L13 – Wireless Networks

50.012 Networks

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Cohort 1: TT7&8 (1.409-10)

Cohort 2: TT24&25 (2.503-4)

Introduction

- It is estimated that half of devices on internet are connected through wireless links![1]
    - With the expected rise of IoT, probably >75% by 2020
- How are wireless links different from wired links?
- This week: wireless communication
    - Overview of topology and operating modes
    - Activity on shared medium access (finally)
    - Physical Layer, fundamental differences in shared medium
- Note: parts of this slide set are from Kurose & Ross chapters 5 and 6 slide sets

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[1]Source: Kurose & Ross slide set

Wireless Networks

Introduction to Wireless Medium

- Fundamental differences to wired medium:
  - Dynamic, changing over time
  - Half-Duplex (until now)
  - Limited communication bandwidth & range
  - Higher error rate
  - Interference from other communication networks
- Broadcast medium
  - Shared Bandwidth among users
  - Everyone in range sees all transmissions

Licensed bands

- The (theoretically infinite) spectrum is segmented into bands
- Each band can be governed by different regulations
- Well-known frequency bands:
  - GSM-900: 880-960 MHz
  - FM radio: 87.9 to 107.9 MHz
  - ISM bands: among others, 2.4 GHz and 5.8 GHz
- The relevant spectrum is mostly allocated
  - New applications will have to co-exist with existing solutions
  - Exclusive use rights of new bands can be sold for a lot of money
    - In 2000, German UMTS bands (1920-1980 MHz) were auctioned for a total of 50.8 billion EUR

(Very) Detailed view of US wireless bands

https://www.ntia.doc.gov/files/ntia/publications/2003-allochrt.pdf

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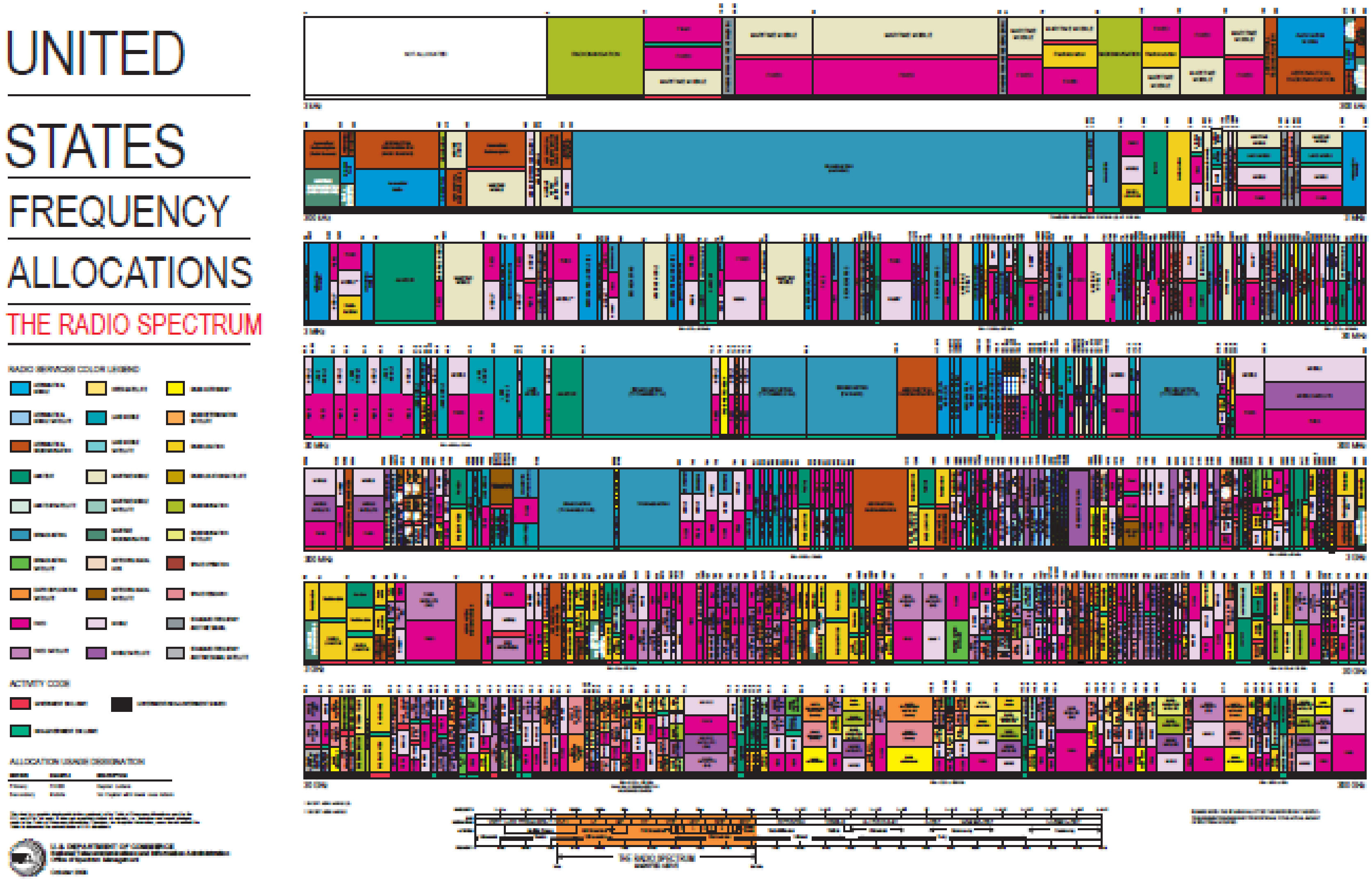
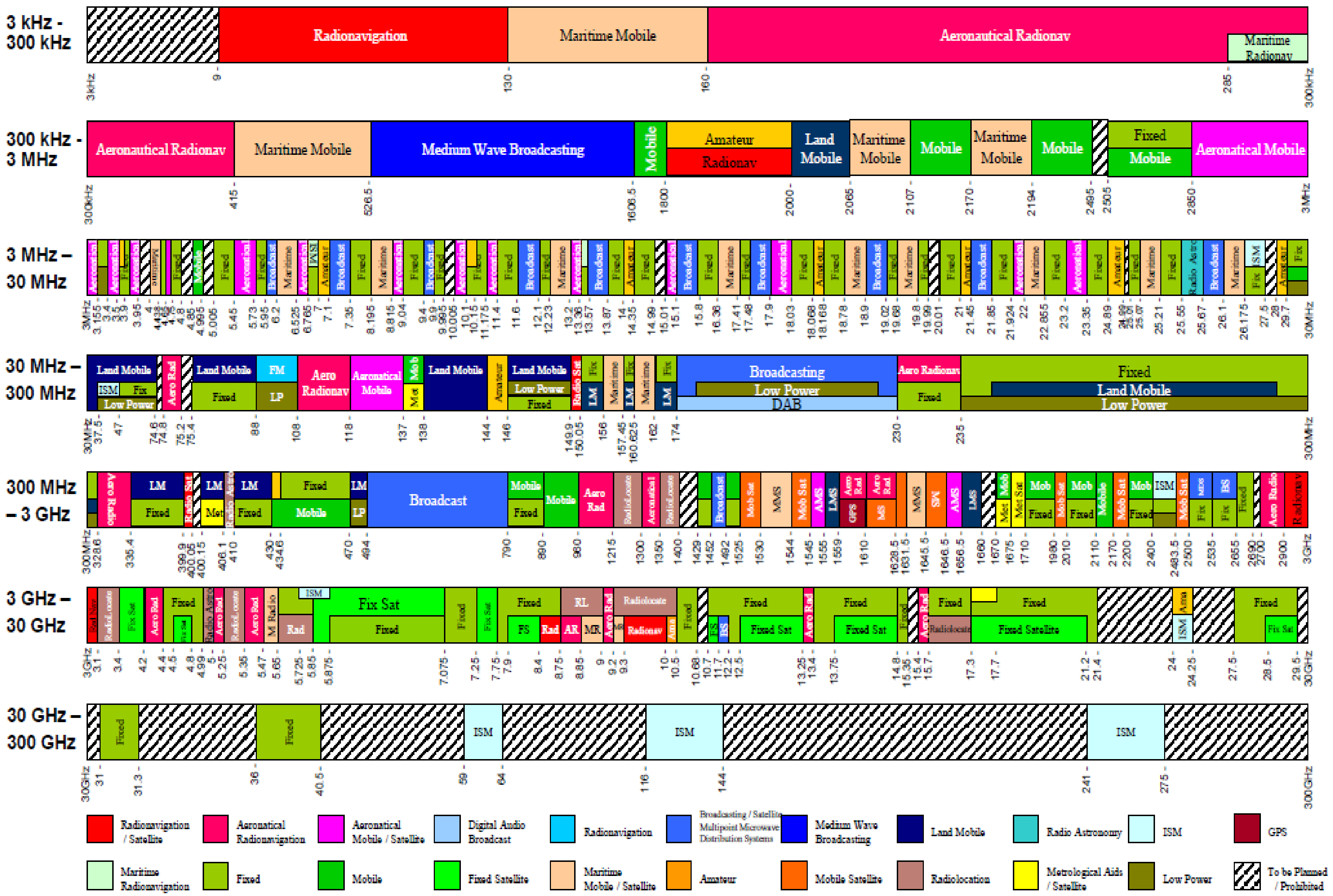


