LECTURE 13: WIRELESS PHYSICAL LAYER & MAC PROTOCOLS

May 8, 2018

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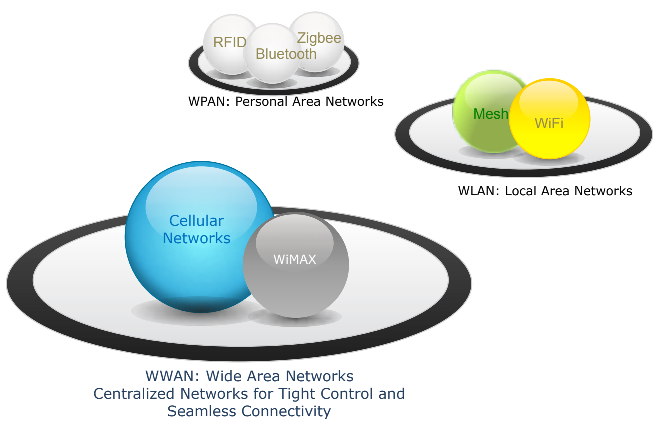
My Goals Today on Physical Layer

2

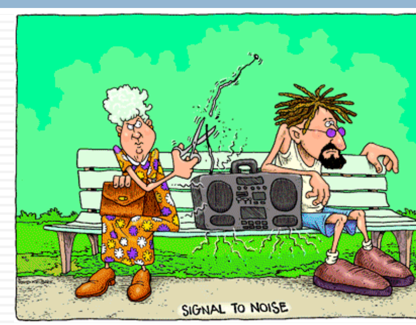
- Make sure you know basic physics of wireless communications
- Expose you to super interesting research on wireless networking

Wireless Networks

3



4 Wireless Signal Propagation 101



If We can See the Wi-Fi Signals…

5

http://gizmodo.com/what-the-world-would-look-like-if-you-could-actually-se-846030448

If We can See the Wi-Fi Signals…

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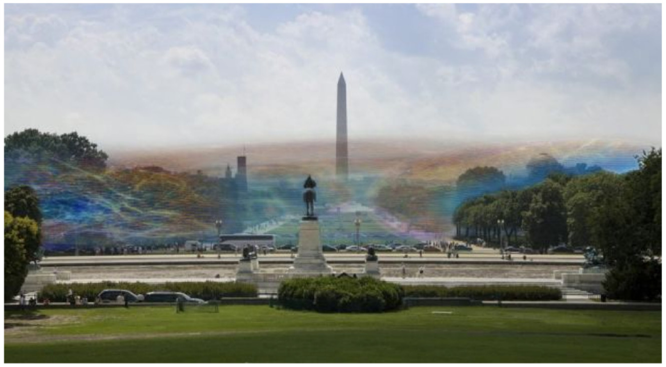

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If We can See the Wi-Fi Signals…

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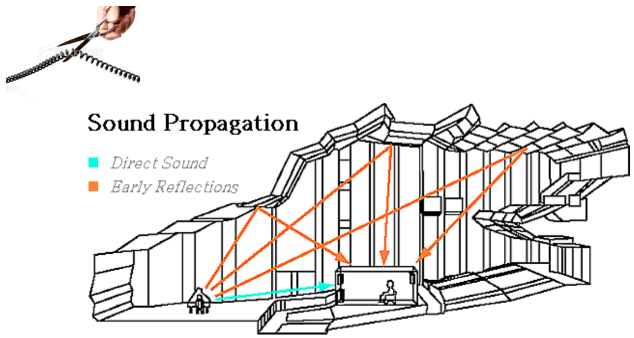
What Happens if We Cut the Wire



Just Consider the Direct Path

- **Free-space pathloss**
  - Transmission power decreases with square of distance

    Signal power loss = $\left(\frac{4\pi d}{\lambda}\right)^2 = \left(\frac{4\pi df}{c}\right)^2$
  - d: distance between TX and RX
  - **λ:** signal wavelength in meters
  - f: signal frequency in hertz
  - c: speed of light in a vacuum

Higher frequency (shorter wavelength) has higher signal loss

Just Consider the Direct Path

- **Free-space pathloss**
  - Transmission power decreases with square of distance

