and can be anything provided common invalid cases (such as all zeros) get rejected.
- *"A sequence of L redundant bits, the CRC, is appended to data so that the resulting number gives R mod P."*
  - *CRC ~= remainder(data ÷ divisor)*
- More powerful than parity: it can detect multi-bit errors.
- Seemingly complex? Need binary multiplication and division.
- Typically L = 32 and P = edb8_8320 and R = FFFF_FFFF
  - Our example: L=3, P=101 (aka 5) and R=0.
  - Choosing good P is crucial in general~.

CRC with 3-bit Divisor P=101

1111

1001



000

010

CRC

0

0

Parity

111

100

same check bits from Parity,
but different ones from CRC

Multiplication by 2^3

$D2 = D * 2^3$

Add three 0's at the end

Binary division by 101

CRC = (D2) rem (101)

Error Detection Code

Sender:

CRC = generateCRC(X div P);

send(X.CRC);

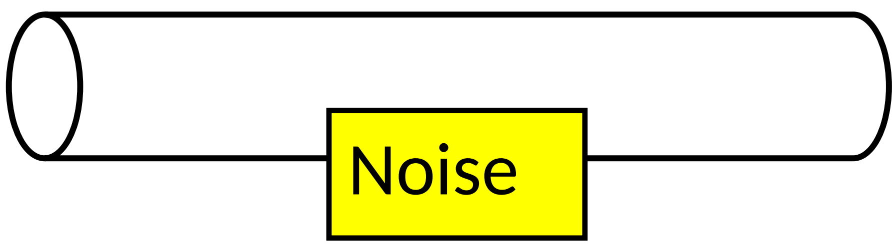
Receiver:

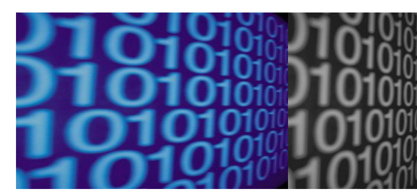
receive(X1.CRC1);

r=generateCRC(X1.CRC1 div P);

if (r != 0) ERROR;

else NOERROR





0s ==

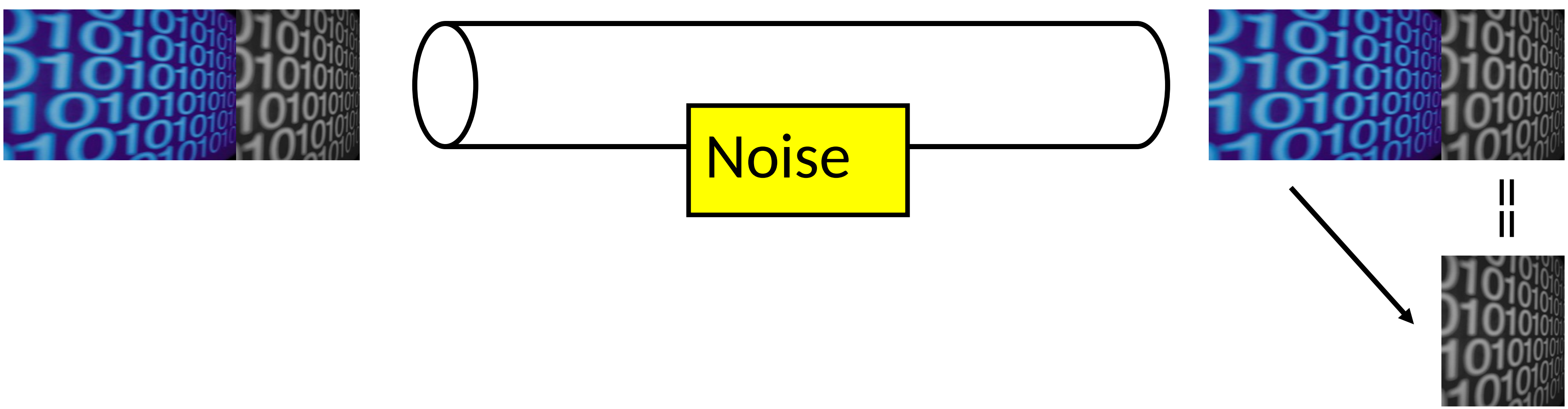
Transforming Error Detection to...

Sender:

```
Y = generateCheckBit(X);
send(XY);
```

Receiver:

```
receive(X1Y1);
Y2=generateCheckBit(X1);
if (Y1 != Y2) ERROR;
else NOERROR
```



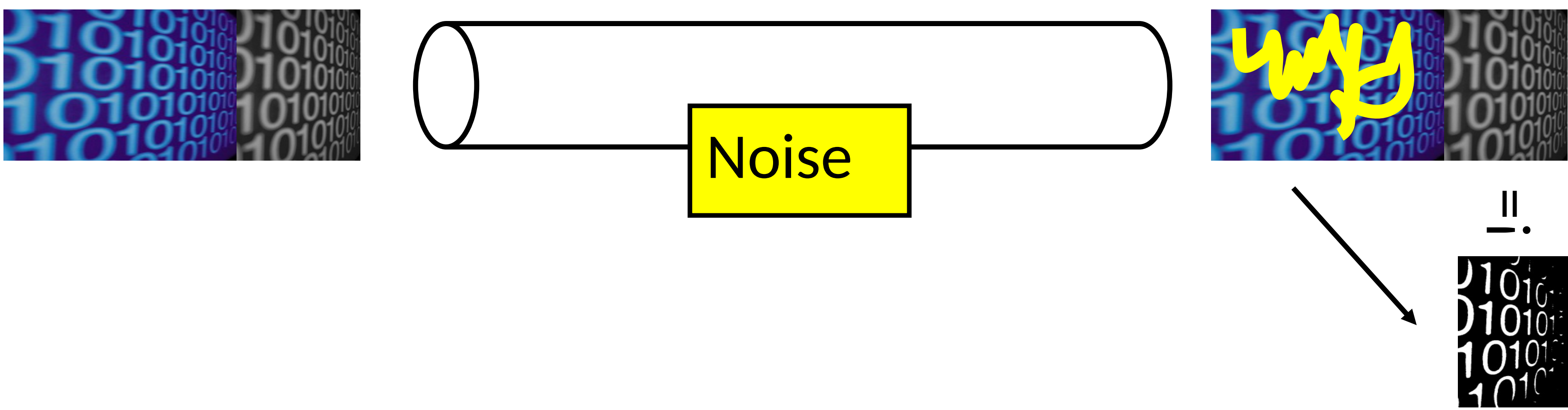
Forward Error Correction (FEC)

Sender:

```
Y = generateCheckBits(X);
send(X.Y);
```

Receiver:

```
receive(X1.Y1);
Y2=generateCheckBits(X1);
if (Y1 != Y2) FIXERROR(X1.Y1);
else NOERROR
```



Forward Error Correction (FEC)

Sender:

Y = generateCheckBits(X);

send(X.Y);

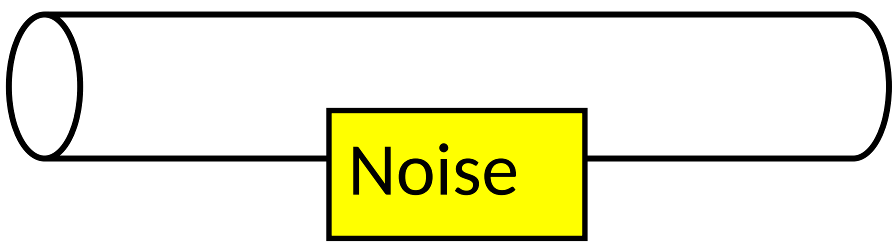
Receiver:

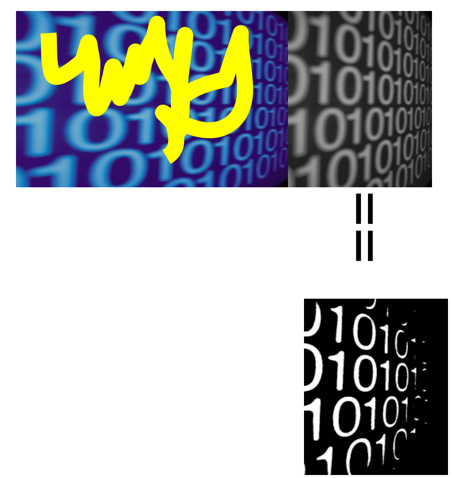
receive(X1.Y1);

Y2=generateCheckBits(X1);

if (Y1 != Y2) FIXERROR(X1.Y1);

else NOERROR

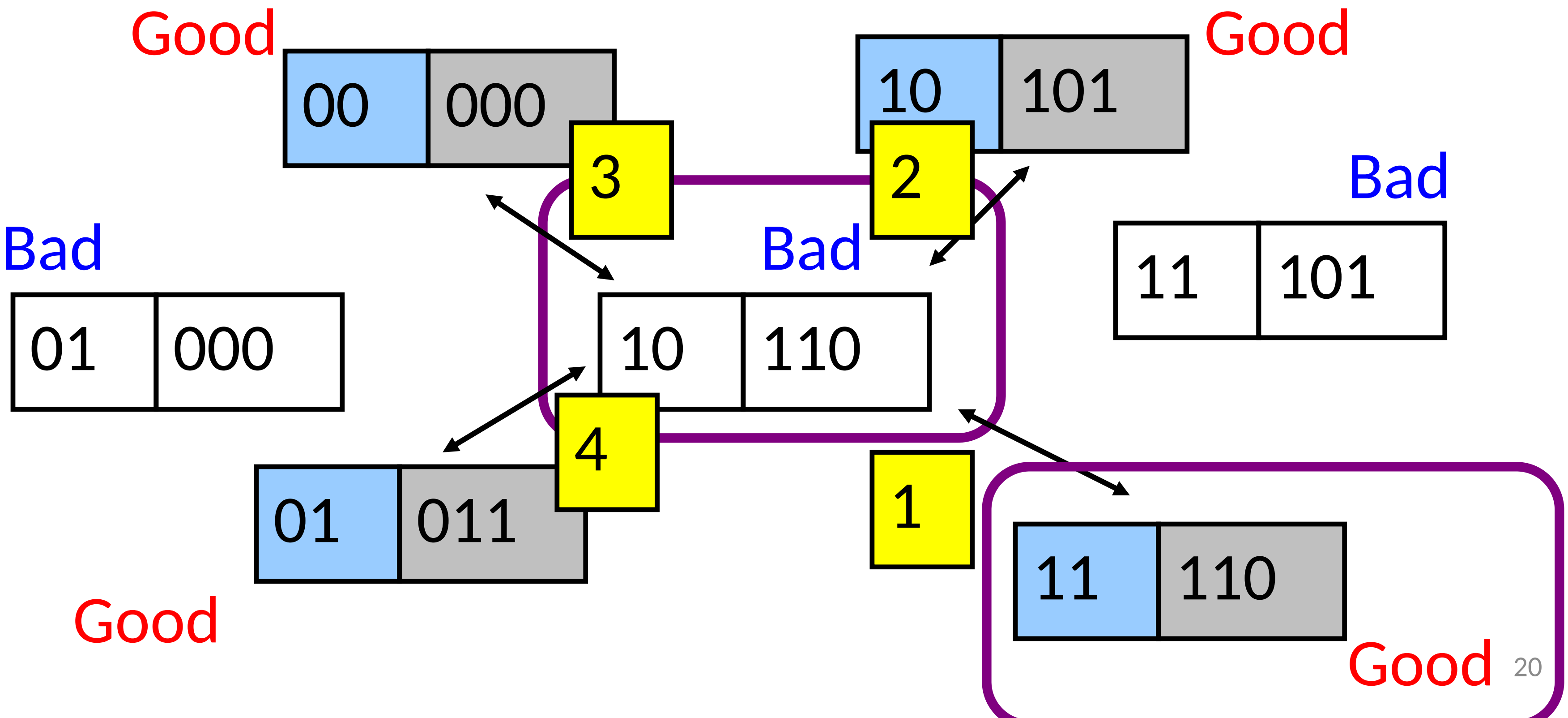




Main FEC approach: Lowest Hamming Distance

Replace erroneous data

by its "closest" error-free data.



Error Detection vs Correction

Error Correction:

- Cons: More check bits, false recovery.
- Pros: No need to re-send.

Error Detection:

- Cons: Need to re-send.
- Pros: Fewer check bits.

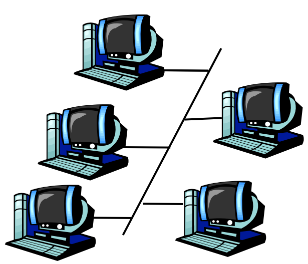
Usage:

- Correction: A lot of noise or expensive to re-send.
- Detection: Less noise or easy to re-send.
- Can be used together!

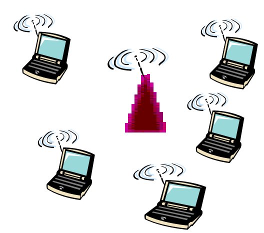
Multiple Access Links and Protocols

Two types of "links":

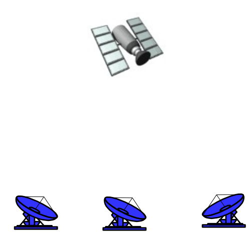
- point-to-point
  - point-to-point link between Ethernet switch and host
- broadcast (shared wire or other medium)
  - old-fashioned wired Ethernet (*here be dinosaurs* – extinct)
  - upstream HFC (Hybrid Fiber-Coax – the Coax may be broadcast or a PON used
  - Home plug or similar powerline networking
  - 802.11 wireless LAN



shared wire (e.g., Coax cabled Ethernet)



shared RF (e.g., 802.11 WiFi)



shared RF (satellite)

humans at a cocktail party (shared air, acoustical)

Multiple Access protocols

- Single, shared broadcast channel/medium.
- Two or more simultaneous transmissions by nodes ? interference not supported
  - collision if node 'receives' two or more signals at the same time

multiple access control (MAC) protocol

- distributed algorithm that determines how nodes share channel, i.e., determine when a node can transmit
- communication about channel sharing must use channel itself!
  - no out-of-band channel for coordination.