Singapore Spectrum Allocation Chart

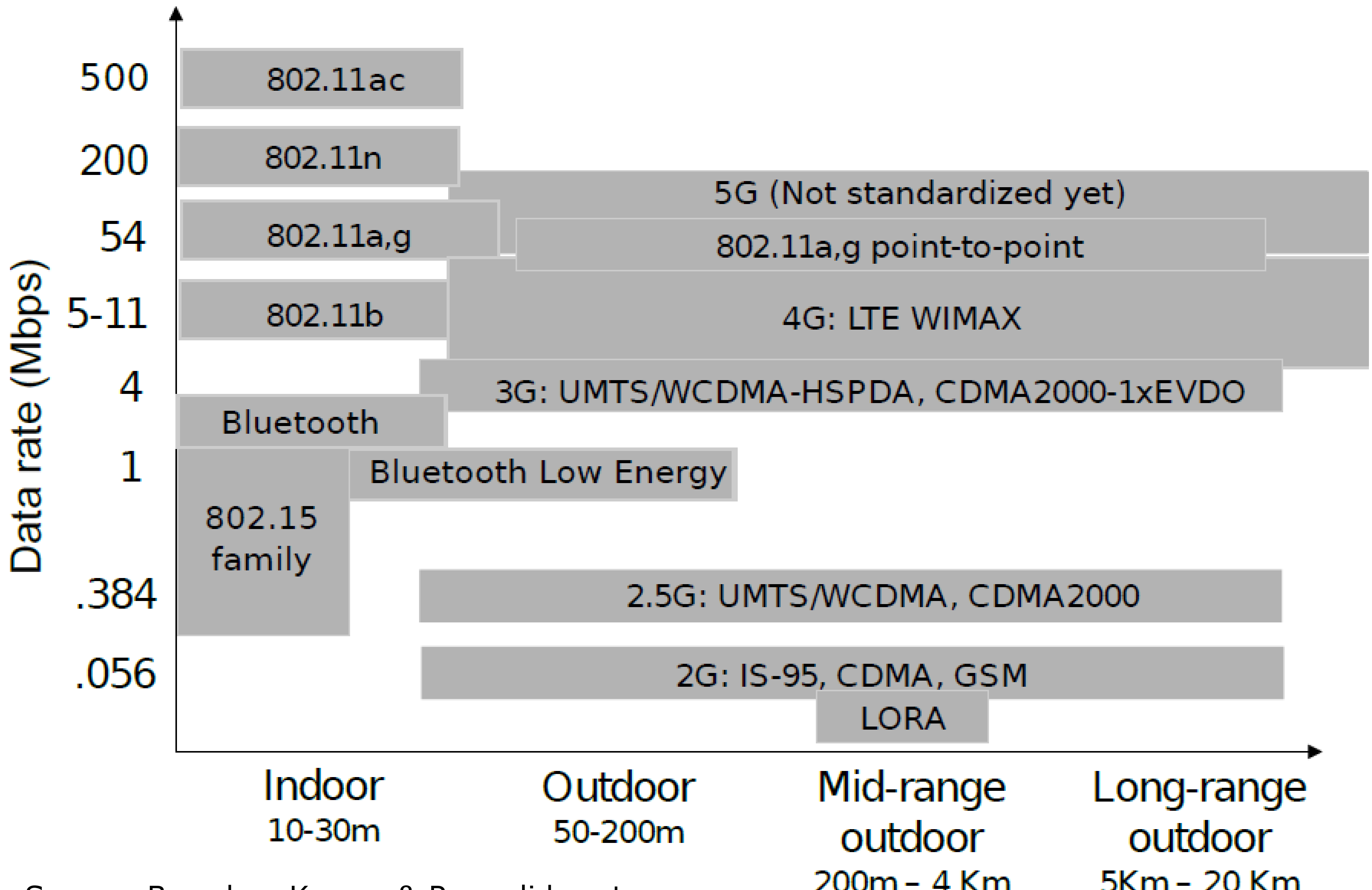
*Frequency Spectrum is not drawn to scale.



Industrial, scientific & medical (ISM) band

- The ISM band is now very important for wireless networks
- Originally reserved for non-communication
  - E.g. Microwaves
  - Pacemakers
- Covers a set of bands, two of them 2.4 GHz and 5.8 GHz
- Now used for short-range communications
  - Bluetooth
  - Cordless digital hand phones
  - Baby monitors
  - 802.11
- All these devices can potentially interfere with each other
- Regulations define max signal strength for ISM transmissions

Comparison of Wireless Standards



Source: Based on Kurose & Ross slide set

Wireless Link Characteristics

important differences from wired link ….