    Signal power loss = $\left(\frac{4\pi d}{\lambda}\right)^2 = \left(\frac{4\pi df}{c}\right)^2$

Freq.	900MHz	2.4GHz	5GHz
Range	902 – 928	2.4 – 2.4835	5.15 – 5.35
Bandwidth	26MHz	83.5MHz	200MHz
Wavelength	0.33m /13.1"	0.125m / 4.9"	0.06m / 2.4"

Just Consider the Direct Path

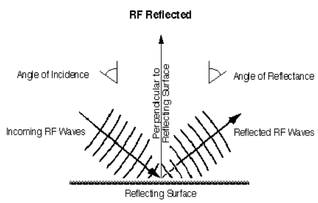
- In general cases

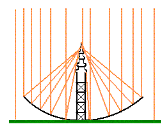
Signal power loss = $\left(\frac{4\pi df}{c}\right)^\alpha$ ← **Pathloss component**

Free space	2
Urban area cellular	2.7 – 3.5
Shadowed urban cell	3 – 5
In building Line-of-Sight (LOS)	1.6 – 1.8
Obstructed in building	4 – 6
Obstructed in factories	2 – 3

Signal Propagation

- **Reflection**
  - Propagation wave impinges on an object larger than its wavelength, eg. buildings, walls

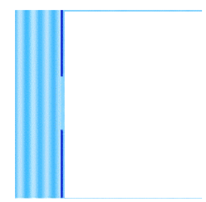


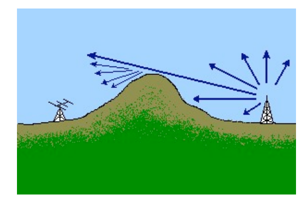


Boost WiFi signals using a beer can!

Signal Propagation

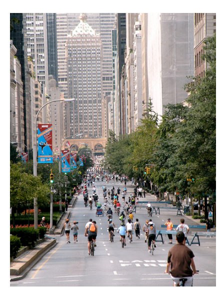
- **Diffraction (shadowing)**
  - Radio path between TX and RX are blocked by surface with sharp irregular edges
  - Waves bend around the obstacle, even when line of sight (LOS) does not exist





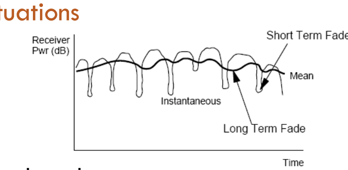
Signal Propagation

- **Scattering**
  - Like diffraction, but at objects smaller than the wavelength of the propagation wave
  - eg. foliage, street signs, lamp posts
  - The most difficult to capture

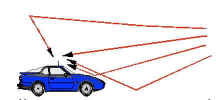


The Impact of Mobility

- Mobility creates signal fluctuations
- **Large-scale fading**
  - Attenuation: in free space, power degrades by $1/d^2$
  - Shadows: signals blocked by obstacles



- **Small-scale fading**
  - Multipath effects
    - Rapid changes in signal strength in a small area or time interval
  - Even when mobile is stationary, the received signals may fade because of the movement of surrounding objects

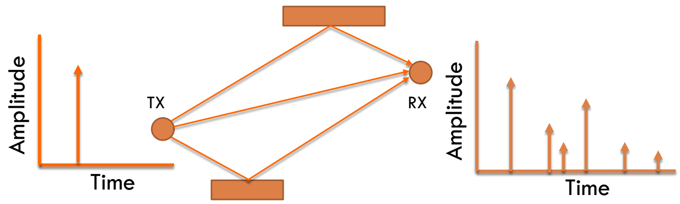


Multipath Fading

17

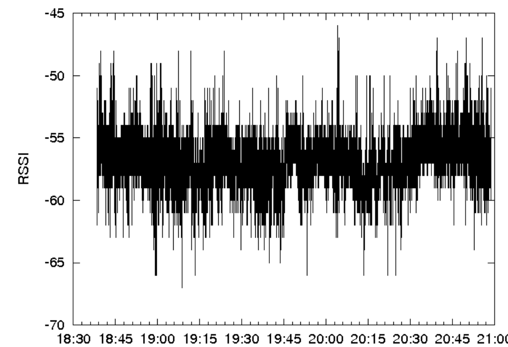
- Signals from different paths arrive at the receiver at different times