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

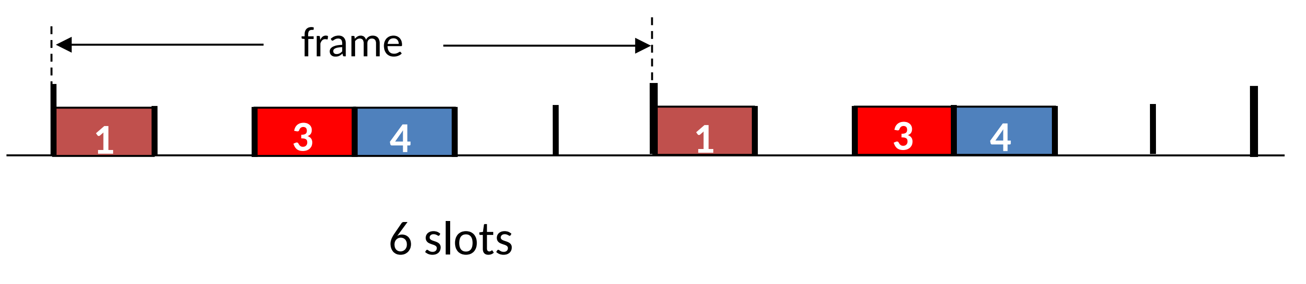
Three broad classes:

- Channel Partitioning
  - divide channel into smaller "pieces" (time slots, frequency, code)
  - (semi-permanently) allocate piece to node for exclusive use
- Random Access
  - channel not divided, allow collisions
  - "recover" from collisions
- "Taking turns"
  - nodes take turns, but nodes with more to send can take longer turns :-)

Channel Partitioning MAC protocols: TDMA
(we discussed this earlier)

TDMA: time division multiple access

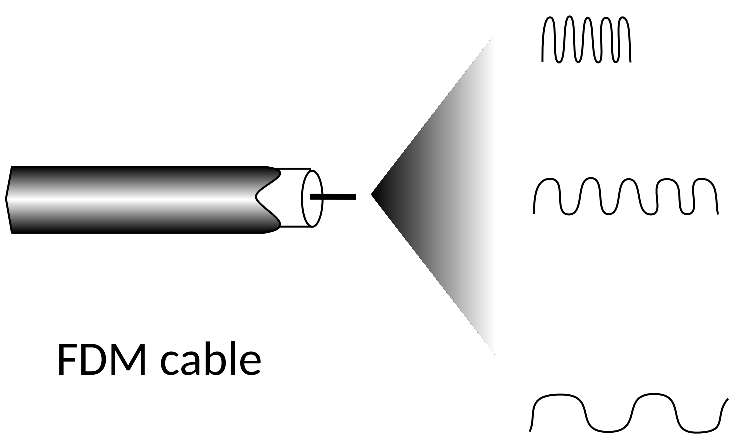
- access to channel in "rounds"
- each station gets fixed length slot (length = pkt trans time) in each round
- unused slots go idle
- example: station LAN, 1,3,4 have pkt, slots 2,5,6 idle

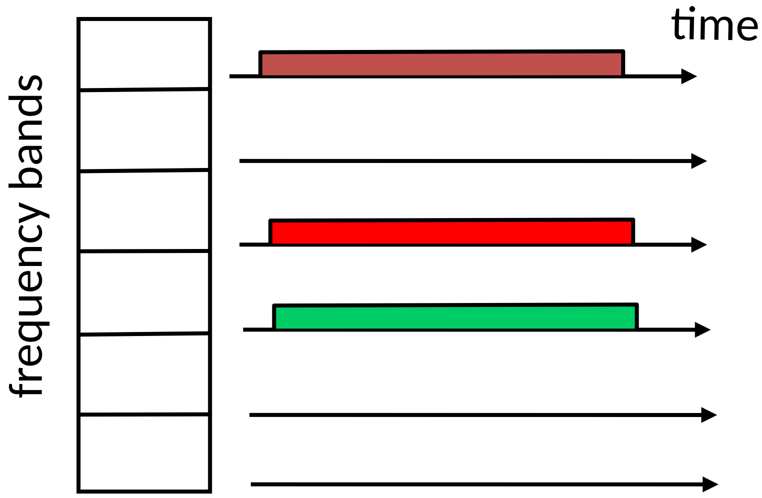


Channel Partitioning MAC protocols: FDMA
(we discussed this earlier)

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: station LAN, 1,3,4 have pkt, frequency bands 2,5,6 idle





"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

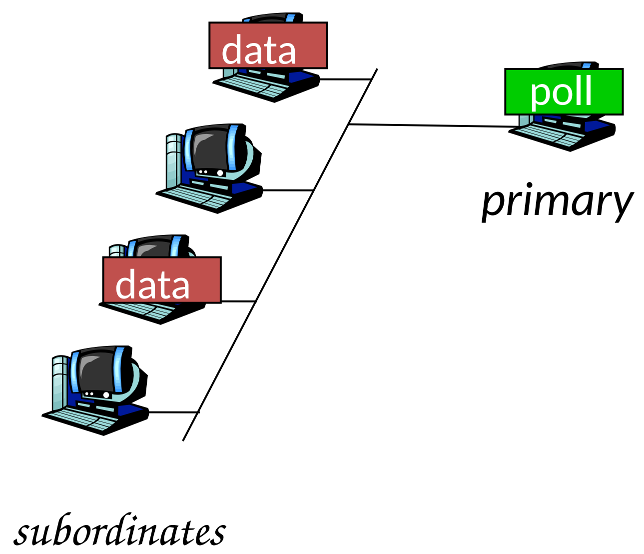
"taking turns" protocols:

resolve contention for the best of possible worlds!

"Taking Turns" MAC protocols

Polling:

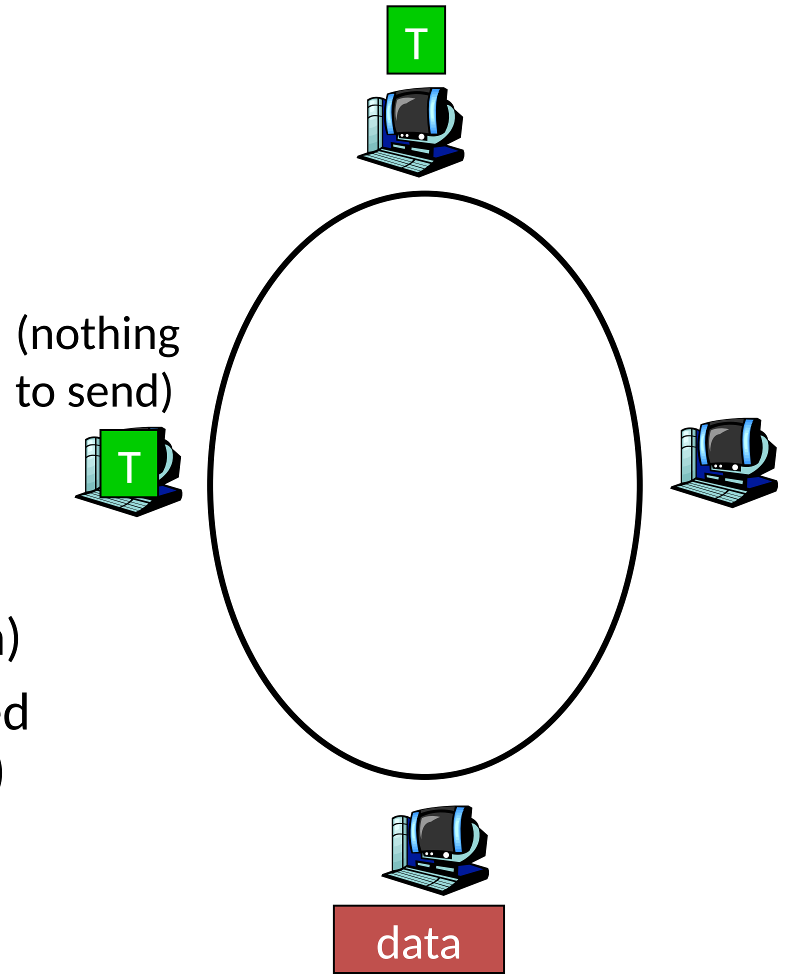
- Primary node "invites" subordinates nodes to transmit in turn
- typically used with simpler subordinate devices
- concerns:
  - polling overhead
  - latency
  - single point of failure (primary)



“Taking Turns” MAC protocols

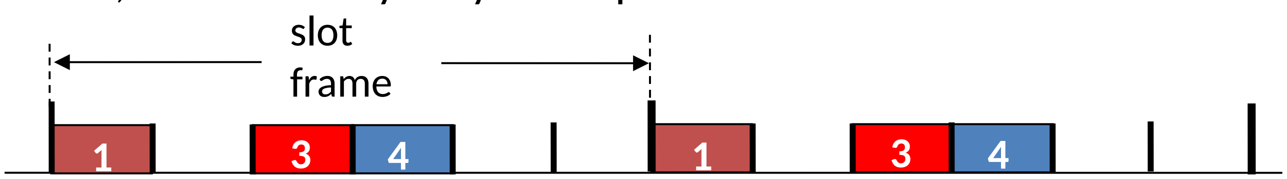
Token passing:

- control **token** passed from one node to next sequentially.
- token message
- concerns:
  - token overhead
  - latency
  - single point of failure (token)
- concerns fixed in part by a slotted ring (many simultaneous *tokens)*

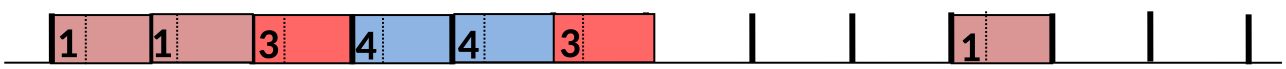


ATM

In TDM, a sender may only use a pre-allocated slot



In ATM, a sender transmits labeled cells whenever necessary



ATM = Asynchronous Transfer Mode – an ugly expression
think of it as ATDM – Asynchronous Time Division Multiplexing

That's a variant of **PACKET SWITCHING** to the rest of us – just like Ethernet
but using
fixed length slots/packets/cells

Use the media when you need it, but
ATM had virtual circuits and these needed setup….

"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:

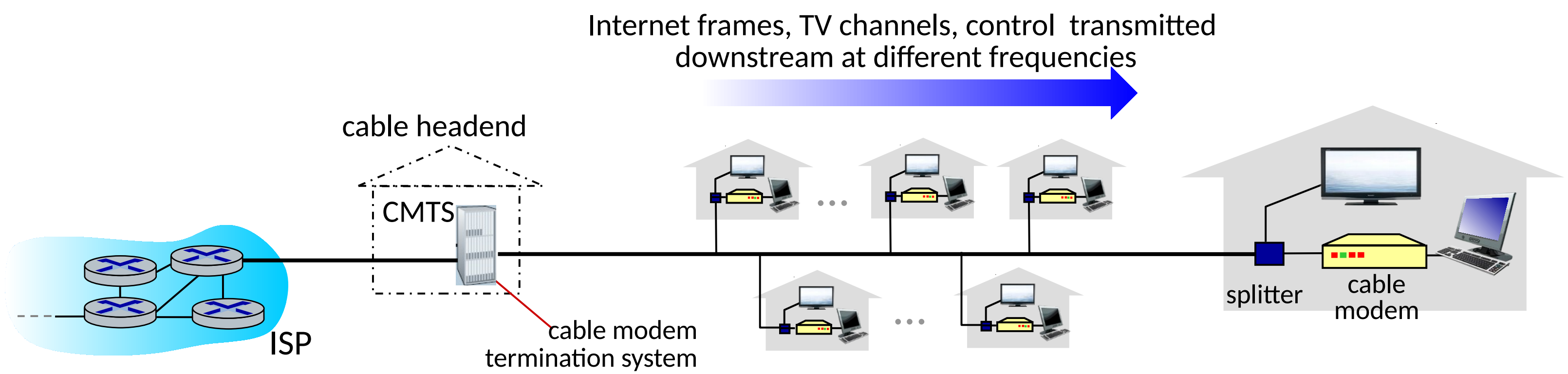
- efficient at low load: single node can fully utilize channel
- high load: collision overhead

"taking turns" protocols:

look for best of both worlds!

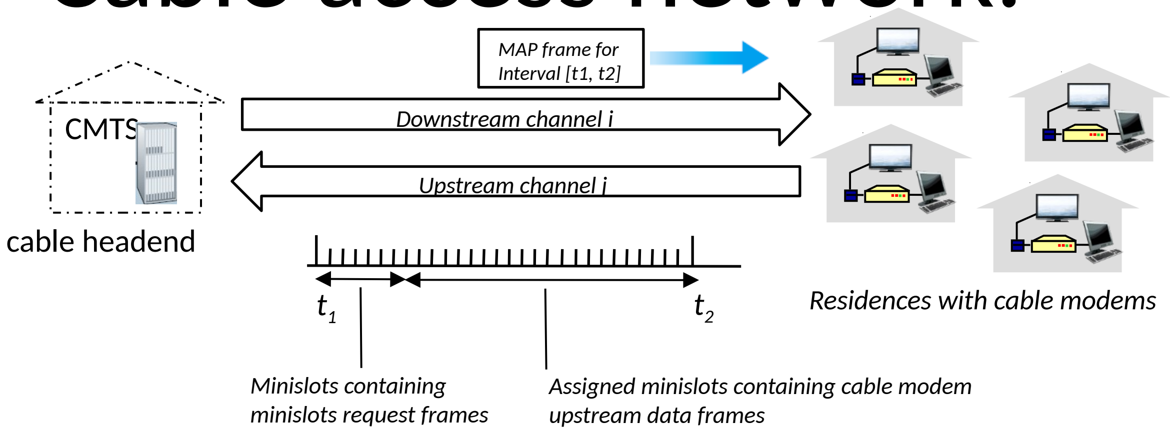
Recall…..

Cable access network: FDM, TDM *and* random access!



- multiple downstream (broadcast) FDM channels: up to 1.6 Gbps/channel
  - single CMTS transmits into channels
- multiple upstream channels (up to 1 Gbps/channel)
  - multiple access: all users contend (random access) for certain upstream channel time slots; others assigned TDM

Cable access network:



DOCSIS: data over cable service interface specification

- FDM over upstream, downstream frequency channels
- TDM upstream: some slots assigned, some have contention
  - downstream MAP frame: assigns upstream slots
  - request for upstream slots (and data) transmitted random access (binary backoff) in selected slots

Random Access MAC Protocols

- When node has packet to send
  - Transmit at full channel data rate
  - No *a priori* coordination among nodes
- Two or more transmitting nodes ⇒ collision
  - Data lost
- Random access MAC protocol specifies:
  - How to detect collisions
  - How to recover from collisions
- Examples
  - ALOHA and Slotted ALOHA
  - CSMA, CSMA/CD, CSMA/CA (wireless)

Key Ideas of Random Access

- Carrier sense
  - *Listen before speaking, and don't interrupt*
  - Checking if someone else is already sending data
  - … and waiting till the other node is done
- Collision detection
  - *If someone else starts talking at the same time, stop*
  - Realizing when two nodes are transmitting at once
  - …by detecting that the data on the wire is garbled
- Randomness
  - *Don't start talking again right away*
  - Waiting for a random time before trying again