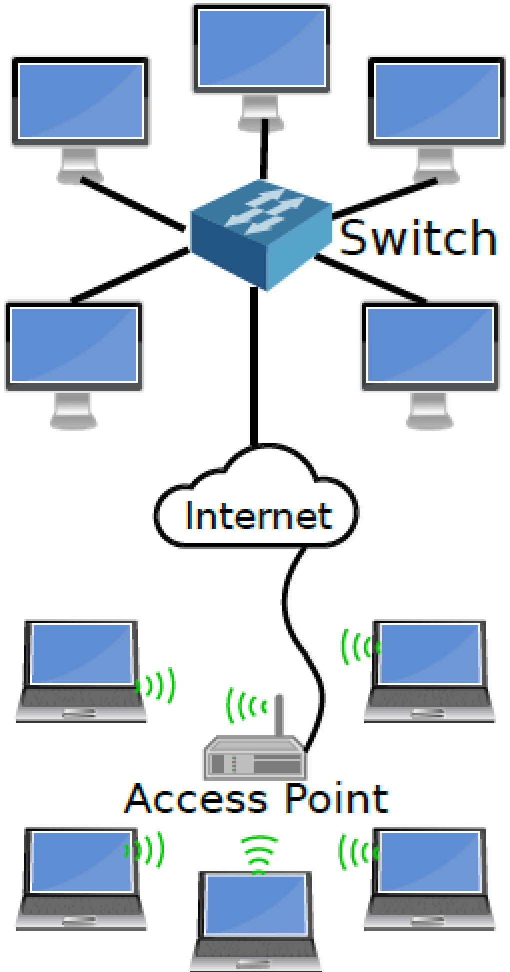
- *decreased signal strength:* radio signal attenuates as it propagates through matter (path loss)
- *interference from other sources:* standardized wireless network frequencies (e.g., 2.4 GHz) shared by other devices (e.g., phone); devices (motors) interfere as well
- *multipath propagation:* radio signal reflects off objects ground, arriving ad destination at slightly different times

…. make communication across (even a point to point) wireless link much more "difficult"

Source: Kurose & Ross slide set

Layout of Wireless Networks

- In wired networks:
  - Hosts, Ethernet cables, switches, Routers,
  - Switches connects hosts, provide link to routers
- In wireless networks: Not too different!
  - Wireless Hosts, Access points connecting to wired networks
  - Access Point (AP) coordinates communication between wireless hosts
  - AP also translates to wired network for outgoing traffic
- But this is only one possible scenario, *infrastructure mode*
- Also: wireless users can be mobile, move from one AP to next



Operating Modes (Single Hop)

- *Infrastructure Mode:*
  - One of more Access Points provide permanent static infrastructure
  - (Mobile) wireless hosts can associate to one of them
  - AP coordinates channel access
- *Ad-Hoc mode:*
  - No access points are used as infrastructure
  - Wireless hosts dynamically connect to their peers
  - Without higher-layer routing protocol, only neighbors can exchange messages
  - Channel access is uncoordinated
- How are neighbors defined? Are not all local nodes neighbors?

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- No, due to limited communication range in wireless
- Only nodes that can directly talk are neighbors

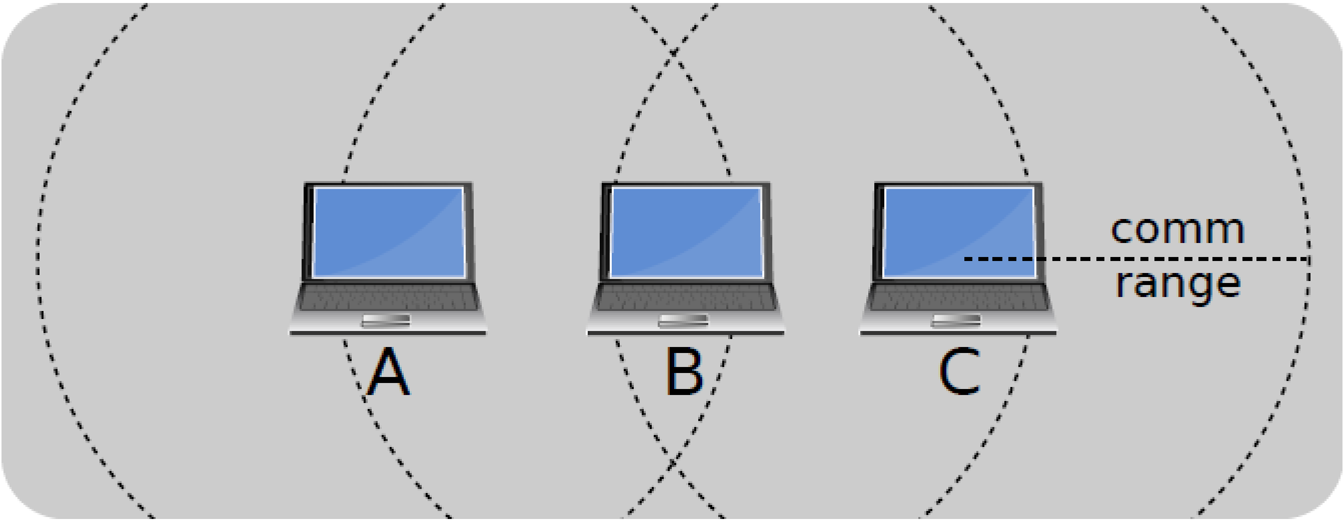
Wireless network taxonomy

- *Single hop, infrastructure based:* all communication is between base station and wireless host over a single wireless hop (eg 802.11, 4G, LTE).
- *Single hop, infrastructure-less:* No base station. Single hop. One of the nodes may act as coordinator. (eg. Bluetooth).
- *Multi-hop, infrastructure based:* Base station is present. However some wireless may have to rely on other wireless nodes to relay their messages to the base station (eg. wireless mesh networks).
- *Multi-hop, infrastructure based:* no base station, no connection to larger Internet. May have to relay to reach other a given wireless node MANET, VANET

Source: Based on Kurose & Ross text

Hidden Node Problem

- Wireless networks use *broadcast medium*
- Although shared medium, not every node sees all transmissions
  - For example, B can see A & C, but A cannot see C
  - Called *Hidden Node* problem



Example of hidden node problem

Introducing Multi-Hop Paths

- Without message forwarding, only single-hop path communication is possible in wireless
  - If AP is not reachable with single hop, node cannot reach Internet
- How to solve this?

Introducing Multi-Hop Paths

- Without message forwarding, only single-hop path communication is possible in wireless
  - If AP is not reachable with single hop, node cannot reach Internet
- How to solve this?

- Ask neighbors to re-broadcast your traffic.
- Eventually, traffic will arrive at target node
- Implemented naively, this will quickly drown the network in re-broadcasted traffic
- Research into this lead to MANETs and mesh networks

Operating Modes (Multi-Hop)

- MANETs/VANETs (Mobile/Vehicular Ad-hoc Networks):
  - No fixed infrastructure, no internet access
  - Uses multi-hop forwarding among peers
- Mesh Networks:
  - APs provide internet connectivity
  - Hosts also forward communication of other wireless hosts
  - Forwarding hosts extend the range for the infrastructure
- But first, lets discuss (un)coordinated shared medium access

Shared Medium Access

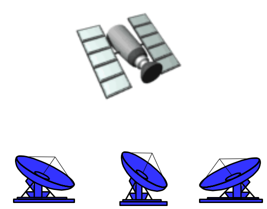
Multiple access links, protocols

two types of "links":

- point-to-point
  - PPP for dial-up access
  - point-to-point link between Ethernet switch, host
- *broadcast (shared wire or medium)*
  - old-fashioned Ethernet
  - upstream HFC
  - 802.11 wireless LAN

shared wire (e.g., cabled Ethernet)

shared RF (e.g., 802.11 WiFi)



shared RF (satellite)

humans at a cocktail party (shared air, acoustical)

Shared Medium Access Activity Part 1

- Goal of this activity: think about shared medium access
- In step 1, everyone prepares 3 sentences that (in total) take about 15 seconds to say
  - Content does not matter, but it should be in English
    - Example: "My favorite color is blue. My favorite animal is a tiger. My favorite car is a beetle."
  - Do not tell others about your sentences
- You have a couple of minutes, please remember your sentences or write them down
- Let me know if everyone on your table is done with its selection

Shared Medium Access Activity Part 2

- Your goal is to learn other group member's sentences
- After my signal, your group has n/2 minutes to exchange everyone's information
- Exchange the sentences one by one, or all together
- Ideally, close your eyes
- You can only talk to each other, no writing, handwaving, etc.
- Questions:
  - How much information did you get successfully?
  - Which problems did you face?
  - How did you solve these problems?