→ Cause inter-symbol interference, limit maximum symbol rate



Received Signal Over Time

18



Modeling Wireless Propagation

19

- Path loss
  - Modeling large-scale fading
- Rayleigh fading
  - Modeling small-scale fading

$$P_L = \left(\frac{4\pi D}{\lambda}\right)^{\alpha} \cdot x \quad \text{in dB}: P_L = 10 \cdot \alpha \log(D) + C + X$$

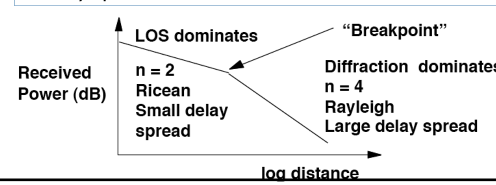
Adding a zero-mean Gaussian random variable in dB to capture shadowing effect

Outdoor Propagation

20

- Comparing two types of deployments (coverage driven)

Parameter	Macrocell	Microcell
Cell radius	1 – 20Km	0.1 – 1Km
TX power	1 – 10W	0.1 – 1W
Fading	Rayleigh	Ricean
Delay spread	0.1 to 10us	10 to 100ns



Indoor Propagation

21

- Signal decays much faster
- Rich obstacles → more multipath effect
- Coverage constrained by walls, etc
- Walls, floors, furniture attenuate/scatter radio signals

Simulating Wireless Environment

22

- A tough task
- Depends on indoor or outdoor
- Attenuation in dB

$$P_L(d) = P_L(d_0) + 10\,\alpha\log(d/d_0) + X + \text{Fading}$$

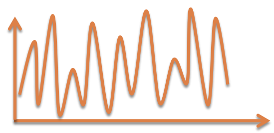
Reference point

- Testbed and real measurements are highly appreciated!

Difference Between Wireless and Wired

23

- **Time-varying**, often unpredictable channel quality
  - Nature of radio propagation, mobility, dynamic environment



- **Interference**
  - Broadcast nature

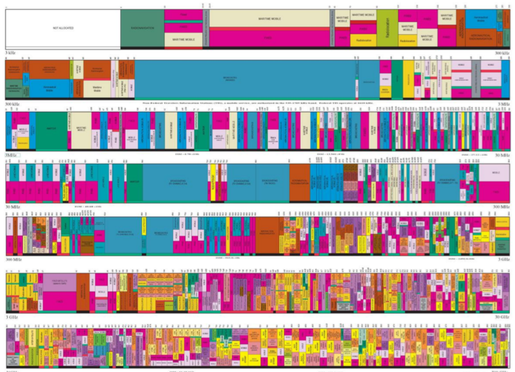
Cool Wireless Research

24

We're Running out of Radio Spectrum

25

- US radio spectrum allocation chart



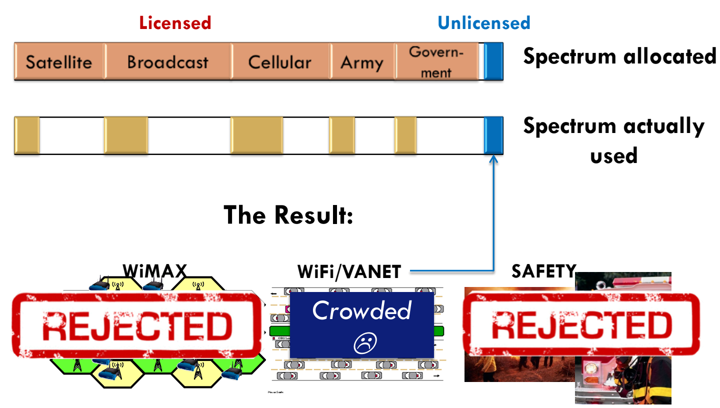
How to Deal with It?