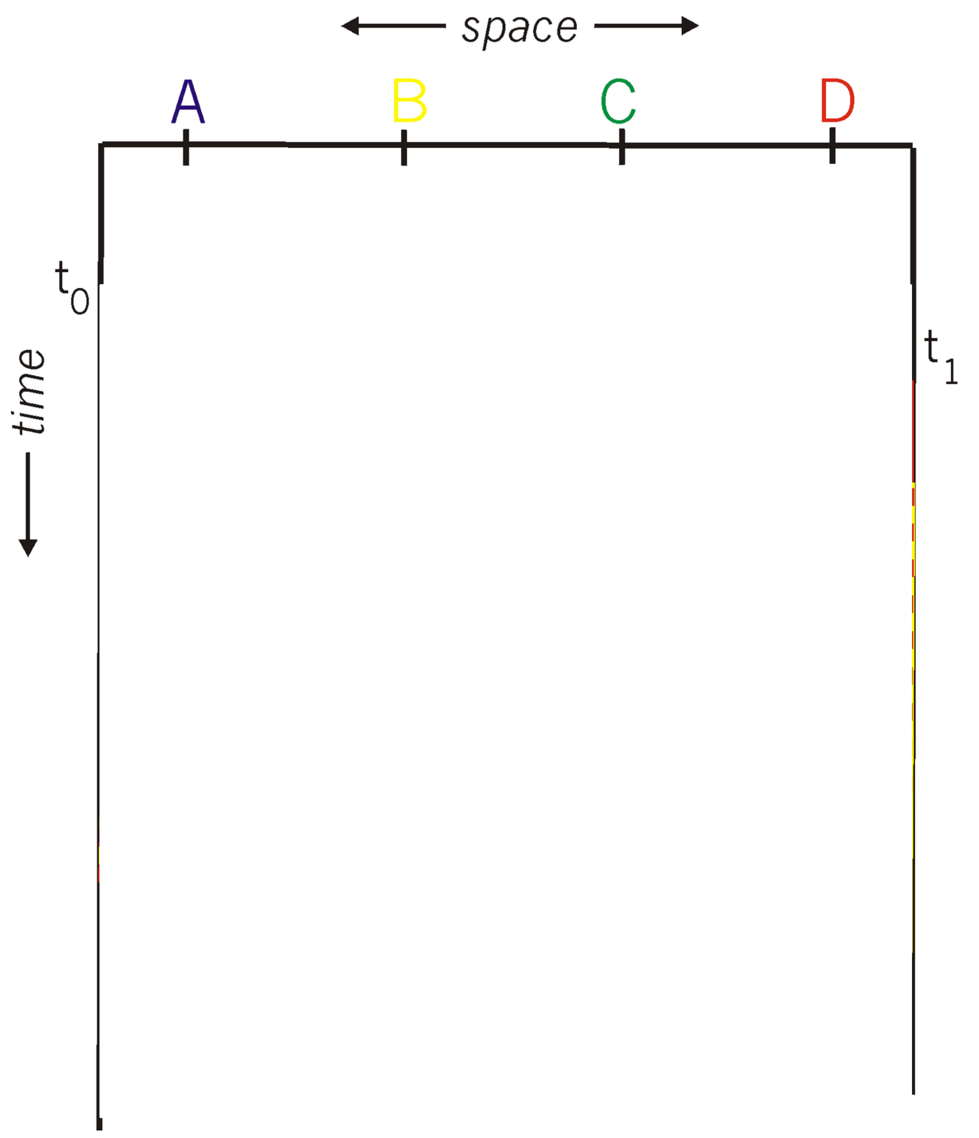
CSMA (Carrier Sense Multiple Access)

- CSMA: listen before transmit
  - If channel sensed idle: transmit entire frame
  - If channel sensed busy, defer transmission
- Human analogy: don’t interrupt others!
- Does this eliminate all collisions?
  - No, because of nonzero propagation delay

CSMA Collisions

Propagation delay: two nodes may not hear each other's before sending.

Would slots hurt or help?



CSMA reduces but does not eliminate collisions

Biggest remaining problem?

Collisions still take full slot!
How do you fix that?

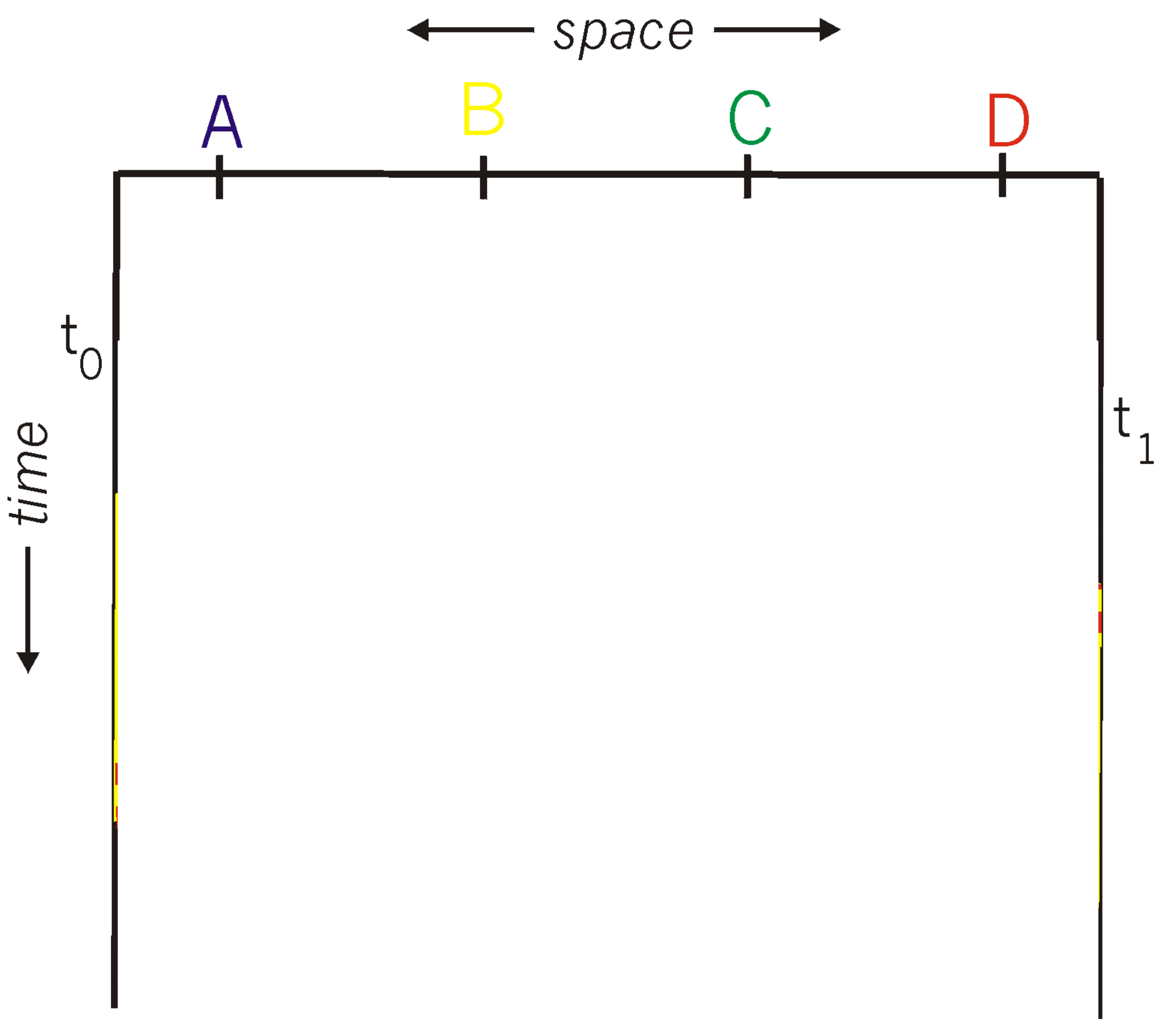
CSMA/CD (Collision Detection)

- CSMA/CD: carrier sensing, deferral as in CSMA
  - **Collisions detected within short time**
  - Colliding transmissions aborted, reducing wastage
- Collision detection easy in wired LANs:
  - Compare transmitted, received signals
- Collision detection difficult in wireless LANs:
  - Reception shut off while transmitting (well, perhaps not)
  - Not perfect broadcast (limited range) so collisions local
  - Leads to use of *collision avoidance* instead (later)

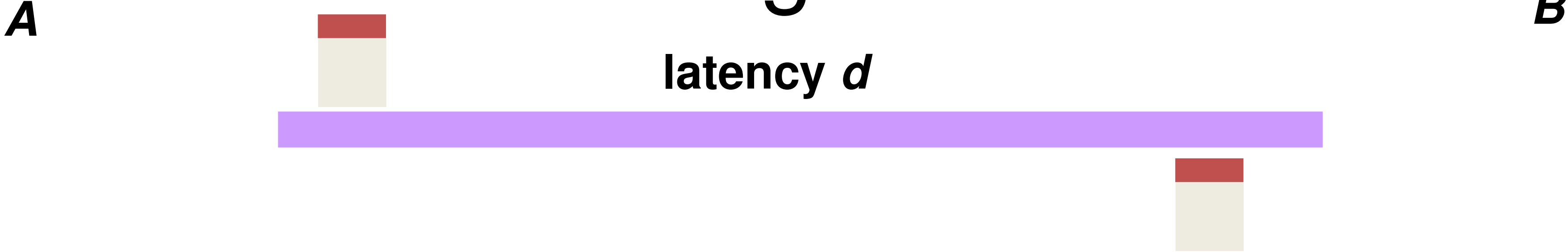
CSMA/CD Collision Detection

B and D can tell that collision occurred.

Note: for this to work, need restrictions on minimum frame size and maximum distance. Why?



Limits on CSMA/CD Network Length



- Latency depends on physical length of link
  - Time to propagate a packet from one end to the other
- Suppose *A* sends a packet at time ***t***
  - And *B* sees an idle line at a time just before ***t*+*d***
  - … so *B* happily starts transmitting a packet
- *B* detects a collision, and sends jamming signal
  - But *A* can't see collision until ***t*+*2d***

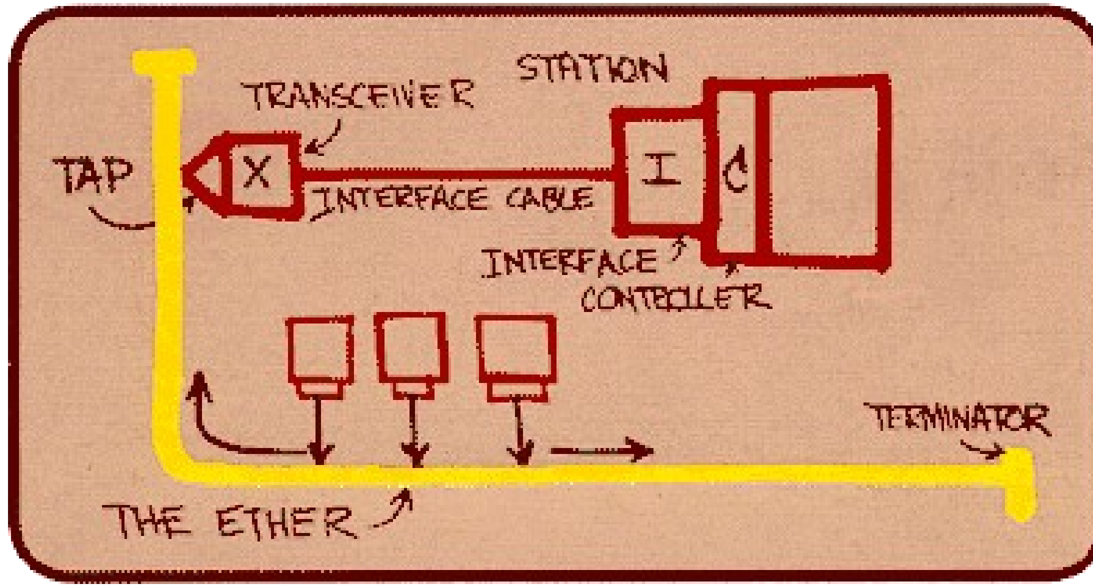
Performance of CSMA/CD

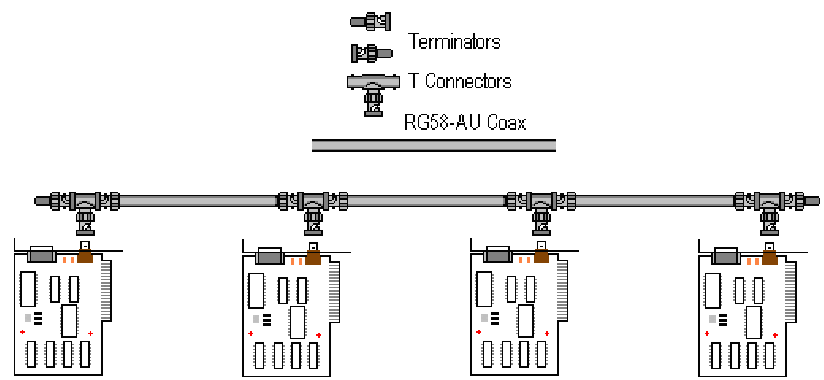
- Time wasted in collisions
  - Proportional to distance d
- Time spend transmitting a packet
  - Packet length p divided by bandwidth b
- Rough estimate for efficiency (K some constant)

$$E \sim \frac{\frac{p}{b}}{\frac{p}{b} + Kd}$$

- Note:
  - For large packets, small distances, E ~ 1
  - As bandwidth increases, E decreases
  - That is why high-speed LANs are all switched aka packets are sent via a switch - (any d is bad)

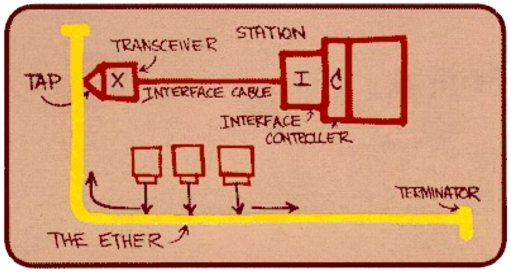
Ethernet…
yet another product of XEROX/PARC





Preamble								Destination MAC						Source MAC						EtherType/ Size		PayLoad					CRC			
1	2	3	4	5	6	7	8	1	2	3	4	5	6	1	2	3	4	5	6	1	2						1	2	3	4

Ethernet: CSMA/CD Protocol



- **Carrier sense**: wait for link to be idle
- **Collision detection**: listen while transmitting
  - No collision: transmission is complete
  - Collision: abort transmission & send **jam** signal
- **Random access**: binary exponential back-off
  - After collision, wait a random time before trying again
  - After m^{th} collision, choose K randomly from {0, ..., 2^m-1}
  - ... and wait for K*512 bit times before trying again
    - Using min packet size as "slot"
    - **If transmission occurring when ready to send, wait until end of transmission (CSMA)**

STARVATION WARNING

- **Carrier sense:** wait for link to be idle
- **Collision detection:** listen while transmitting
  - No collision: transmission is complete
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  - … and wait for K*512 bit times before trying again
    - Using min packet size as "slot"
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Benefits of Ethernet

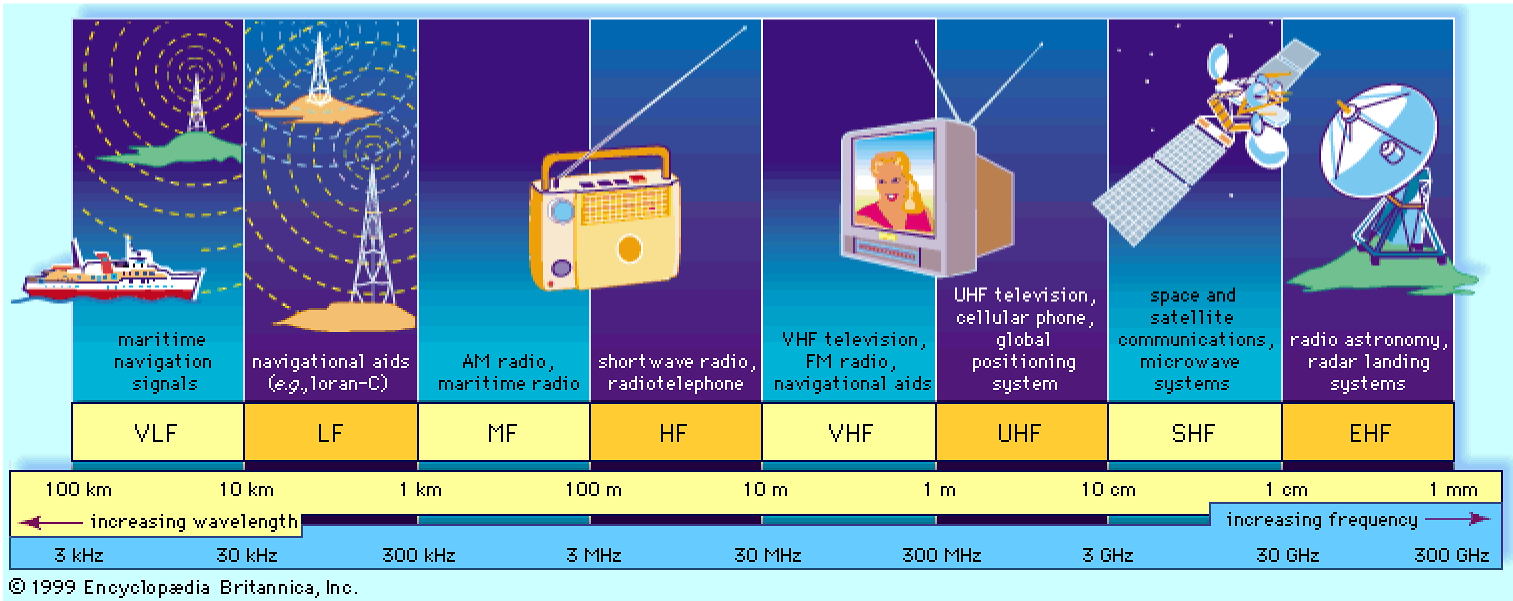
- Easy to administer and maintain
- Inexpensive
- Increasingly higher speed
- Evolvable!