Discussion on Shared Medium Access

- Central Problems in Shared Medium Access
  - How to coordinate the sequence of transmissions among users?
  - How to detect that you can start transmission?
  - How to signal that you are done transmitting?
  - How to detect collisions?
  - How to react to collisions?
- We now look at schemes to coordinate channel access
  - Centrally coordinated vs. uncoordinated

Multiple access protocols

- single shared broadcast channel
- two or more simultaneous transmissions by nodes: interference
  - *collision* if node receives two or more signals at the same time

multiple access protocol

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

An ideal multiple access protocol

given: broadcast channel of rate R bps

desiderata:

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: taxonomy

three broad classes:

- *channel partitioning*
  - divide channel into smaller "pieces" (time slots, frequency, code)
  - 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

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 ➜ "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

Source: Kurose & Ross slide set

Slotted ALOHA

assumptions:

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

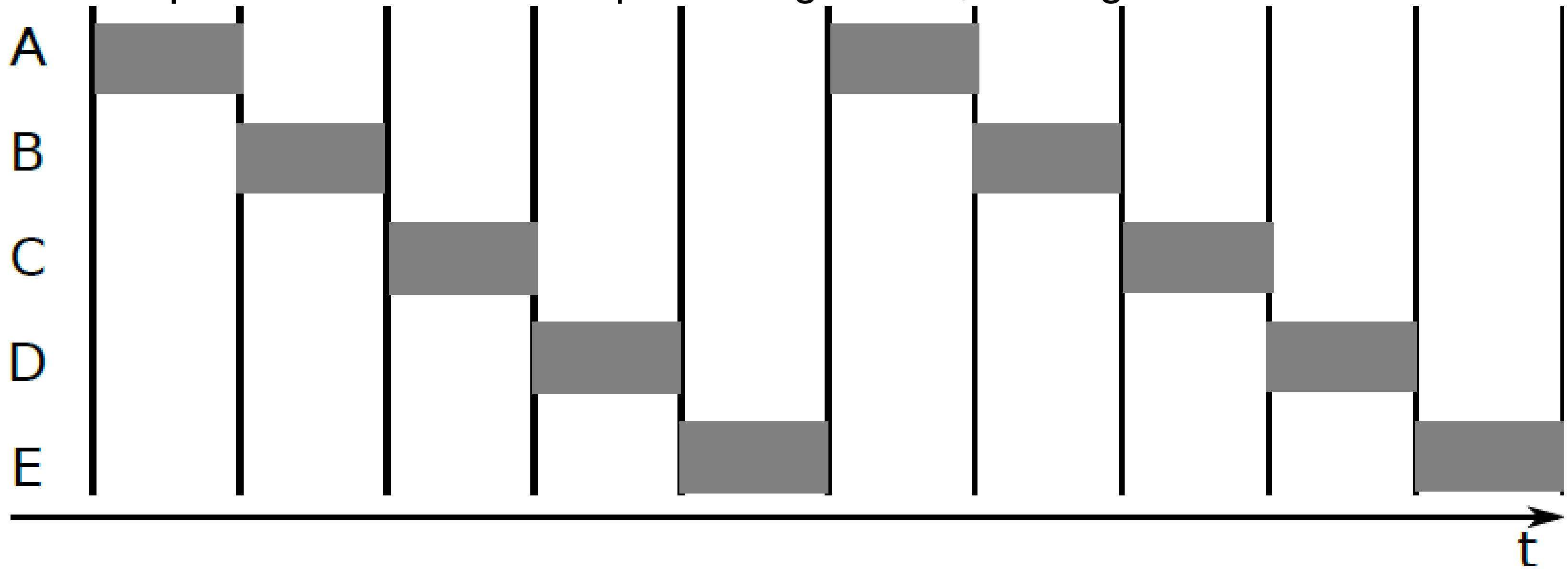
operation:

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

Source: Kurose & Ross slide set

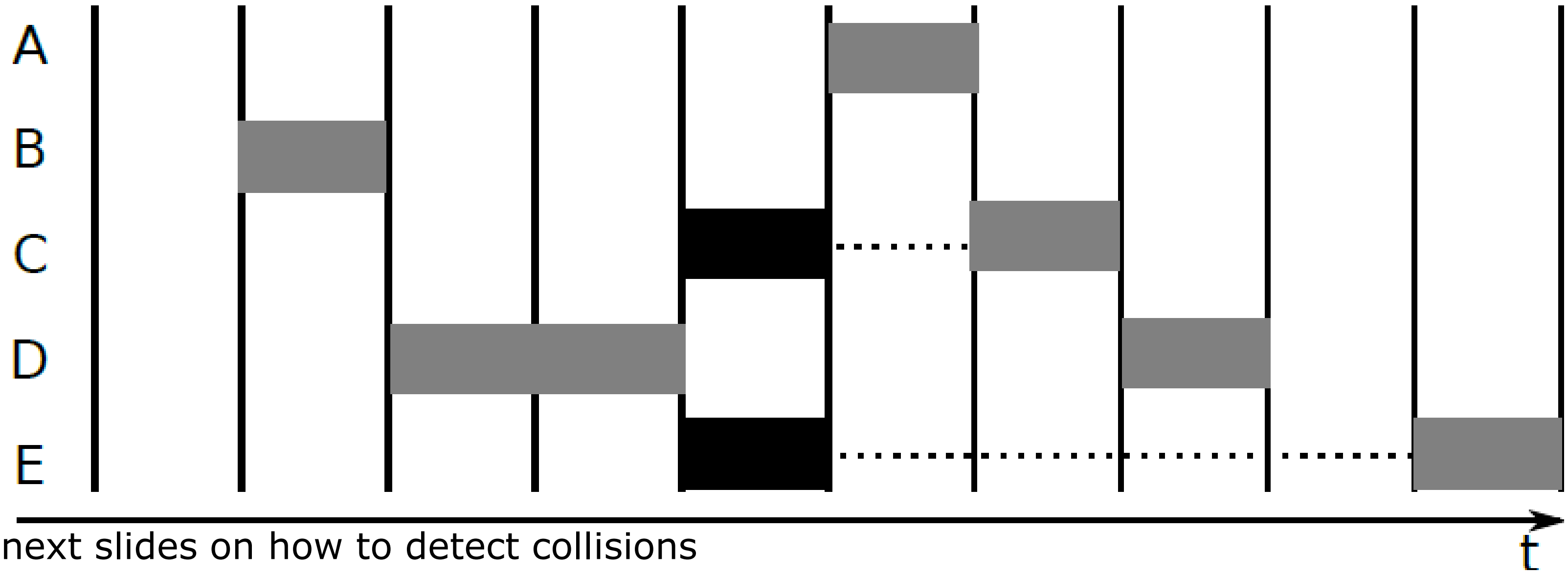
Time Division Multiple Access (TDMA)