26

- Utilize existing spectrum more efficiently
- Explore new territory of spectrum

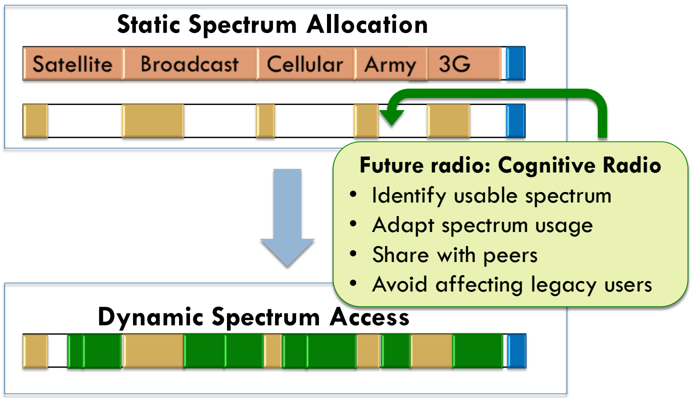
The Same for Existing Radio Spectrum

28



A New Access Paradigm

29



Research Topics

30

- Spectrum sharing (Networking)
  - Opportunistic access w/o harming primary users

- Spectrum auctions (Networking + Economics)
  - Obtain exclusive spectrum usage

- Spectrum enforcement
  - No unauthorized spectrum use (spectrum misuse)

How to Deal with It?

31

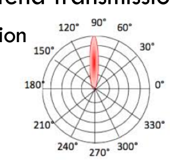
- Utilize existing spectrum more efficiently

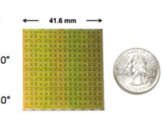
- Explore new territory of spectrum

60GHz Wireless Technology

32

- 57 – 64GHz frequency band
  - Unlicensed 7GHz bandwidth (anyone can use for free!)
- Small interference footprint
  - High frequency → fast signal attenuation
- Use directional antennas to extend transmission range
  - Focus energy in a narrow direction
  - Two types of antennas
    - Horn antenna
    - Antenna array





Visual Light Communication (VLC)

33

- Transmit bits by changing the light intensity of LEDs
  - Remember Morse code?
  - Optical spectrum: 430 – 790THz frequency band

- Why LEDs
  - Can be switched on/off up to million times per second
  - Changes won't be perceivable to human eyes!
- The future with lights as wireless APs!

A TED talk:
http://www.ted.com/talks/harald_haas_wireless_data_from_every_light_bulb

Full Duplex Wireless Radio

34

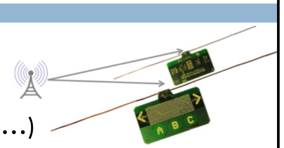
- Wireless radio conventionally can only either talk or listen at a given time
  - Radio's own transmit power >> the received signal power from others
- Enabling full-duplex transmission by canceling self-interference
  - 2 TX antennas + 1 RX antenna
  - 1 TX antenna + 1 RX antenna
  - 1 TX/RX antenna

http://sing.stanford.edu/fullduplex/

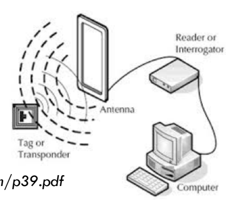
Battery-Free Wireless Communications

35

- Ambient backscatter
  - Leverage existing wireless signals in the air (TV, radio, Wi-Fi…)
  - Transmit 1s and 0s by reflecting or not reflecting these signals
  - Harvest energy from wireless signals



- Similar to the principle of RFIDs



http://conferences.sigcomm.org/sigcomm/2013/papers/sigcomm/p39.pdf

Rethink Wireless Signals

36

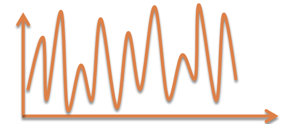
- So for they are only for communications
- Can we leverage them to do something else?
  - Gesture recognition
    - http://wisee.cs.washington.edu/
    - https://www.usenix.org/conference/nsdi14/technical-sessions/presentation/kellogg
  - Tracking people in the next room
    - https://www.usenix.org/conference/nsdi15/technical-sessions/presentation/adib
    - http://people.csail.mit.edu/fadel/wivi/
  - Scan tumors inside user's body
    - http://conferences.sigcomm.org/hotnets/2013/papers/hotnets-final75.pdf
  - Imaging
    - https://homes.cs.washington.edu/~gshyam/Papers/wision.pdf
    - http://www.cs.ucsb.edu/~yibo/doc/60gradar-hotmobile15.pdf
- What's your **big** wireless idea? ☺

37 Wireless MAC Protocols

How is Wireless Different?