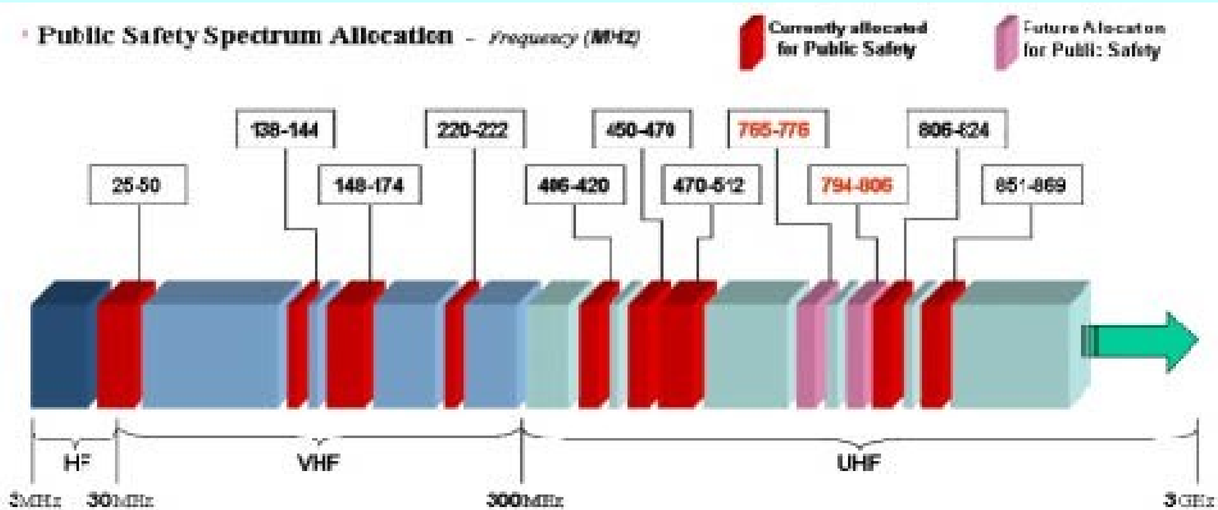
Evolution of Ethernet

- Changed everything except the frame format
  - From single coaxial cable to hub-based star
  - From shared media to switches
  - From electrical signaling to optical
- Lesson #1
  - The right interface can accommodate many changes
  - Implementation is hidden behind interface
- Lesson #2
  - Really hard to displace the dominant technology
  - Slight performance improvements are not enough


Bluetooth
WiMAX
5G
4G
802.11g
W-CDMA
HSDPA
EV-DO
RTT
UMTS-TDD
802.11a
Wireless-USB
Wi-Fi
802.11.1
WiFi
CDMA2000
802.11b
UMTS
LTE
GPRS
iBurst
OFDM
CDMA
HSPA
Zigbee
802.11n
802.15.4
Wibree
EDGE
6G
WCDMA
GSM

The Wireless Spectrum





Metrics for evaluation / comparison of wireless technologies

- Bitrate or Bandwidth
- Range - PAN, LAN, MAN, WAN
- Two-way / One-way
- Multi-Access / Point-to-Point
- Digital / Analog
- Applications and industries
- Frequency – Affects most physical properties:
  - Distance (free-space loss)
  - Penetration, Reflection, Absorption
  - Energy proportionality
  - Policy: Licensed / Deregulated
  - Line of Sight (Fresnel zone)
  - Size of antenna

➢ Determined by wavelength – $\lambda = \frac{v}{f},$)

Wireless Communication Standards

- Cellular (800/900/*1700*/1800/1900Mhz):
  - 2G: GSM / CDMA / GPRS /EDGE
  - 3G: CDMA2000/UMTS/HSDPA/EVDO
  - 4G: LTE, WiMax
- IEEE 802.11 (aka WiFi): (some examples)
  - b: 2.4Ghz band, 11Mbps (*~4.5 Mbps operating rate*)
  - g: 2.4Ghz, 54-108Mbps (*~19 Mbps operating rate*)
  - a: 5.0Ghz band, 54-108Mbps (*~25 Mbps operating rate*)
  - n: 2.4/5Ghz, 150-600Mbps (4x4 mimo)
  - ac: 2.4/5Ghz, 433-1300Mbps (improved coding 256-QAM)
  - ad: 60Ghz, 7Gbps
  - af: 54/790Mhz, 26-35Mbps (TV whitespace)
- IEEE 802.15 – lower power wireless:
  - 802.15.1: 2.4Ghz, 2.1 Mbps (Bluetooth)
  - 802.15.4: 2.4Ghz, 250 Kbps (Sensor Networks)

What Makes Wireless Different?

- Broadcast and multi-access medium…
  - err, so….

- BUT, Signals sent by sender don't always end up at receiver intact
  - Complicated physics involved, which we won't discuss
  - But what can go wrong?

Lets focus on 802.11

aka - WiFi …
What makes it special?

Deregulation > Innovation > Adoption > Lower cost = Ubiquitous technology

JUST LIKE ETHERNET – not lovely but sufficient

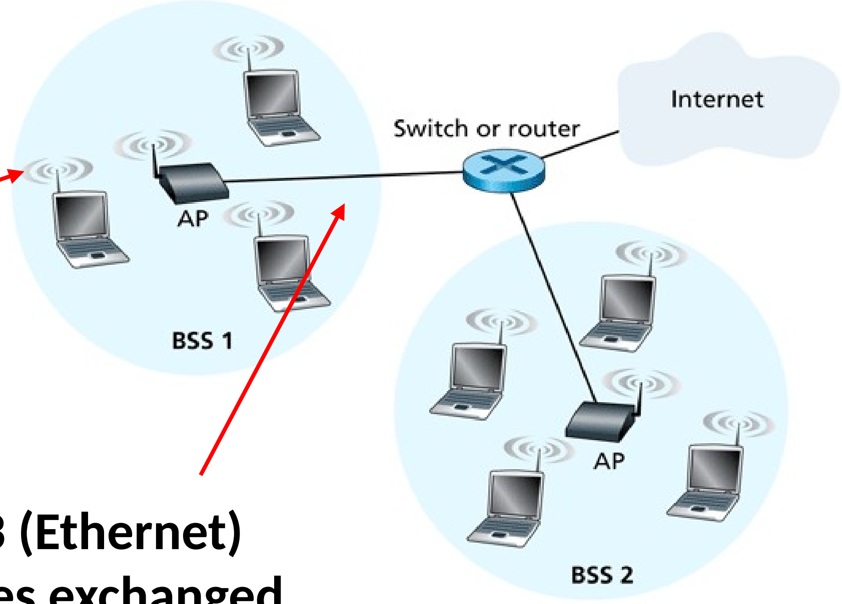
IEEE 802.11 Wireless LAN

IEEE 802.11 standard	Year	Max data rate	Range	Frequency
802.11b	1999	11 Mbps	30 m	2.4 Ghz
802.11g	2003	54 Mbps	30m	2.4 Ghz
802.11n (WiFi 4)	2009	600	70m	2.4, 5 Ghz
802.11ac (WiFi 5)	2013	3.47Gpbs	70m	5 Ghz
802.11ax (WiFi 6)	2020 (exp.)	14 Gbps	70m	2.4, 5 Ghz
802.11af	2014	35 – 560 Mbps	1 Km	unused TV bands (54-790 MHz)
802.11ah	2017	347Mbps	1 Km	900 Mhz

- all use CSMA/CA for multiple access, and have base-station and ad-hoc network versions

802.11 Architecture

802.11 frames exchanges



802.3 (Ethernet) frames exchanged

Figure 6.7 ♦ IEEE 802.11 LAN architecture

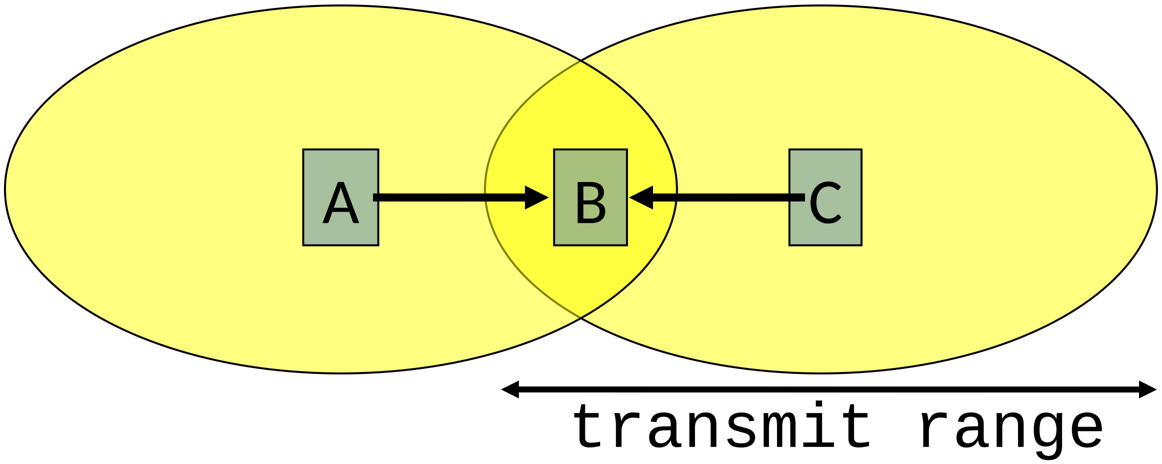
- Designed for limited area
- AP's (Access Points) set to specific channel
- Broadcast beacon messages with SSID (Service Set Identifier) and MAC Address periodically
- Hosts scan all the channels to discover the AP's
  - Host associates with AP

Wireless Multiple Access Technique?

- Carrier Sense?
  - Sender can listen before sending
  - What does that tell the sender?

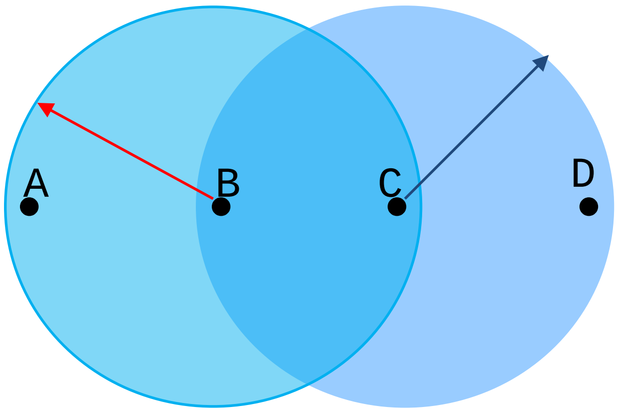
- Collision Detection?
  - Where do collisions occur?
  - How can you detect them?

Hidden Terminals



- A and C can both send to B but can't hear each other
  - A is a *hidden terminal* for C and vice versa
- Carrier Sense will be ineffective

Exposed Terminals



- Exposed node: B sends a packet to A; C hears this and decides not to send a packet to D (despite the fact that this will not cause interference)!
- Carrier sense would prevent a successful transmission.

Key Points

- No concept of a global collision
  - Different receivers hear different signals
  - Different senders reach different receivers
- Collisions are at receiver, not sender
  - Only care if receiver can hear the sender clearly
  - It does not matter if sender can hear someone else
  - As long as that signal does not interfere with receiver
- Goal of protocol:
  - Detect if receiver can hear sender
  - Tell senders who might interfere with receiver to shut up

Basic Collision Avoidance

- Since can't detect collisions, we try to *avoid* them
- Carrier sense:
  - When medium busy, choose random interval
  - Wait that many **idle** timeslots to pass before sending

- When a collision is inferred, retransmit with binary exponential backoff (like Ethernet)
  - Use ACK from receiver to infer "no collision"
  - Use exponential backoff to adapt contention window

IEEE 802.11 MAC Protocol: CSMA/CA

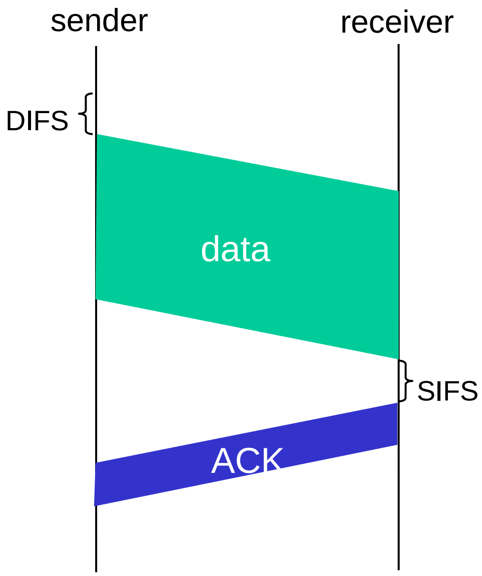
802.11 sender

1 if sense channel idle for **DIFS** then
transmit entire frame (no CD)

2 if sense channel busy then
start random backoff time
timer counts down while channel idle
transmit when timer expires
if no ACK, increase random backoff interval, repeat 2

802.11 receiver

if frame received OK
return ACK after **SIFS** (ACK needed due to hidden terminal problem)

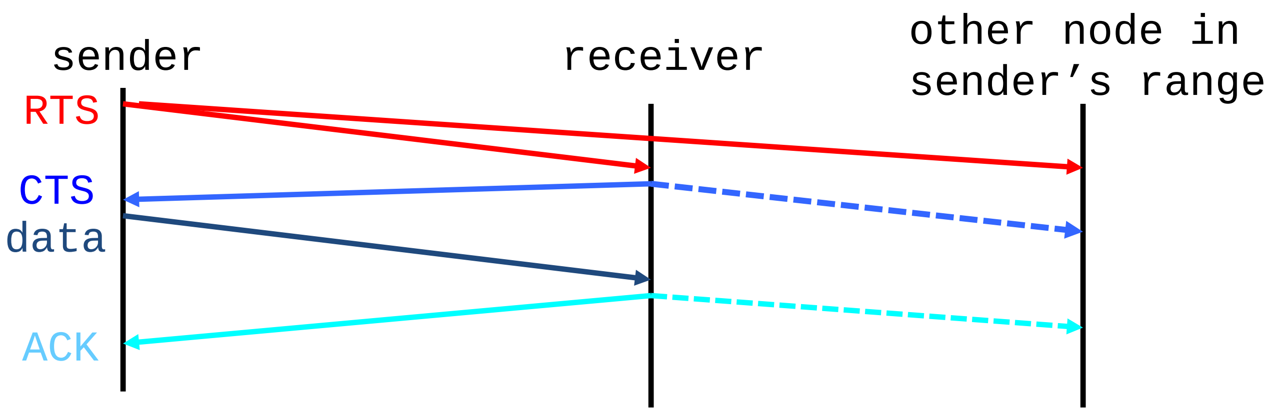


Avoiding collisions

idea: sender "reserves" channel use for data frames using small reservation packets