- Requires central coordination for access
- Simple scheme:
  - Use discrete time slots
  - Every node gets dedicated time slot to transmit
  - No collisions possible!
- Not very efficient: if no data to send, slot is unused
- Dynamic variants exist, that allocate slots based on demand
- Disadvantages:
  - Requires infrastructure & pre-configuration, management effort



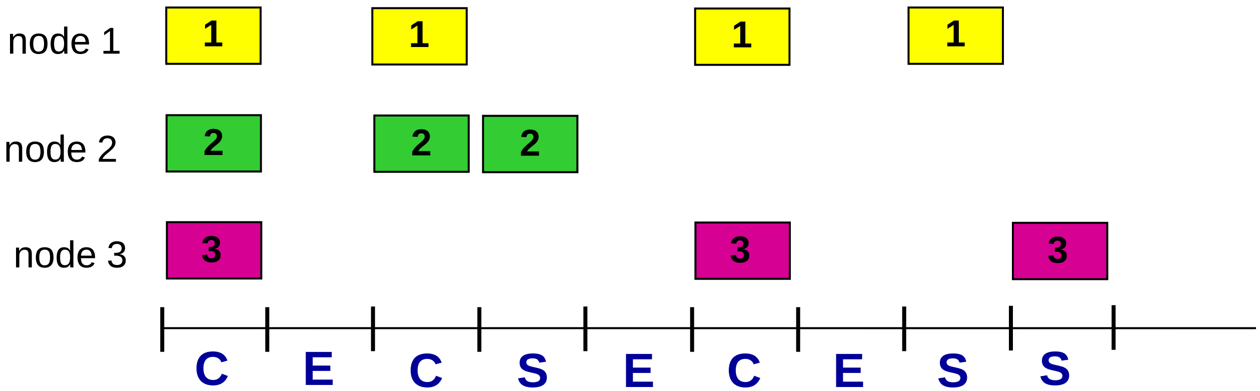
(Slotted) ALOHA

- "TDMA without coordination"
- Time is again divided into discrete slots of uniform length
- Nodes will transmit at start of slot, max one slot
    - Note: Time-sync required
- No predefined sequence for channel access
- If two nodes transmit at same time -> collision!
    - If collision detected, retransmit after random delay
- ALOHA works surprisingly well for low effort, low load networks



[2]See next slides on how to detect collisions

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
- clock synchronization

Source: Kurose & Ross slide set

Slotted ALOHA: efficiency

efficiency: long-run fraction of successful slots (many nodes, all with many frames to send)

- *suppose: N* nodes with many frames to send, each transmits in slot with probability *p*
- prob that given node has success in a slot = $p(1-p)^{N-1}$
- prob that *any* node has a success = $Np(1-p)^{N-1}$

- max efficiency: 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:

max efficiency = .37

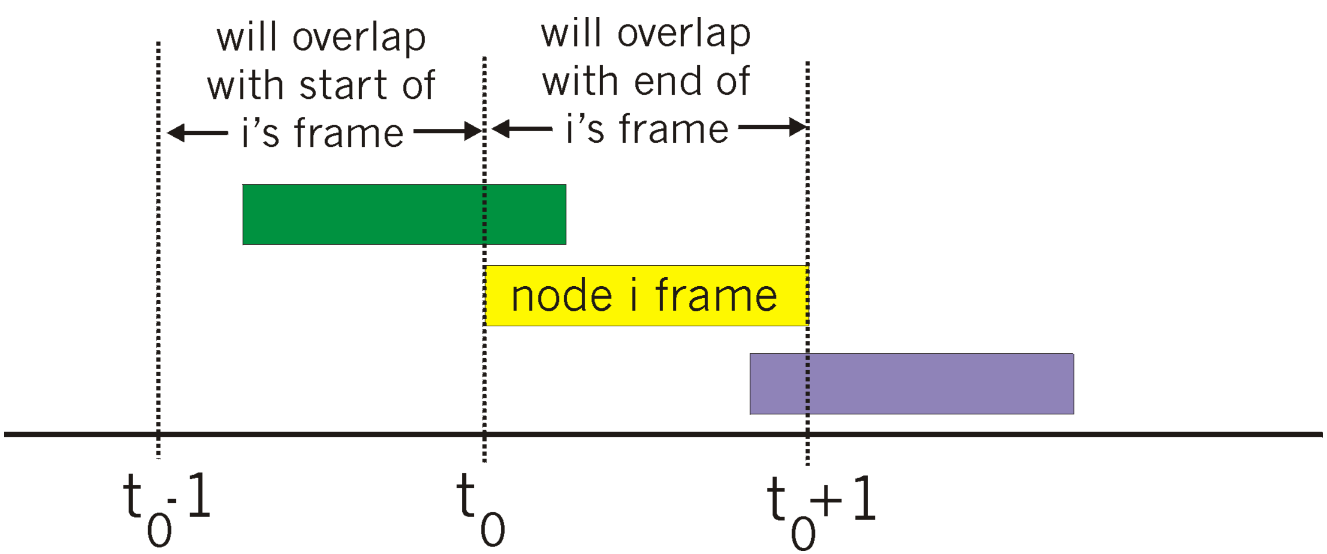
at best: channel used for useful transmissions 37% of time!

!

Source: Kurose & Ross slide set

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 $[t_0-1, t_0+1]$



Source: Kurose & Ross slide set

Pure ALOHA efficiency

P(success by given node) = P(node transmits) $\cdot$

P(no other node transmits in $[t_0\text{-}1, t_0]$ $\cdot$

P(no other node transmits in $[t_0\text{-}1, t_0]$

$$= p \cdot (1-p)^{N-1} \cdot (1-p)^{N-1}$$

$$= p \cdot (1-p)^{2(N-1)}$$

… choosing optimum p and then letting n $\longrightarrow \infty$

$$= 1/(2e) = .18$$

even *worse* than slotted Aloha!

CSMA (carrier sense multiple access)

CSMA: listen before transmit:

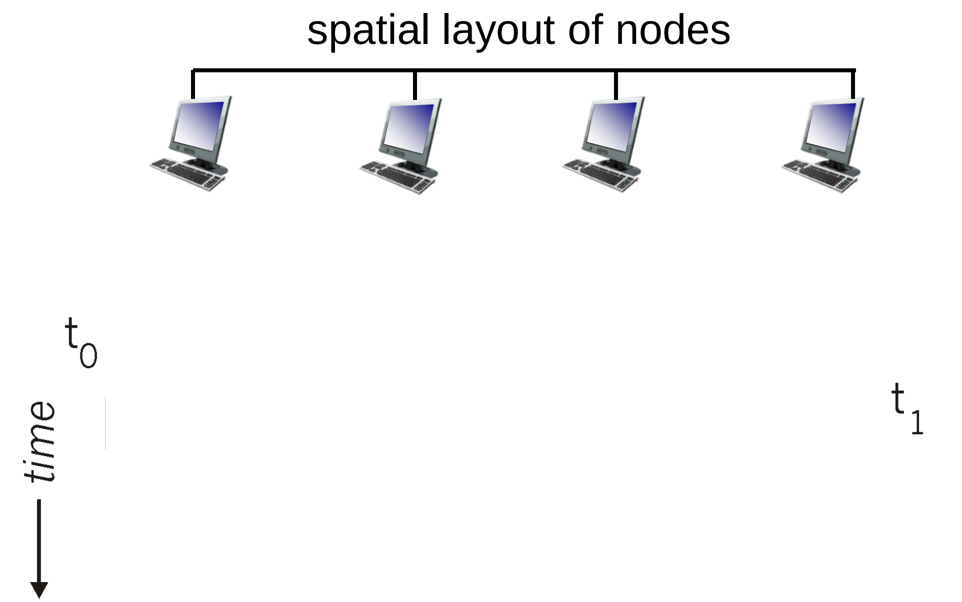
if channel sensed idle: transmit entire frame

- if channel sensed busy, defer transmission

- human analogy: don't interrupt others!