38

- **Time-varying**, often unpredictable channel quality
  - Nature of radio propagation, mobility, dynamic environment



- **Interference**
  - Broadcast nature

The More, The Messier

39

Role of MAC

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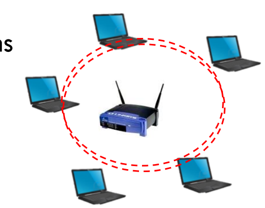
- Select transmission rate to adapt to channel variations
- Avoid interference
- Provide fairness



MAC Categories

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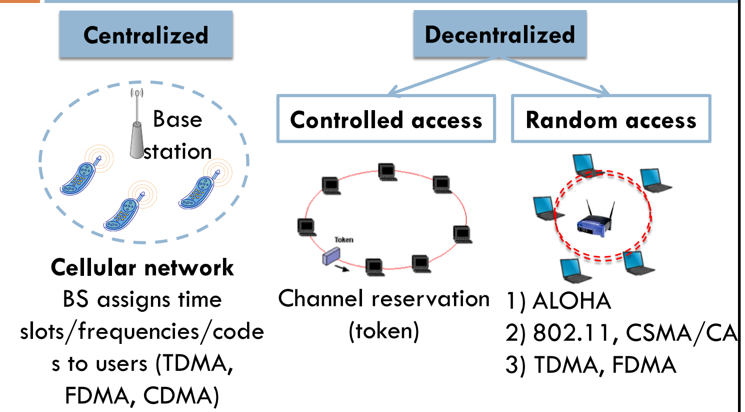
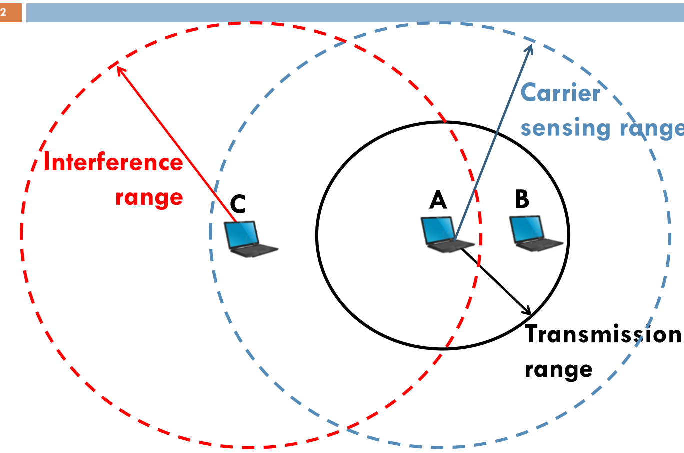


All These Ranges

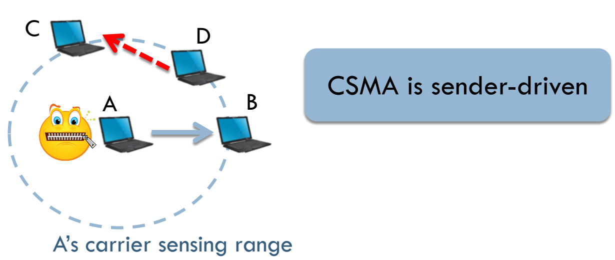
42



Carrier Sense Medium Access (CSMA)

43

- Sense before transmitting
  - Channel idle: transmit
  - Channel busy: defer transmission to avoid collision



Discussion Time

44

- Is CSMA good enough?

Discussion Time

45

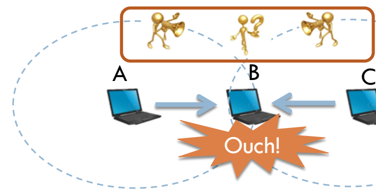
- Is CSMA good enough?

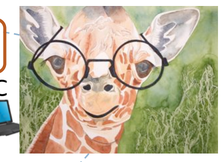
CSMA is sender-driven,
but interference is receiver-driven

Hidden Terminal Problem

46

- Limited sensing range →
  Cannot always sense ongoing transmissions
- A is communicating with B
- C cannot sense A's transmission, so C also transmits
  → Collision occurs at B