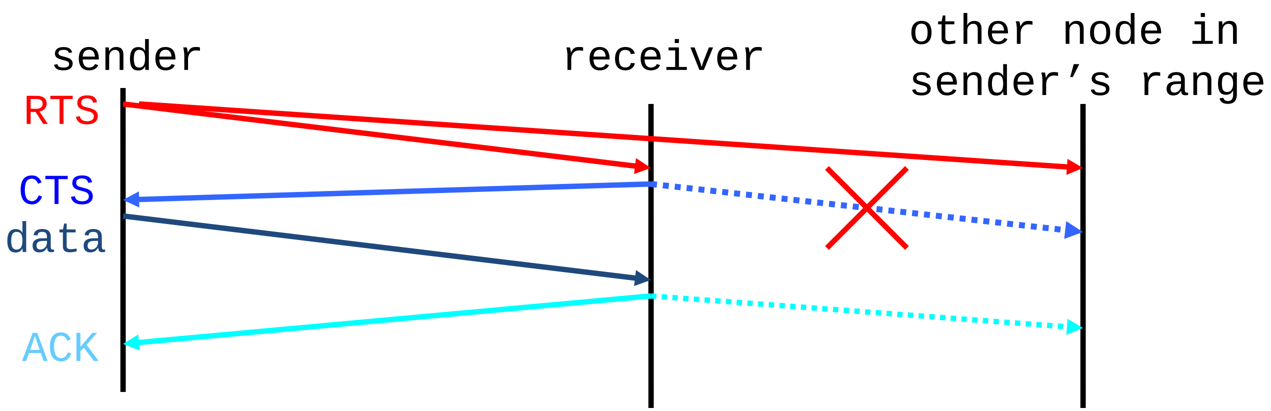
- sender first transmits *small* request-to-send (RTS) packet to BS using CSMA
  - RTSs may still collide with each other (but they're short)
- BS broadcasts clear-to-send CTS in response to RTS
- CTS heard by all nodes
  - sender transmits data frame
  - other stations defer transmissions

CSMA/CA – and in this case RTS/CTS



- Before every data transmission
  - Sender sends a Request to Send (RTS) frame containing the length of the transmission
  - Receiver respond with a Clear to Send (CTS) frame
  - Sender sends data
  - Receiver sends an ACK; now another sender can send data
- When sender doesn't get a CTS back, it assumes collision

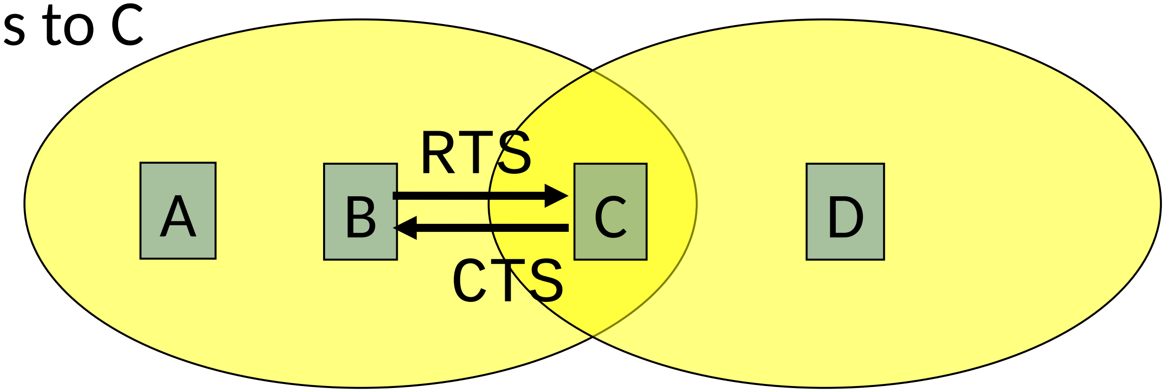
CSMA/CA, con't



- If other nodes hear RTS, but not CTS: send
  - Presumably, destination for first sender is out of node's range …
  - … Can cause problems when a CTS is lost
- When you hear a CTS, you keep quiet until scheduled transmission is over (hear ACK)

RTS / CTS Protocols (CSMA/CA)

B sends to C

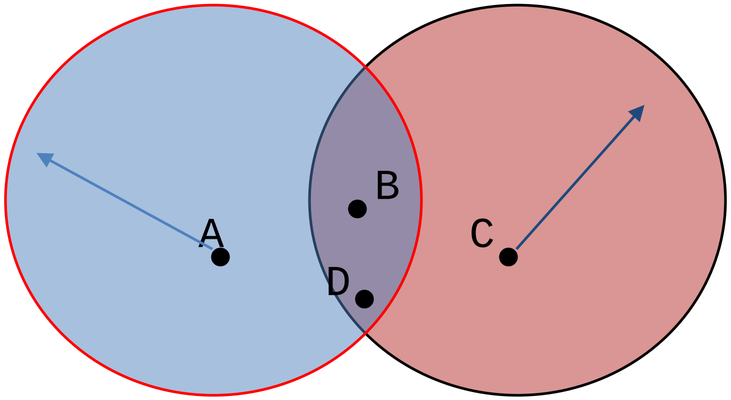


Overcome hidden terminal problems with contention-free protocol

1. B sends to C Request To Send (RTS)
2. A hears RTS and defers (to allow C to answer)
3. C replies to B with Clear To Send (CTS)
4. D hears CTS and defers to allow the data
5. B sends to C

Preventing Collisions Altogether

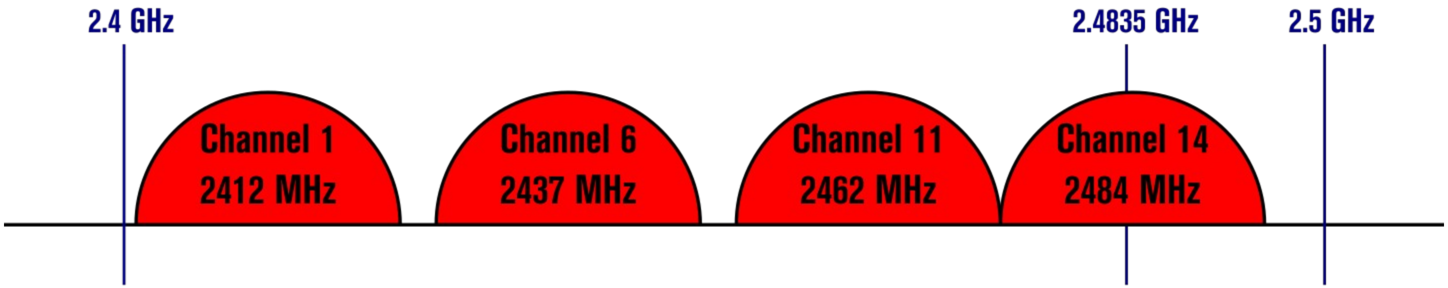
- Frequency Spectrum partitioned into several channels
  - Nodes within interference range can use separate channels



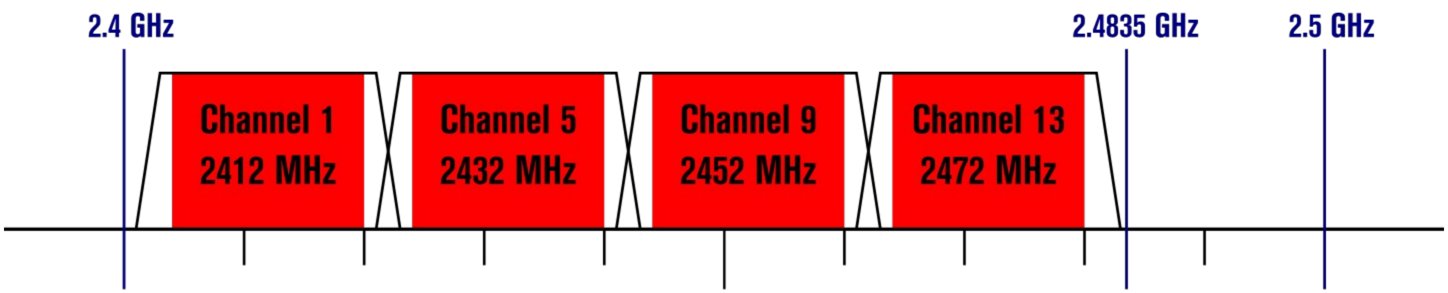
  - Now A and C can send without any interference!
- Most cards have only 1 transceiver
  - **Not full-duplex: Cannot send and receive at the same time**
  - Aggregate Network throughput doubles

Non-Overlapping Channels for 2.4 GHz WLAN

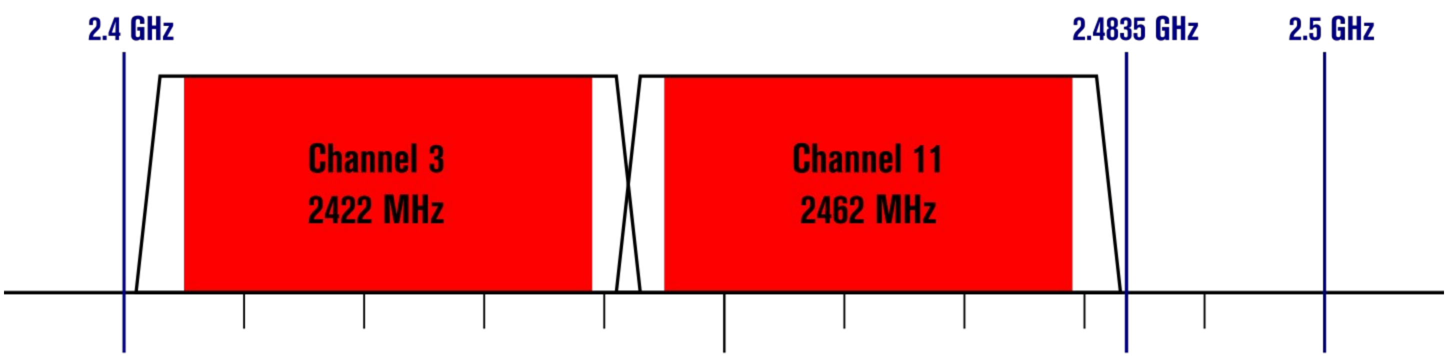
802.11b (DSSS) channel width 22 MHz

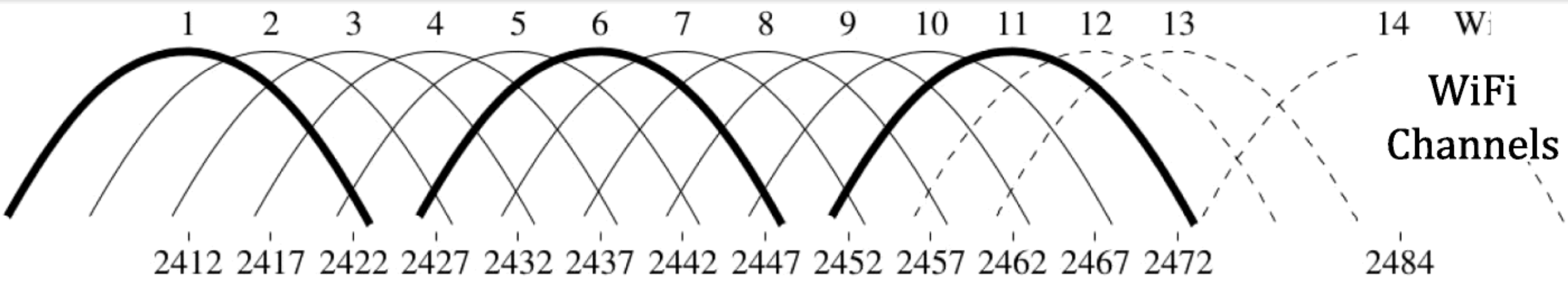


802.11g/n (OFDM) 20 MHz ch. width – 16.25 MHz used by sub-carriers



802.11n (OFDM) 40 MHz ch. width – 33.75 MHz used by sub-carriers



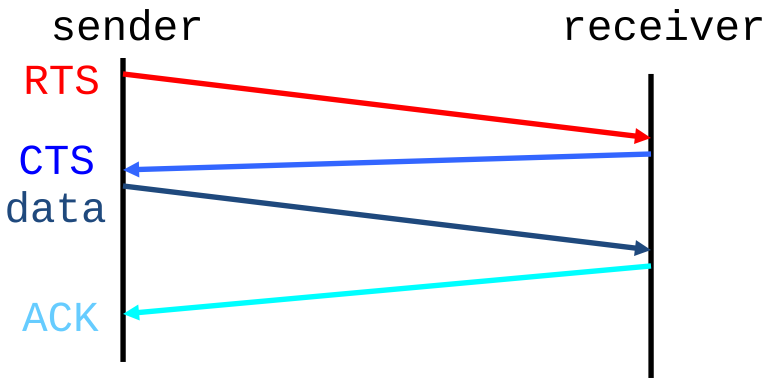

1 2 3 4 5 6 7 8 9 10 11 12 13 14
WiFi Channels
2412 2417 2422 2427 2432 2437 2442 2447 2452 2457 2462 2467 2472 2484

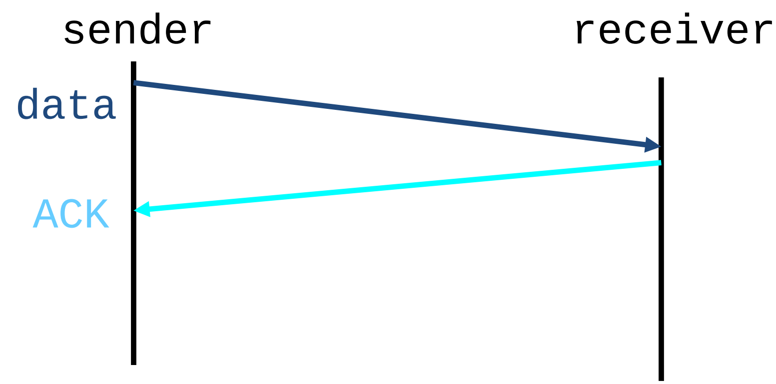
Wifi has been evolving!

Using dual band (2.4GHz + 5GHz), multiple channels, MIMO, Meshing WiFi

Outside this introduction but the state of the art is very fast and very flexible

CSMA/CA and RTS/CTS





RTS/CTS

- helps with hidden terminal
- good for high-traffic Access Points
- often turned on/off dynamically

Without RTS/CTS

- lower latency -> faster!
- reduces wasted b/w

if the *Pr(collision)* is low

- good for when net is small and not *weird*

eg no hidden/exposed terminals

CSMA/CD vs CSMA/CA (without RTS/CTS)

CD Collision Detect

wired – listen and talk

1. Listen for others
2. Busy? goto 1.
3. Send message (and listen)
4. Collision?
    a. JAM
    b. increase your BEB
    c. sleep
    d. goto 1.