Source: Kurose & Ross slide set

CSMA collisions

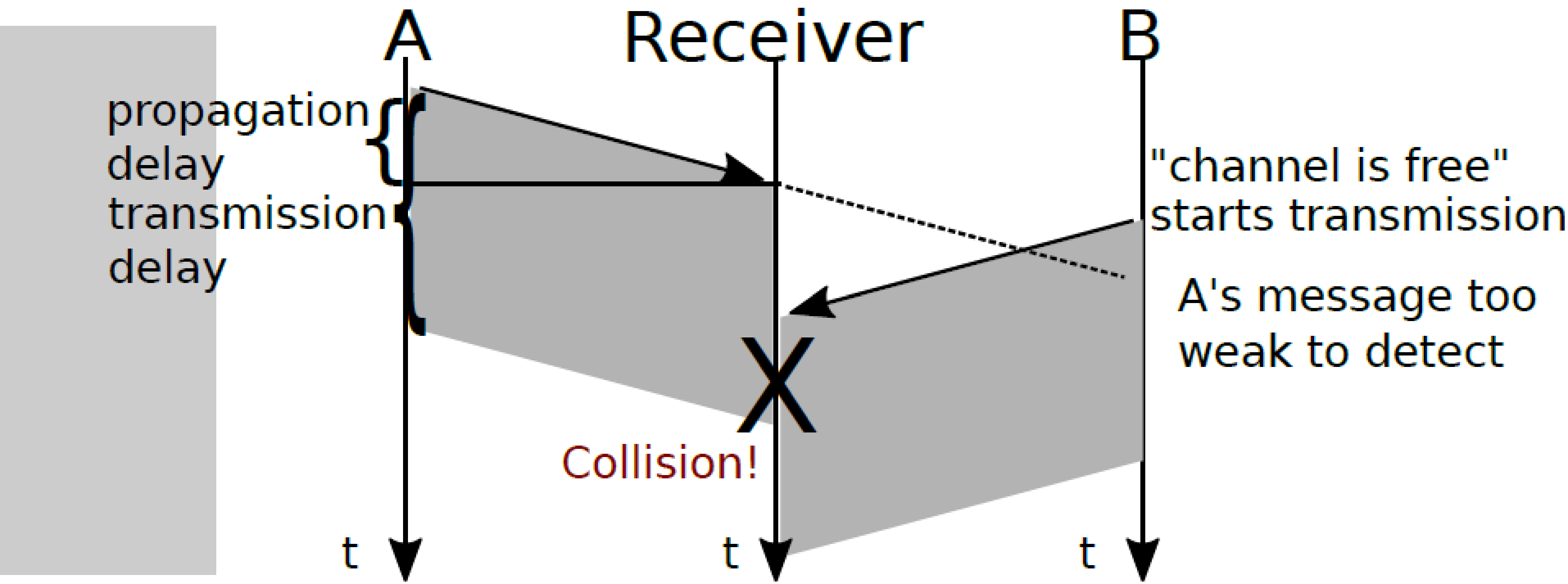


- collisions *can* still occur: propagation delay means two nodes may not hear each other's transmission
- collision: entire packet transmission time wasted
  - distance & propagation delay play role in in determining collision probability

Source: Kurose & Ross slide set

Undetected Collisions

- Even if nodes only start transmitting on a free channel, undetected collisions can occur on wireless channel
  - E.g., due to hidden node problem or propagation delay
  - It is also hard to listen while sending in wireless



CSMA/CD (collision detection)

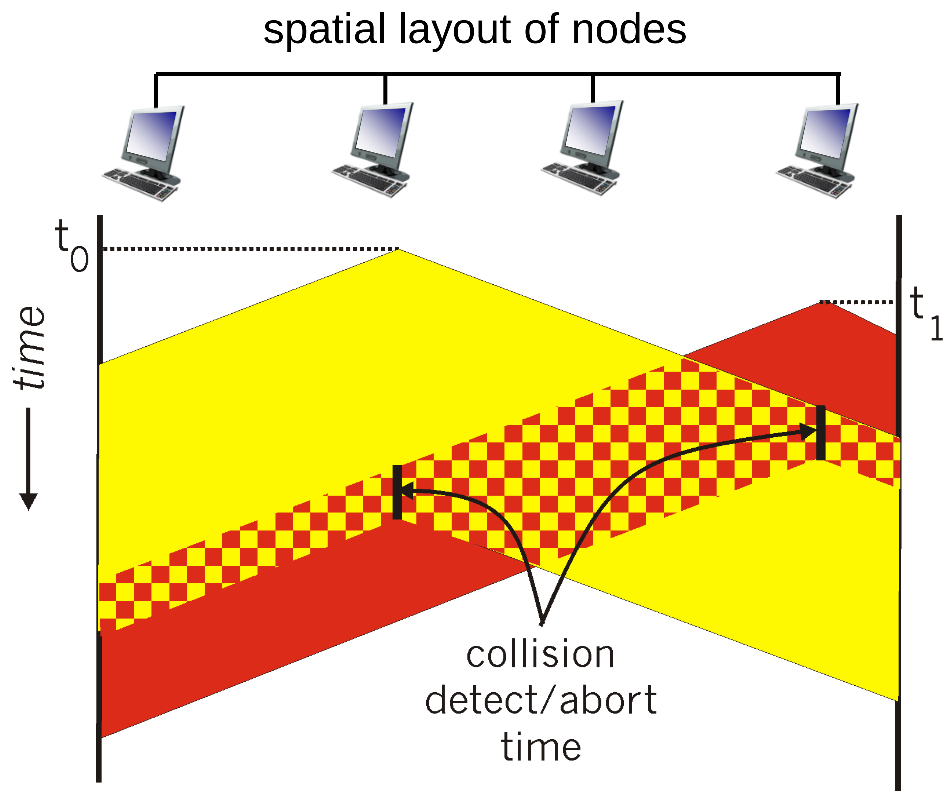
CSMA/CD: carrier sensing, deferral as in CSMA

  - 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: received signal strength overwhelmed by local transmission strength
- human analogy: the polite conversationalist

Source: Kurose & Ross slide set

CSMA/CD (collision detection)



Source: Kurose & Ross slide set

Ethernet CSMA/CD algorithm

1. NIC receives datagram from network layer, creates frame
2. If NIC senses channel idle, starts frame transmission. If NIC senses channel busy, waits until channel idle, then transmits.
3. If NIC transmits entire frame without detecting another transmission, NIC is done with frame !
4. If NIC detects another transmission while transmitting, aborts and sends jam signal
5. After aborting, NIC enters *binary (exponential) backoff:*
   - after *m*th collision, NIC chooses *K* at random from $\{0,1,2, \ldots, 2^m-1\}$. NIC waits $K \cdot 512$ bit times, returns to Step 2
   - longer backoff interval with more collisions

Source: Kurose & Ross slide set

CSMA/CD efficiency

- t_{prop} = max prop delay between 2 nodes in LAN
- t_{trans} = time to transmit max-size frame

$$efficiency = \frac{1}{1 + 5t_{prop}/t_{trans}}$$

- efficiency goes to 1
  - as t_{prop} goes to 0
  - as t_{trans} goes to infinity
- better performance than ALOHA: and simple, cheap, decentralized!