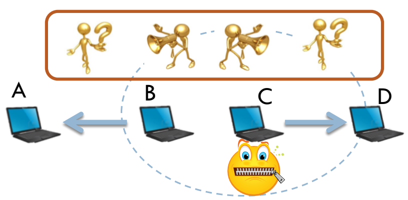


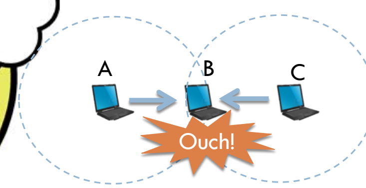


Exposed Terminal Problem

47

- Defer transmissions when it's not necessary
- C wants to transmit to D but hears B
- C defers its transmission although it won't disturb A's reception



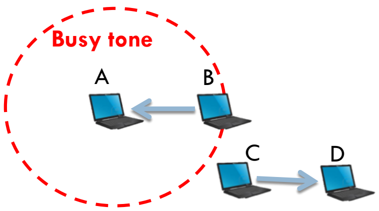


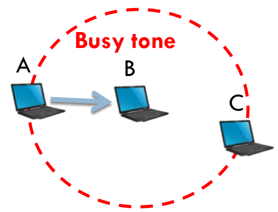
48

Solution #1: Avoid it

49

- Busy tone
  - **Receiver** broadcasts a busy tone while receiving data
  - Nodes hearing busy tone keep silent





Solution #2: Avoid it

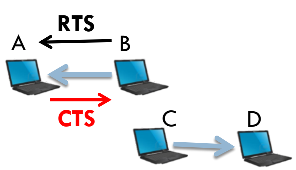
50

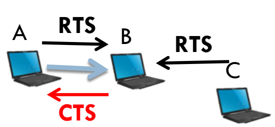
- MACA* (Karn90)
  - Transmitter sends a **Request-to-Send (RTS)** to receiver
  - Receiver responds with a **Clear-to-Send (CTS)**
  - Nodes hearing RTS keep silent for a short time so that transmitter can receive CTS
  - Nodes hearing CTS keep silent for the duration of the transmission

** MACA - A New Channel Access Method for Packet Radio. Philip Karn.*

Example of RTS and CTS

51





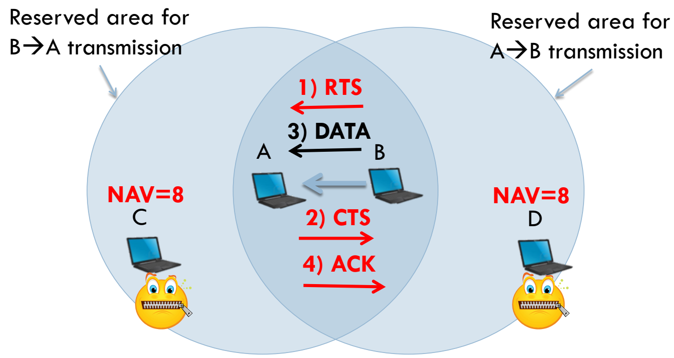
802.11MAC (CSMA/CA)

52

- Carrier Sense Medium Access/**Collision Avoidance**
- Carrier sense
  - When a node wants to transmit, it waits until the channel is idle
- Collision avoidance
  - RTS and CTS packets carrying **NAV** (remaining duration to keep quiet)
  - Nodes overhearing CTS keep silent for NAV (avoid HT)
  - Nodes overhearing RTS keep silent for NAV (avoid collision w/ ACK)
  - Once channel is idle, wait for randomly chosen duration before transmitting again → **backoff**

CSMA/CA Example

53



CSMA/CA

54

- Carrier Sense Medium Access/**Collision Avoidance**
- Carrier sense **Physical carrier sense (energy detection)**
  - When a node wants to transmit, it waits until the channel is idle
- Collision avoidance **Virtual carrier sense (packet sniffing)**
  - RTS and CTS packets carrying NAV (remaining duration to keep quiet)
  - Nodes overhearing CTS keep silent for NAV (avoid HT)
  - Nodes overhearing RTS keep silent for NAV (avoid collision w/ ACK)

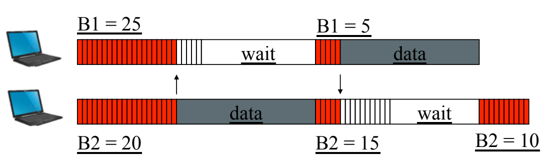
Collision avoidance (random backoff)

  - Once channel is idle, wait for randomly chosen duration before transmitting again → **backoff**

Random Backoff

55

- When transmitting a packet, choose a backoff interval within [0, CW]
  - **CW: contention window**
- Count down the backoff interval when the medium is idle
  - Freeze the count-down if medium is busy
- When backoff interval reaches 0, transmit RTS



Put All Together: Transmit or Not Transmit?