CA Collision Avoidance

wireless – talk OR listen

1. Listen for others
2. Busy? goto 1.
3. Send message
4. Wait for ACK (*MAC ACK*)
5. Got No ACK from MAC?
    a. increase your BEB
    b. sleep
    c. goto 1.

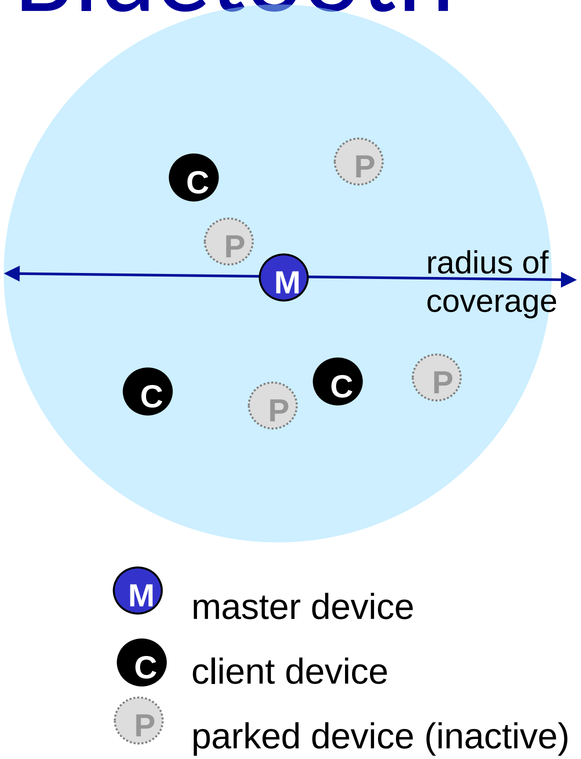
802.11: advanced capabilities

power management

- node-to-AP: "I am going to sleep until next beacon frame"
  - AP knows not to transmit frames to this node
  - node wakes up before next beacon frame
- beacon frame: contains list of mobiles with AP-to-mobile frames waiting to be sent
  - node will stay awake if AP-to-mobile frames to be sent; otherwise sleep again until next beacon frame

Personal area networks: Bluetooth

- TDM, 625 μsec sec. slot
- FDM: sender uses 79 frequency channels in known, pseudo-random order slot-to-slot (spread spectrum)
  - other devices/equipment not in piconet only interfere in some slots
- parked mode: clients can "go to sleep" (park) and later wakeup (to preserve battery)
- bootstrapping: nodes self-assemble (plug and play) into piconet



Summary of MAC protocols

- *channel partitioning,* by time, frequency or code
  - Time Division (TDMA), Frequency Division (FDMA), Code Division (CDMA)
- *random access* (dynamic),
  - ALOHA, S-ALOHA, CSMA, CSMA/CD
  - carrier sensing: easy in some technologies (wire), hard in others (wireless)
  - CSMA/CD used in (old-style, coax) Ethernet, and PowerLine
  - CSMA/CA used in 802.11
- *taking turns*
  - polling from central site, token passing
  - Bluetooth, FDDI, IBM Token Ring

MAC Addresses

- MAC (or LAN or physical or Ethernet) address:
  - function: *get frame from one interface to another physically-connected interface (same network)*
  - 48 bit MAC address (for most LANs)
    - *burned* in NIC ROM, nowadays usually software settable and set at boot time

```
awm22@rio:~$ ifconfig eth0
eth0      Link encap:Ethernet  HWaddr 00:30:48:fe:c0:64
          inet addr:128.232.33.4  Bcast:128.232.47.255  Mask:255.255.240.0
          inet6 addr: fe80::230:48ff:fefe:c064/64 Scope:Link
          UP BROADCAST RUNNING MULTICAST  MTU:1500  Metric:1
          RX packets:215084512 errors:252 dropped:25 overruns:0 frame:123
          TX packets:146711866 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:1000
          RX bytes:170815941033 (170.8 GB)  TX bytes:86755864270 (86.7 GB)
          Memory:f0000000-f0020000
```

LAN Address (more)

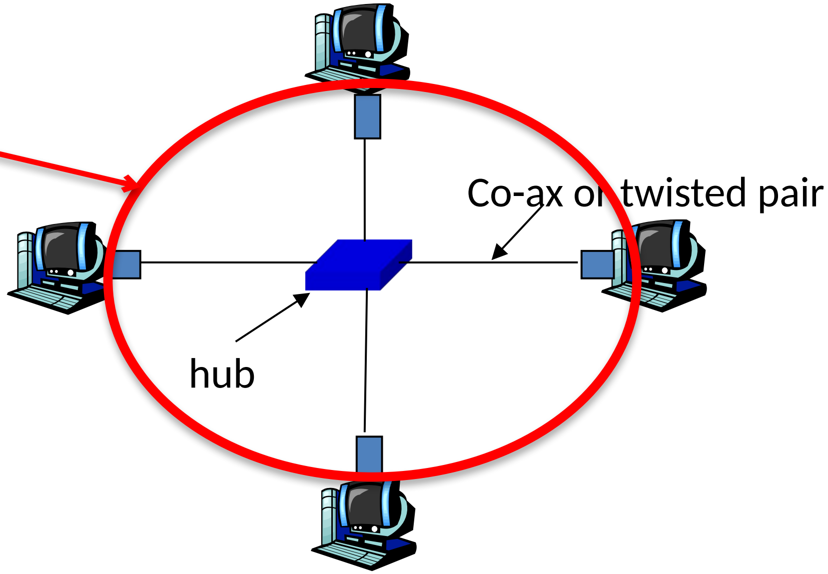
- MAC address allocation administered by IEEE
- manufacturer buys portion of MAC address space (to assure uniqueness)
- analogy:
  - (a) MAC address: like a National Insurance Number
  - (b) IP address: like a postal address
- MAC flat address ➜ portability
  - can move LAN card from one LAN to another
- IP hierarchical address NOT portable
  - address depends on IP subnet to which node is attached

Hubs

… physical-layer ("dumb") repeaters:

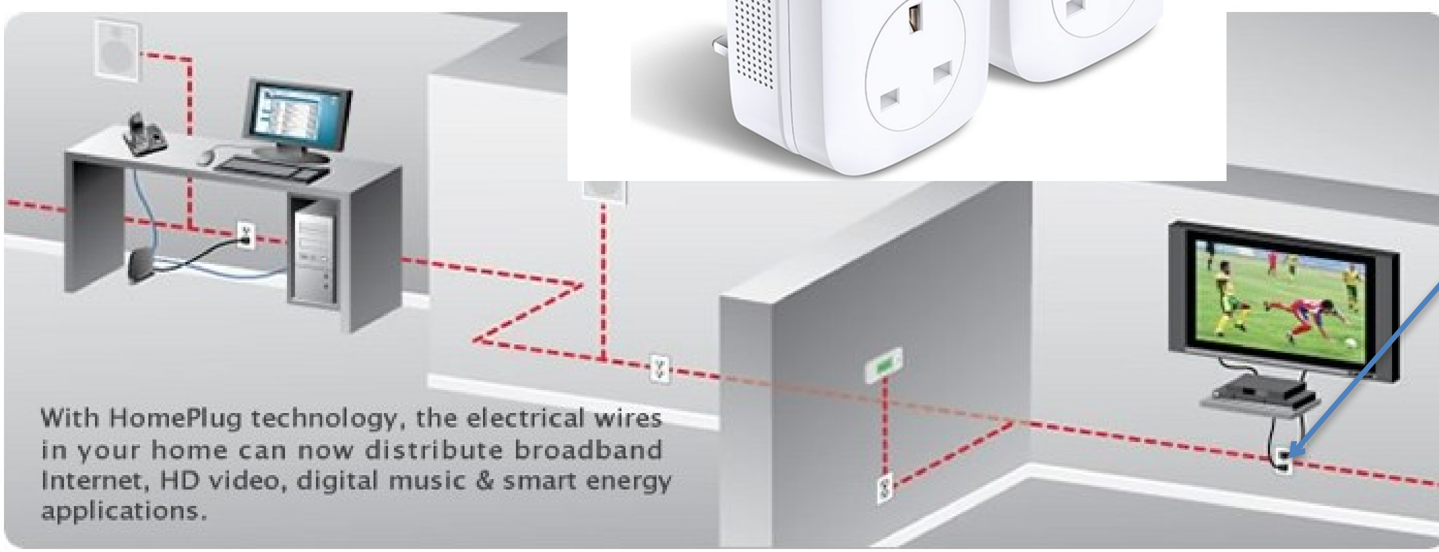
- bits coming in one link go out *all* other links at same rate
- all nodes connected to hub can collide with one another
- no frame buffering
- no CSMA/CD at hub: host NICs detect collisions

Collision Domain
in CSMA/CD *speak*

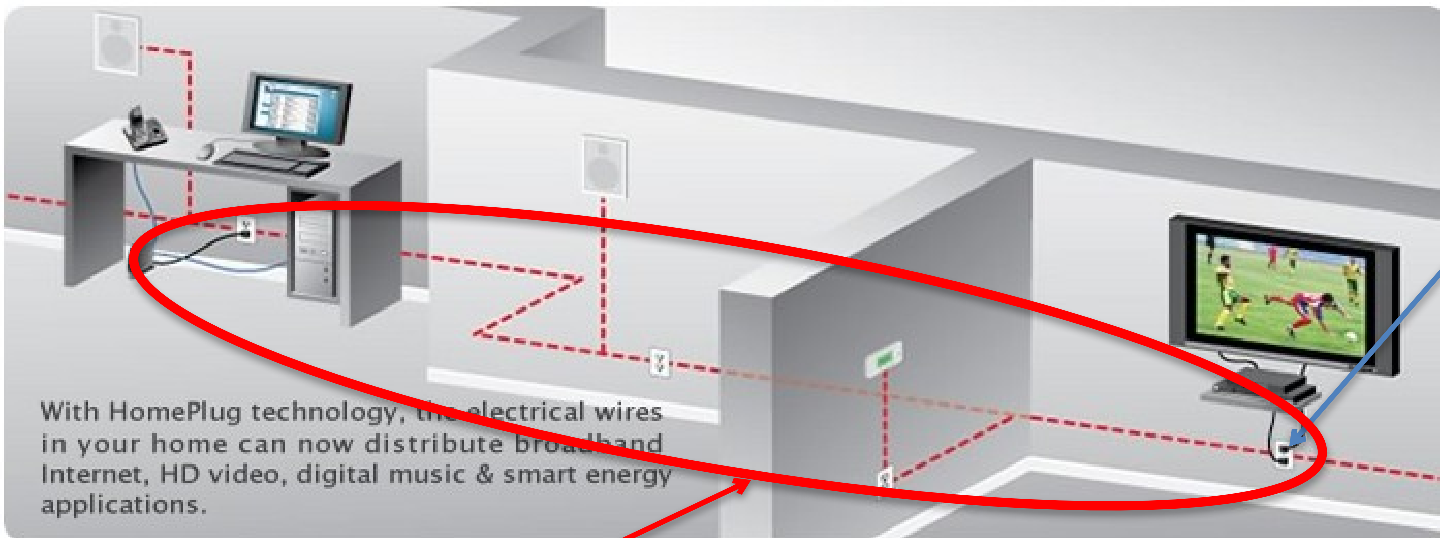


CSMA in our home

Home Plug Powerline Networking….



Home Plug and similar Powerline Networking….



Collision Domain
in CSMA *speak*

To secure network traffic on a specific HomePlug network, each set of adapters use an encryption key common to a specific HomePlug network

Switch (example: Ethernet Switch)

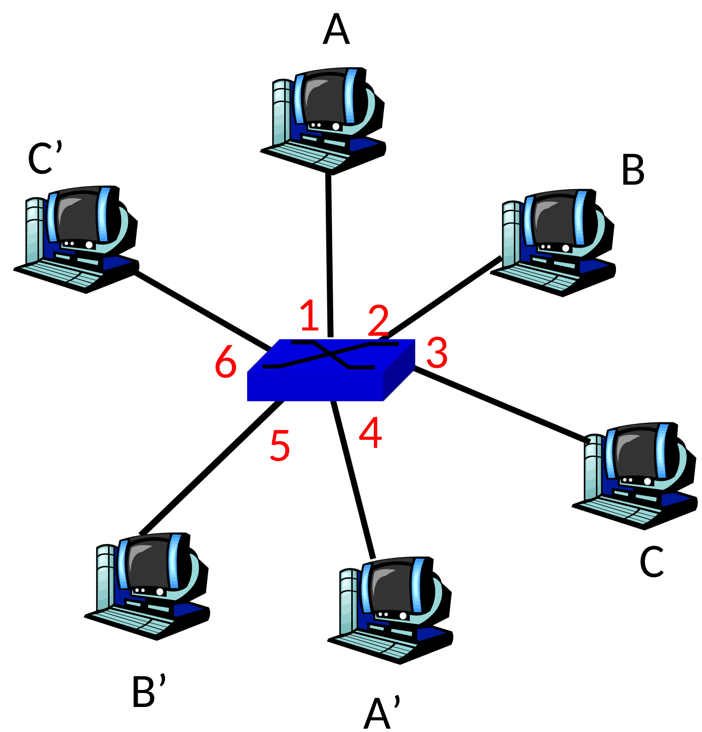
- link-layer device: smarter than hubs, take *active* role
  - store, forward Ethernet frames
  - examine incoming frame's MAC address, selectively forward frame to one-or-more outgoing links when frame is to be forwarded on segment, uses CSMA/CD to access segment
- *transparent*
  - hosts are unaware of presence of switches
- *plug-and-play, self-learning*
  - switches do not need to be configured

If you want to connect different physical media
(optical – copper – coax – wireless - ….)

you **NEED** a switch.
Why? (Because for each link the media access protocol is specialised)

Switch: allows *multiple* simultaneous transmissions

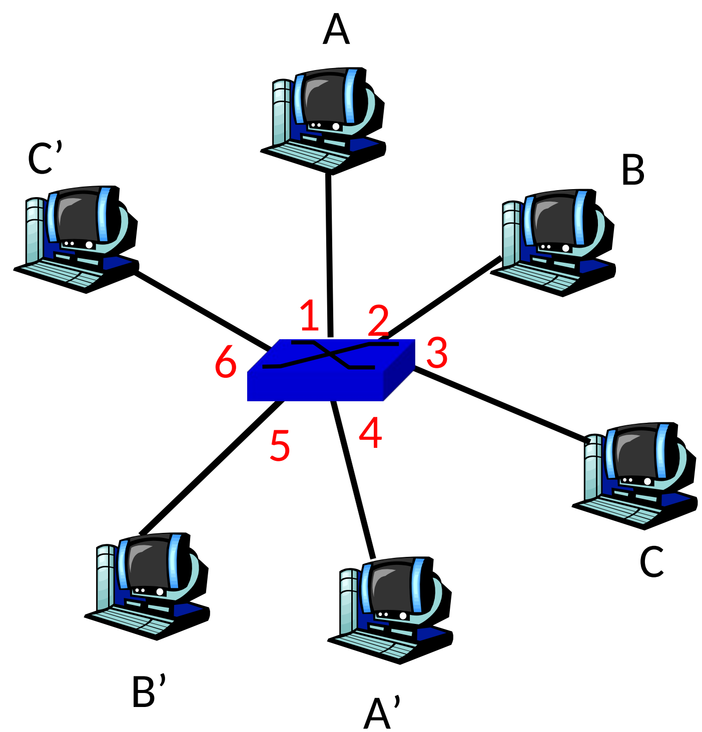
- Hosts have dedicated, direct connection to switch
- (Switches buffer packets)
- Ethernet protocol used on *each* incoming link, but no collisions; full duplex
  - each link is its own collision domain
- *switching:* A-to-A' and B-to-B' simultaneously, without collisions
  - not possible with dumb hub.