Source: Kurose & Ross slide set

IEEE 802.11 MAC Protocol: CSMA/CA

802.11 sender

1 if sense channel idle for **DIFS**[1] then

transmit entire frame (no CD)

2 if sense channel busy then

start random backoff time

timer counts down while channel idle

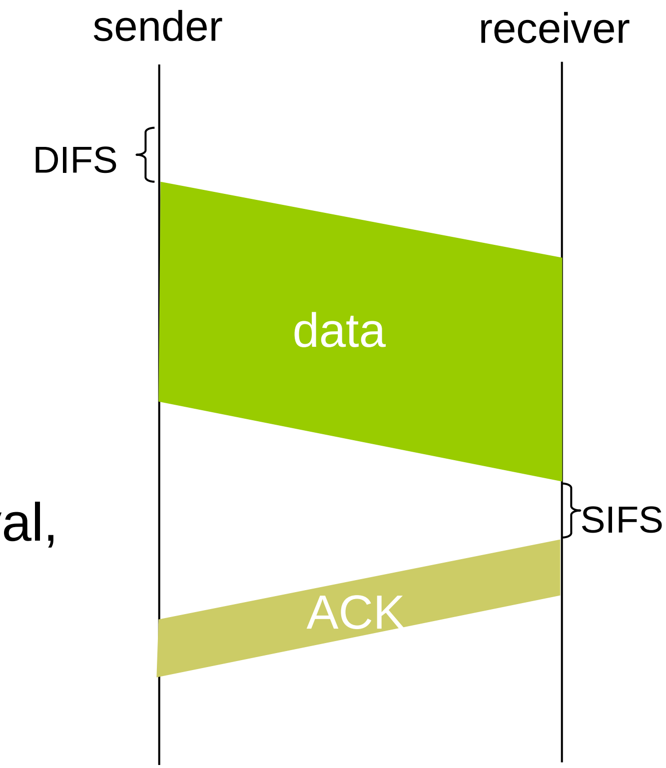
transmit when timer expires

if no ACK, increase random backoff interval, repeat 2

802.11 receiver

- if frame received OK

return ACK after **SIFS**[1] (ACK needed due to hidden terminal problem)



[1] DIFS – distributed inter frame spacing
SIFS – short inter frame spacing

Source: Kurose & Ross slide set

"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

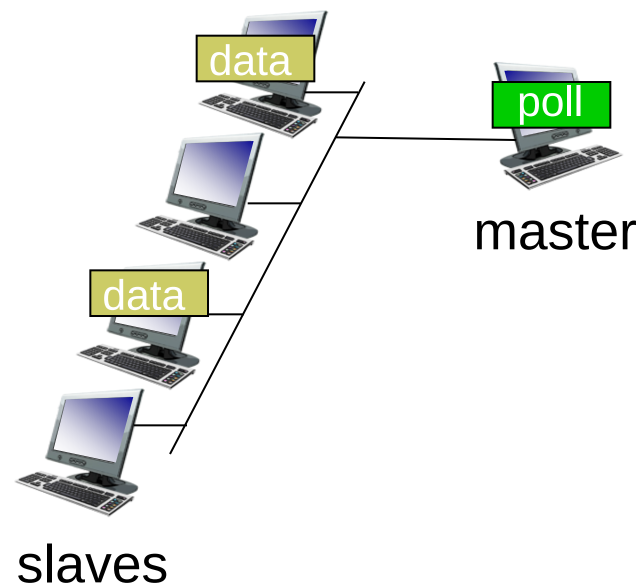
"taking turns" protocols

look for best of both worlds!

“Taking turns” MAC protocols

polling:

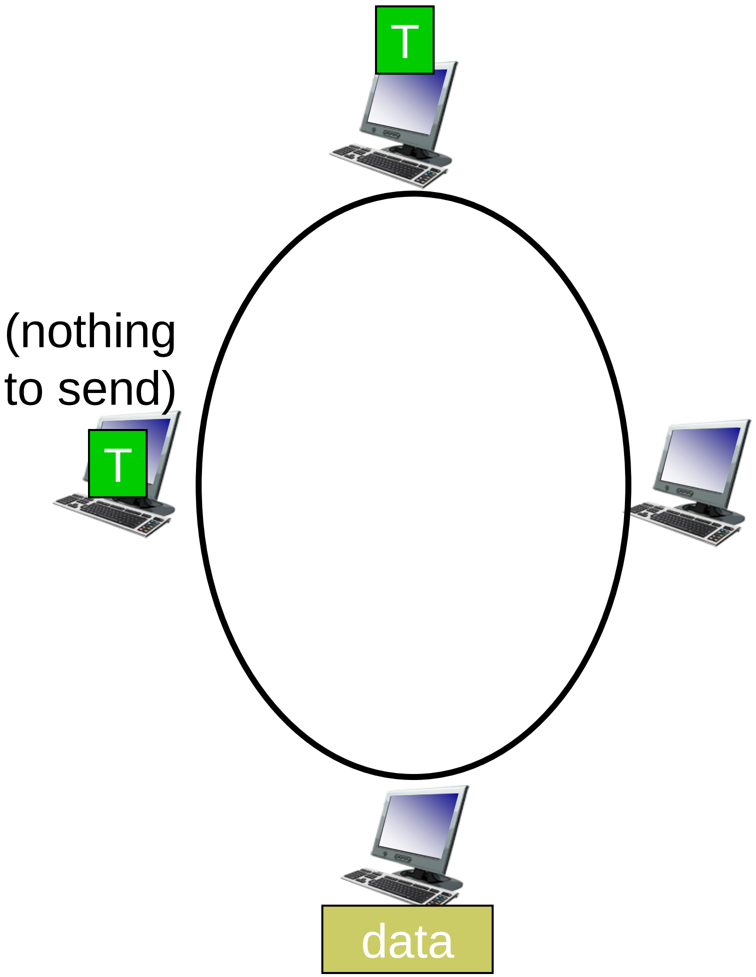
- master node “invites” slave nodes to transmit in turn
- typically used with “dumb” slave devices
- concerns:
  - polling overhead
  - latency
  - single point of failure (master)