56

- Sense the channel

→ If the channel is idle, wait for the **DIFS** interval (Distributed Inter Frame Space)

- If the channel is still idle, transmit
- For control packets (CTS/ACK), wait for **SIFS** interval (Short Inter Frame Space)
  - *Why?*

→ If the channel is busy, wait until it's free

- Choose a random backoff interval
- Then still wait for DIFS interval
- …

How to Choose the Backoff Interval?

57

- The time spent on counting down backoff interval is part of MAC overhead
  - Channel is idle!
- Tricky to pick the right CW
  - Large CW → large MAC overhead
  - Small CW → many collisions
- What's your solution?

802.11 DCF (Distributed Coordination Function)

58

- CW depends the #of contending nodes
  - Varies over time

→ Adapt CW based on collision occurrence

Binary Exponential Backoff

59

- When a node fails to receive CTS in response to RTS, it **doubles** its CW
- When a node successfully completes a data transfer, **restore CW to CWmin**
  - CWmin=31 for 802.11b, and 15 for 802.11g
- Any problems?
  - Fast oscillation in CW
  - Unfairness occurs when one node has backed off much more than other nodes

Key reason: CW is reduced too fast!

MACAW* Solution

60

- Update CW by **exponential increase, linear decrease**
  - When a node successfully transfers data, reduces CW by 1
  - *How does it compare to TCP's congestion control?*
- Append CW value to the packet
  - Each node maintains CW independently
  - CW as an indication of the level of congestion in the receiver vicinity

** MACAW: A Media Access Protocol for Wireless LAN's. SIGCOMM'94 (http://www.cs.mcgill.ca/~cs535/docs/BhD94.pdf)*

Solution #3: Deal with it

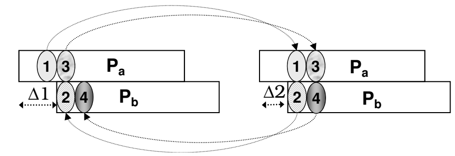
62

- Can we design receiver to cancel/utilize the impact of interference?

ZigZag Decoding

63

- Leverage two facts of 802.11 transmissions
  - Sender **retransmits** packet until it's ACKed or timed out
  - Senders **jitter** every transmissions by a random interval



Step #1: decode chunk 1 from the 1st collided packet
Step #2: subtract chunk 1 from 2nd collided packet and decode chunk 2
Step #3: subtract chunk 2 from the 1st collided packet to get chunk 3
….

802.11

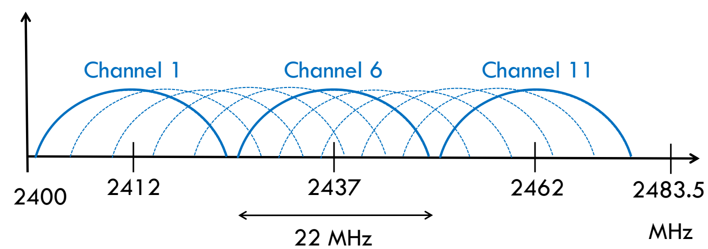
64

- 802.11b (1997/1999)
  - 2.4 GHz, DSSS/FHSS, up to 11 Mbps
- 802.11a (1999)
  - 5 GHz, OFDM, up to 54 Mbps
- 802.11g (2003)
  - 2.4 GHz, OFDM, up to 54 Mbps
- 802.11n (2009)
  - 2.4/5 GHz, MIMO-OFDM (at most 4 MIMO streams), 300 – 500 Mbps
- 802.11ac (2013)
  - 5 GHz, MIMO-OFDM (at most 8 MIMO streams), > 1 Gbps!

802.11 Channels

65

- 802.11b: 11 channels in US
  - Each channel is 20+2 MHz wide
  - Three orthogonal channels



Takeaways

- Wireless medium is prone to hidden and exposed terminal problems
  - CSMA/CA, 802.11 MAC
  - Use Wireshark to sniff RTS/CTS packets
- Avoid or deal with interference