switch with six interfaces (1,2,3,4,5,6)

Switch Table

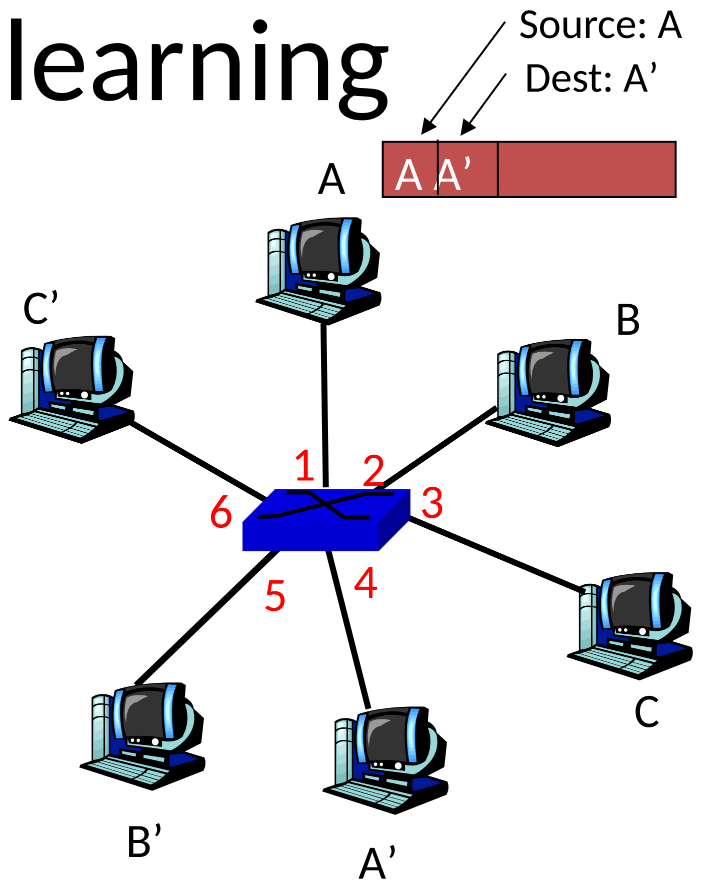
- Q: how does switch know that A' reachable via interface 4, B' reachable via interface 5?
- A: each switch has a switch table, each entry:
  - (MAC address of host, interface to reach host, time stamp)
- looks like a routing table!
- Q: how are entries created, maintained in switch table?
  - something like a routing protocol?



switch with six interfaces (1,2,3,4,5,6)

Switch: self-learning

- 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



MAC addr	interface	TTL
A	*1*	*60*

Switch table (initially empty)

Switch: frame filtering/forwarding

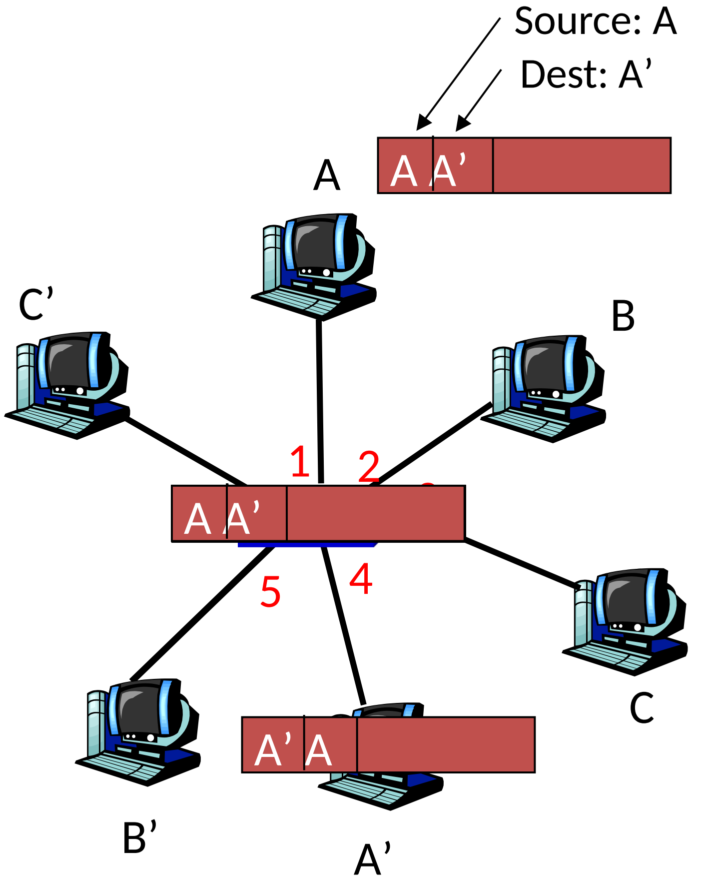
When frame received:

1. record link associated with sending host
2. index switch table using MAC dest address
3. **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

Self-learning, forwarding: example

- frame destination unknown: *flood*
- destination A location known: selective send

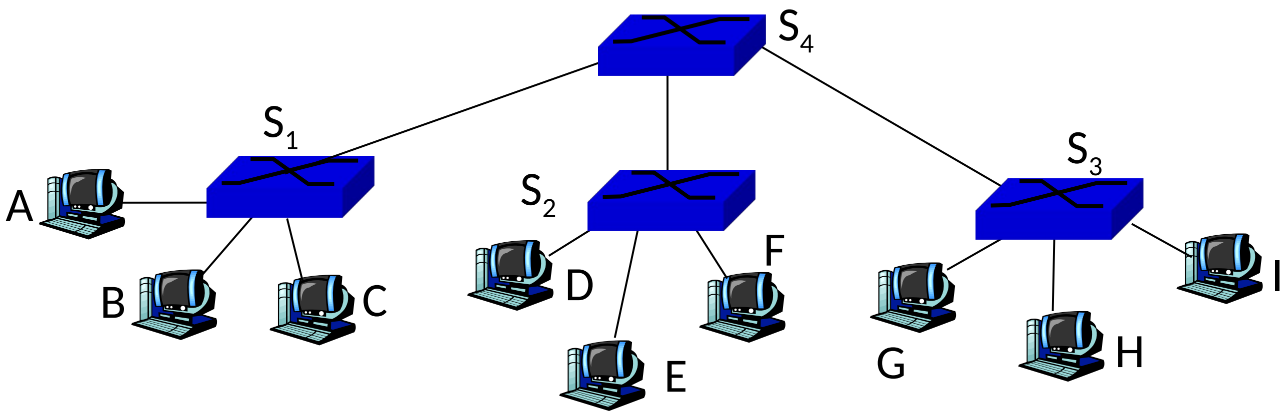


MAC addr	interface	TTL
A	*1*	*60*
A'	*4*	*60*

Switch table (initially empty)

Interconnecting switches

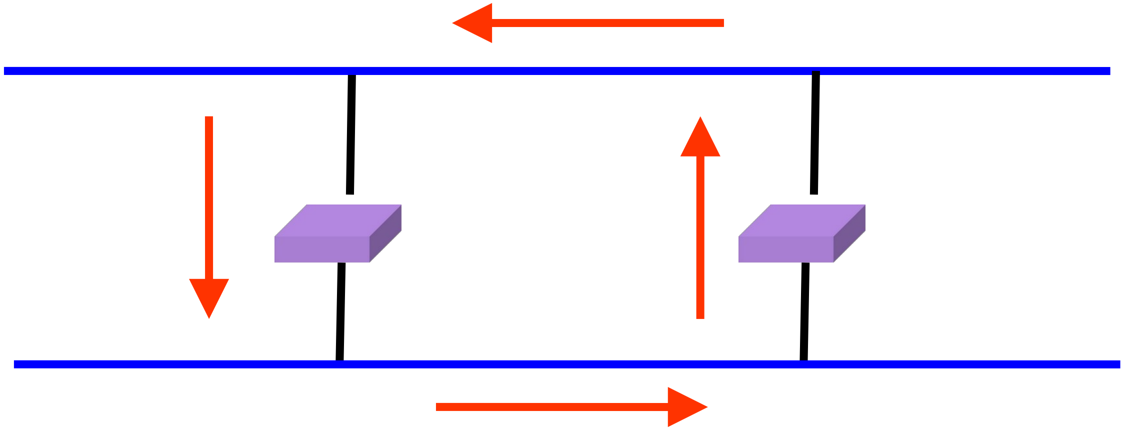
- switches can be connected together



- Q: sending from A to G - how does S_1 know to forward frame destined to F via S_4 and S_3?
- A: self learning! (works exactly the same as in single-switch case – flood/forward/drop)

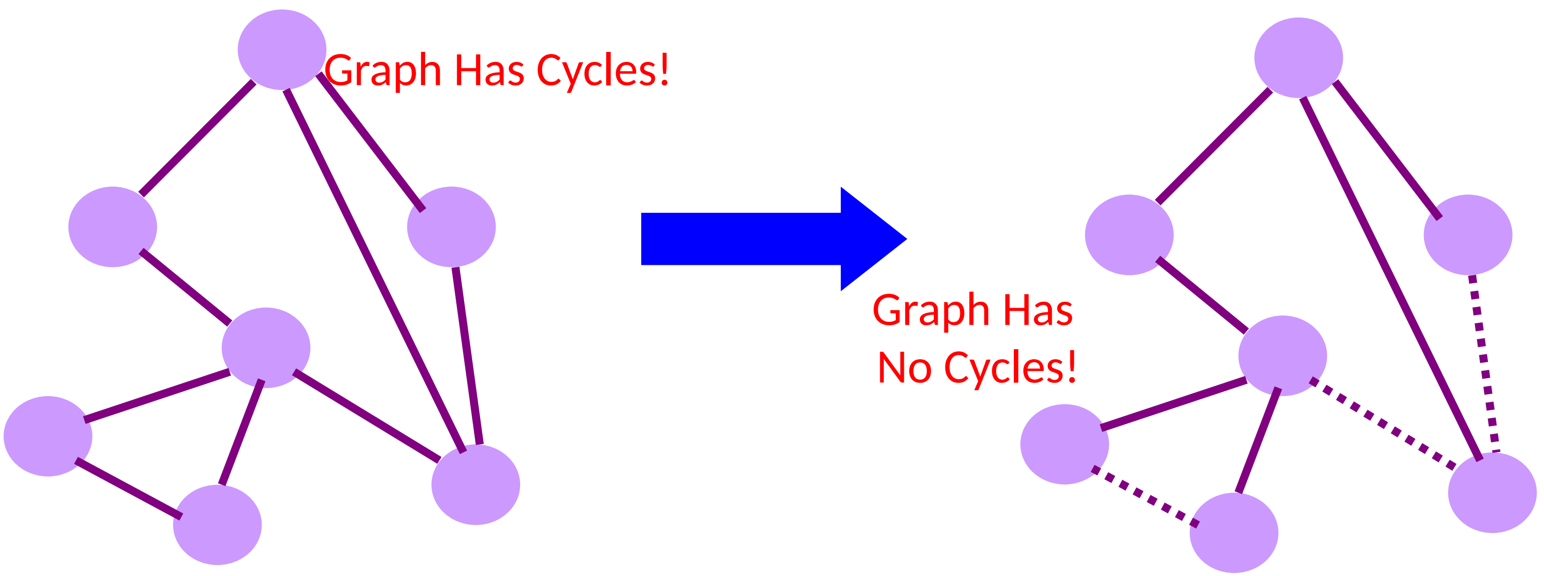
Flooding Can Lead to Loops

- Flooding can lead to forwarding loops
  - E.g., if the network contains a cycle of switches
  - "Broadcast storm"



Solution: Spanning Trees

- Ensure the forwarding topology has no loops
  - Avoid using some of the links when flooding
  - … to prevent loop from forming
- Spanning tree
  - Sub-graph that covers all vertices but *contains no cycles*
  - Links not in the spanning tree do not forward frames



What Do We Know?

- *"Spanning tree algorithm is an algorithm to create a tree out of a graph that includes all nodes with a minimum number of edges connecting to vertices."*

- Shortest paths to (or from) a node form a tree

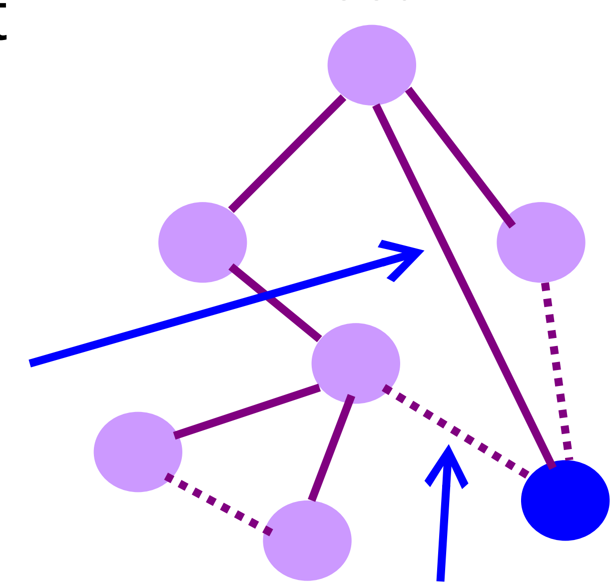
- So, algorithm has two aspects :
  - Pick a root
  - Compute shortest paths to it

- Only keep the links on shortest-path

Constructing a Spanning Tree

- Switches need to elect a root
  - The switch w/ smallest identifier (MAC addr)
- Each switch determines if each interface is on the shortest path from the root
  - Excludes it from the tree if not

- Messages (Y, d, X)
  - From node X
  - Proposing Y as the root
  - And the distance is d

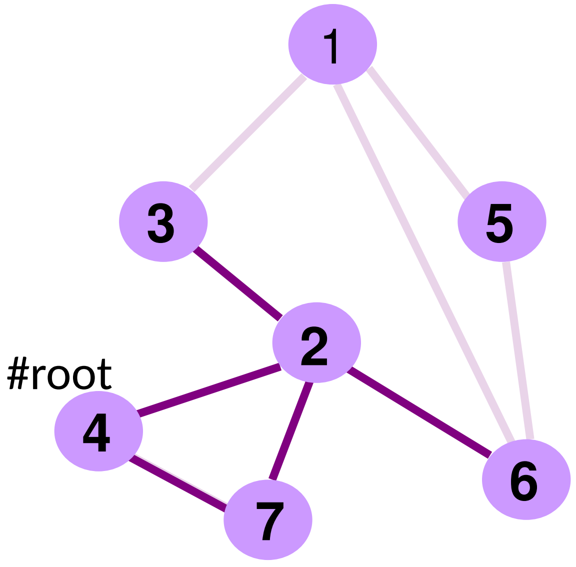


Steps in Spanning Tree Algorithm

- Initially, each switch proposes itself as the root
  - Switch sends a message out every interface
  - … proposing itself as the root with distance 0
  - Example: switch X announces (X, 0, X)
- Switches update their view of the root
  - Upon receiving message (Y, d, Z) from Z, check Y's id
  - If new id smaller, start viewing that switch as root
- Switches compute their distance from the root
  - Add 1 to the distance received from a neighbor
  - Identify interfaces not on shortest path to the root
  - … and exclude them from the spanning tree
- If root or shortest distance to it changed, "flood" updated message (Y, d+1, X)