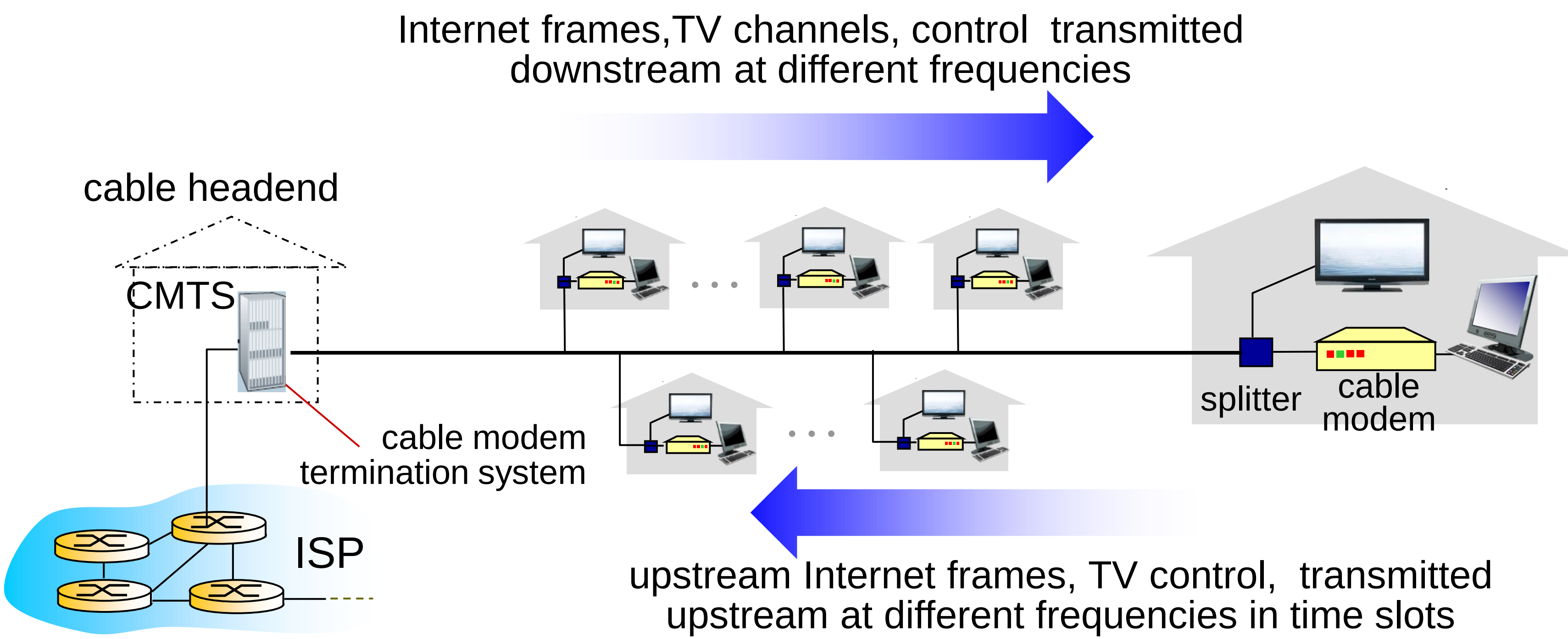
"Taking turns" MAC protocols

token passing:

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

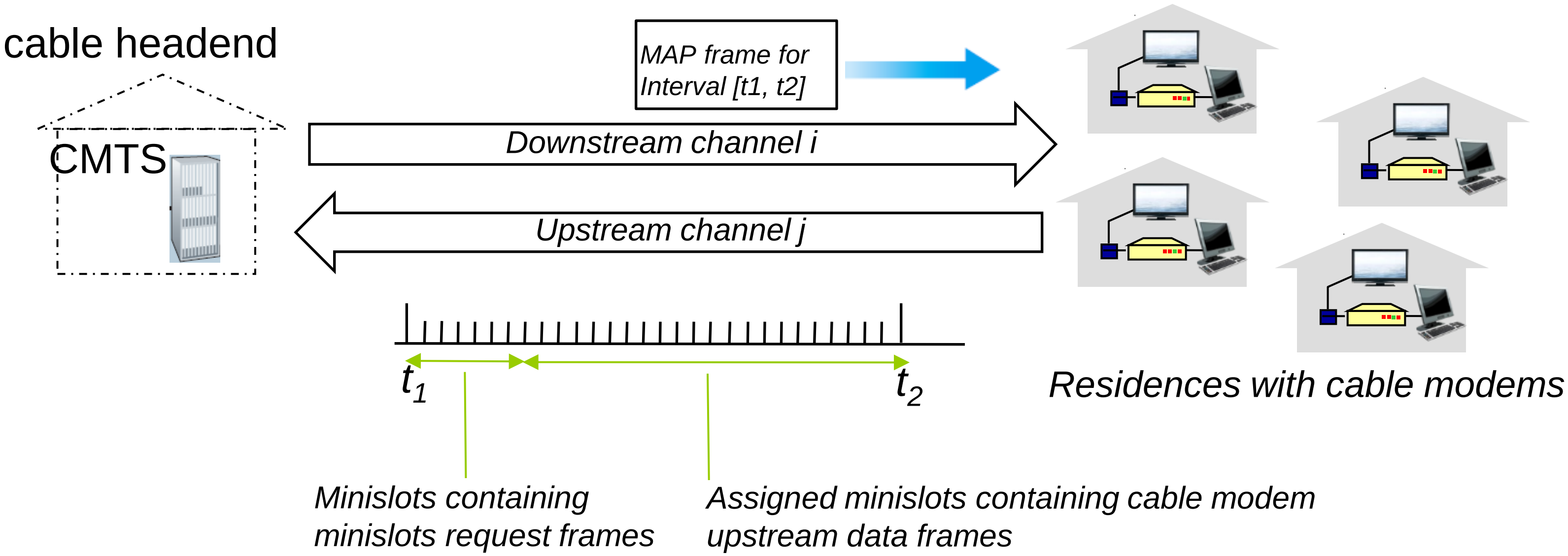


Cable access network



- *multiple* 40Mbps downstream (broadcast) channels
  - single CMTS transmits into channels
- *multiple* 30 Mbps upstream channels
  - *multiple access: all* users contend for certain upstream channel time slots (others assigned)

Cable access network



DOCSIS: data over cable service interface spec

- 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

Summary of MAC protocols

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- *channel partitioning,* by time, frequency or code
  - Time Division, Frequency Division
- *random access* (dynamic),
  - ALOHA, S-ALOHA, CSMA, CSMA/CD
  - carrier sensing: easy in some technologies (wire), hard in others (wireless)
  - CSMA/CD used in Ethernet
  - CSMA/CA used in 802.11
- *taking turns*
  - polling from central site, token passing
  - bluetooth, FDDI, token ring

Homework 6 (due 11:59 11-10-2018)

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CSMA/CD Collision

Consider two nodes, A and B, that use the slotted ALOHA protocol to contend for a channel. Let node A's retransmission probability be p_A and node B's retransmission probability be p_B.

a) Provide a formula for node A's average normalized throughput. What is the total efficiency of the protocol with these two nodes?

b) If $p_A = 3p_B$, is node A's average normalized throughput three times as large as that of node B? Why or why not? If not, how can you choose p_A and p_B to make that happen?

c) In general, suppose there are N nodes, among which node A has transmission probability 4p and all other nodes have retransmission probability p.

d) Provide expressions to compute the average normalized throughputs of node A and that of any other node.

Submit answer on eDimension.

Conclusion

- We discussed the main differences of wired and wireless networks
- Brief overview of topologies and protocols
- How to handle shared medium access
  - TDMA
  - Slotted ALOHA
  - Carrier Sense Multiple Access (CSMA)
  - Avoid collisions (CA)