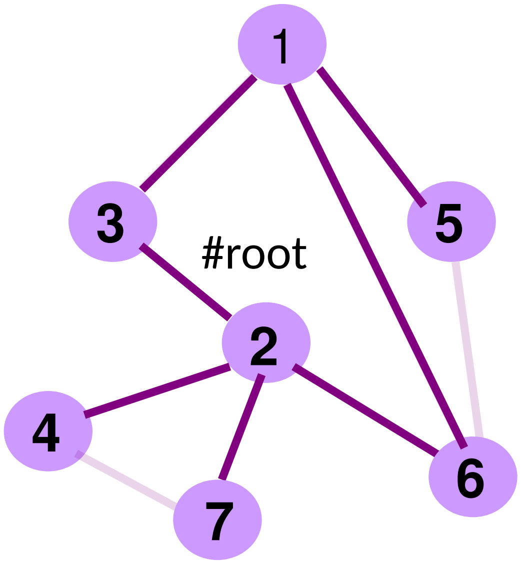
Example From Switch #4's Viewpoint

- Switch #4 thinks it is the root
  - Sends (4, 0, 4) message to 2 and 7
- Then, switch #4 hears from #2
  - Receives (2, 0, 2) message from 2
  - … and thinks that #2 is the root
  - And realizes it is just one hop away
- Then, switch #4 hears from #7
  - Receives (2, 1, 7) from 7
  - And realizes this is a longer path
  - So, prefers its own one-hop path
  - And removes 4-7 link from the tree



Example From Switch #4's Viewpoint

- Switch #2 hears about switch #1
  - Switch 2 hears (1, 1, 3) from 3
  - Switch 2 starts treating 1 as root
  - And sends (1, 2, 2) to neighbors
- Switch #4 hears from switch #2
  - Switch 4 starts treating 1 as root
  - And sends (1, 3, 4) to neighbors
- Switch #4 hears from switch #7
  - Switch 4 receives (1, 3, 7) from 7
  - And realizes this is a longer path
  - So, prefers its own three-hop path
  - And removes 4-7 link from the tree



Robust Spanning Tree Algorithm

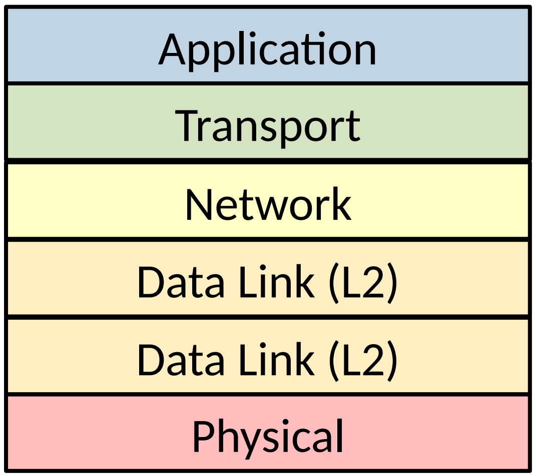
- Algorithm must react to failures
  - Failure of the root node
    - Need to elect a new root, with the next lowest identifier
  - Failure of other switches and links
    - Need to recompute the spanning tree
- Root switch continues sending messages
  - Periodically reannouncing itself as the root (1, 0, 1)
  - Other switches continue forwarding messages
- Detecting failures through timeout (soft state)
  - If no word from root, times out and claims to be the root
  - Delay in reestablishing spanning tree is ***major problem***
  - Work on rapid spanning tree algorithms…

Given a switch-tree of a given size, link length, speed of computation, …

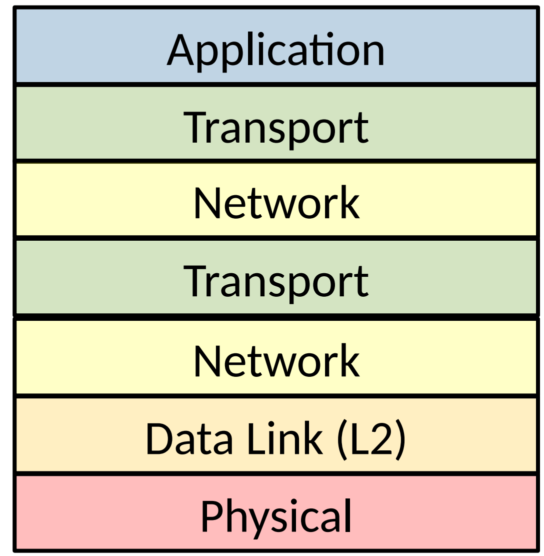
How long does a failure take to rectify?

Weirder "Data Link Layer" Networks

VLAN



VPN



Datacenter

"so you think your LAN has a lot of computers…."

Datacenter networks

10's to 100's of thousands of hosts, often closely coupled, in close proximity:

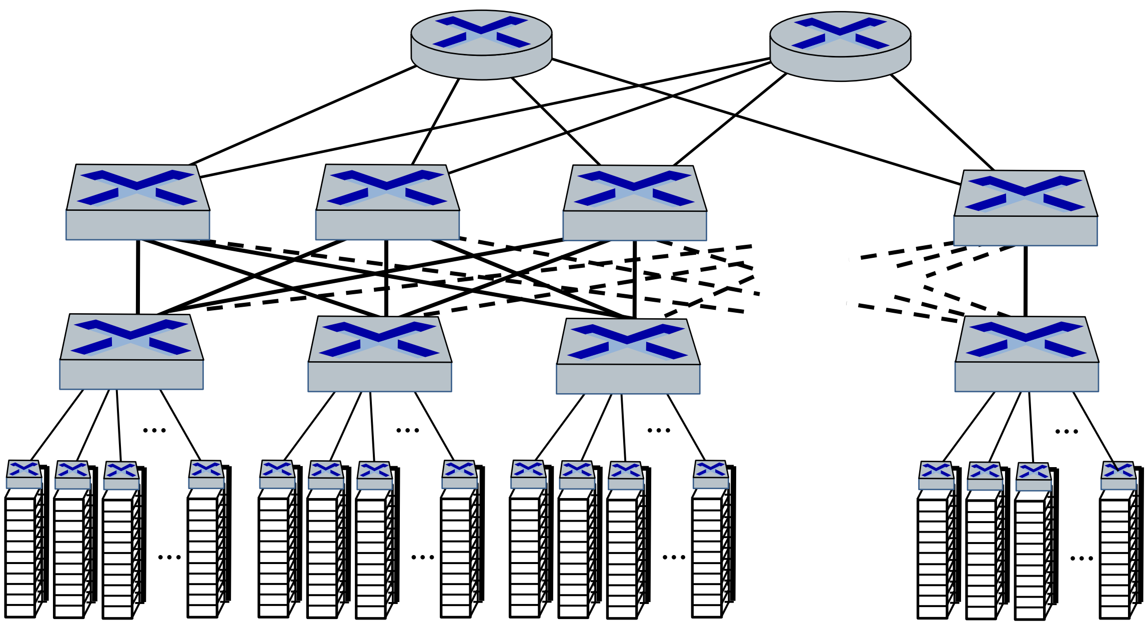
- e-business (e.g. Amazon)
- content-servers (e.g., YouTube, Akamai, Apple, Microsoft)
- search engines, data mining (e.g., Google)

challenges:

- multiple applications, each serving massive numbers of clients
- reliability
- managing/balancing load, avoiding processing, networking, data bottlenecks

Inside a 40-ft Microsoft container, Chicago data center

Datacenter networks: network elements



Border routers

- connections outside datacenter

Tier-1 switches

- connecting to ~16 T-2s below

Tier-2 switches

- connecting to ~16 TORs below

Top of Rack (TOR) switch

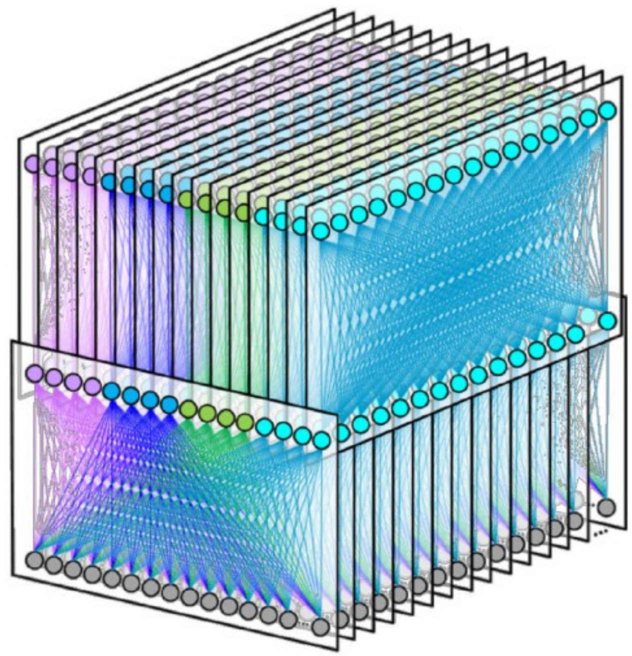
- one per rack
- 40-100Gbps Ethernet to blades

Server racks

- 20- 40 server blades: hosts

Datacenter networks: network elements

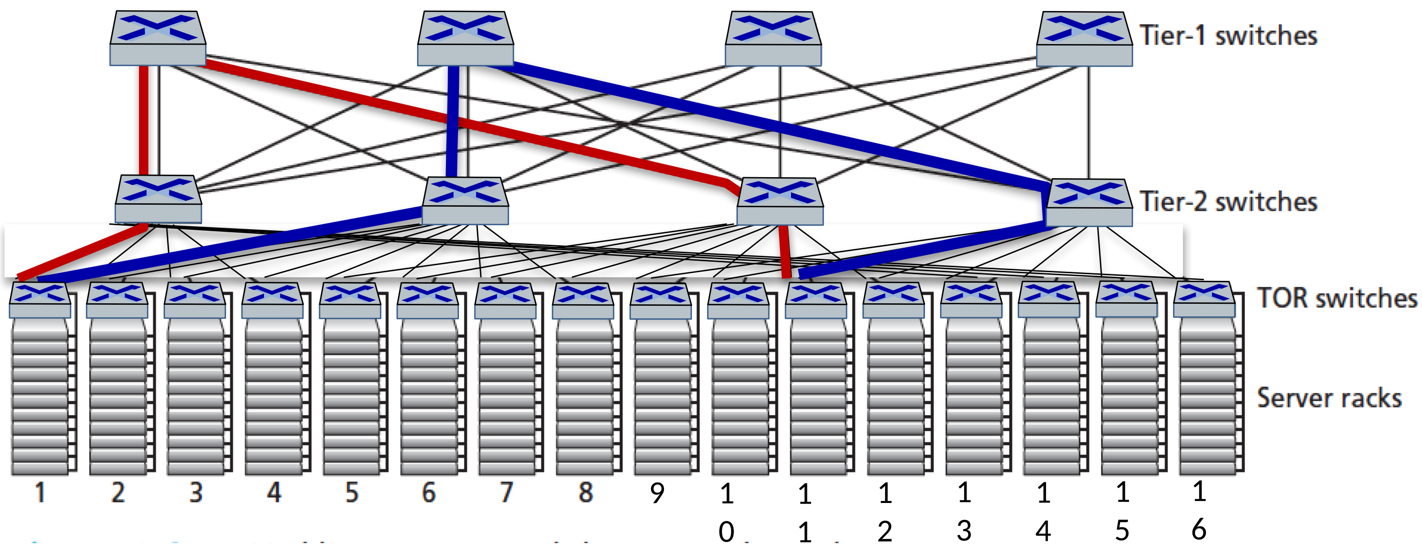
Facebook F16 data center network topology:



https://engineering.fb.com/data-center-engineering/f16-minipack/ (posted 3/2019)

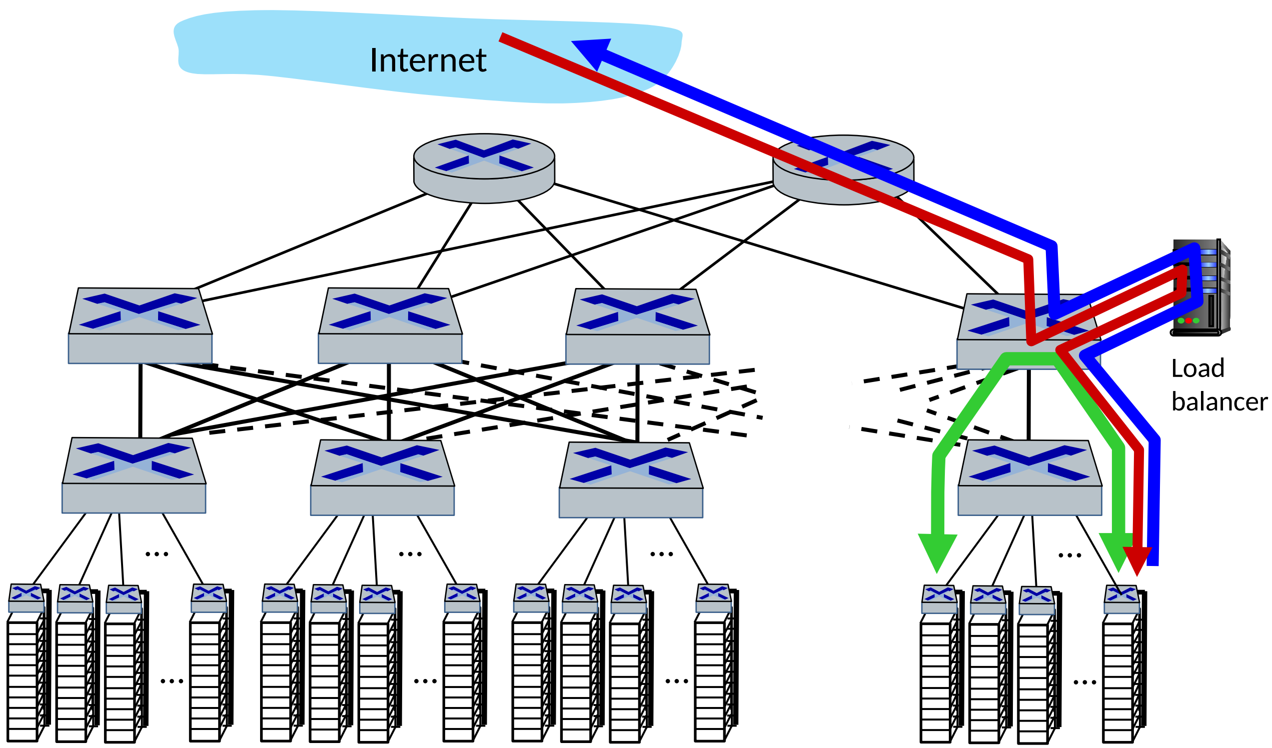
Datacenter networks: multipath

- rich interconnection among switches, racks:
  - increased throughput between racks (multiple routing paths possible)
  - increased reliability via redundancy



two disjoint paths highlighted between racks 1 and 11

Datacenter networks: application-layer routing



load balancer: application-layer routing

- receives external client requests
- directs workload within data center
- returns results to external client (hiding data center internals from client)

Summary

- principles behind data link layer services:
  - error detection, correction
  - sharing a broadcast channel: multiple access
  - link layer addressing
- instantiation and implementation of various link layer technologies
  - Ethernet
  - switched LANS
  - WiFi
- algorithms
  - Binary Exponential Backoff
  - Spanning Tree