18-452/18-750
Wireless Networks and Applications
Lecture 12:
802.11 Standards

Peter Steenkiste

Spring Semester 2024

http://www.cs.cmu.edu/~prs/wirelessS24/

Outline

- 802.11 power control
- 802.11 QoS
- 802.11b through g
- How do further increase bit rates?
- How about short data short transfers?
- 802.11n through ax

IEEE 802.11 Family
High Level

Protocol	Release Data	Freq.	Rate (typical)	Rate (max)	Range (indoor)
Legacy	1997	2.4 GHz	1 Mbps	2Mbps	?
802.11a	1999	5 GHz	25 Mbps	54 Mbps	~30 m
802.11b	1999	2.4 GHz	6.5 Mbps	11 Mbps	~30 m
802.11g	2003	2.4 GHz	25 Mbps	54 Mbps	~30 m
802.11n	2009	2.4/5 GHz	200 Mbps	600 Mbps	~50 m
802.11ac	2013	5 GHz	100s Mbps	3.5 Gbps	~50 m
802.11ad	2012	60 GHz	~1 Gbps	6.7 Gbps	~10 m
802.11ax	2021 est	5 GHz	~1 Gbps	9.6 Gbps	~50 m
802.11ay	2021 est	60 GHz	1< Gbps	20 Gbps	~10 m

IEEE 802.11 Family
Technology

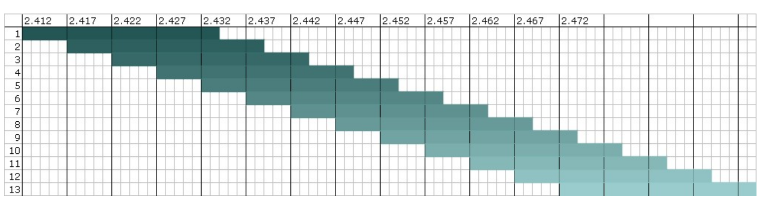
Protocol	Release Data	Bands GHz	PHY Features	Max Rate	Channel Width
802.11a	1999	5	OFDM	54 Mbps	20 MHz
802.11b	1999	2.4	DSSC/CCK	11 Mbps	20 MHz
802.11g	2003	2.4	OFDM	54 Mbps	20 Mhz
802.11n	2009	2.4. 5	OFDM, BF, MIMO-d	600Mbps	20, 40 MHz
802.11ac	2013	5	OFDM, BF MU-MIMO-d	3.5 Gbps	20, 40, 80, 160 Mhz
802.11ad	2016	60	BF	6.7 Gbps	2.16 GHz
802.11ax	2021	2.4, 5, 6	MU-MIMO, OFDMA, BF	9.6 Gbps	20, 40, 80, 160 Mhz
802.11ay	2021	60	MU-MIMO	20 Gbps	2.16, 4.32, 8.64 Ghz

Legend

- DSSS: Direct Sequence Spread Spectrum
- CCK: Complementary Code Keying
- OFDM: Orthogonal Frequency Division Multiplexing
- MIMO: Multiple In Multiple Out
  - » MIMO-d: MIMO downstream only
- BF: Beam Forming
- MU-MIMO: Multi-User MIMO
  - » MU-MIMO-d: MU-MIMO downstream only
- OFDMA: Orthogonal Frequency Division Multiple Access
  - » Implies OFDM

802.11b Channels

- In the UK and most of EU: 13 channels, 5MHz apart, 2.412 – 2.472 GHz
- In the US: only 11 channels
- Each channel is 22MHz
- Significant overlap
- Non-overlapping channels are 1, 6 and 11



802.11b Physical Layer

- FHSS (legacy)
  - 2 & 4 GFSK
  - Using one of 78 hop sequences, hop to a new 1MHz channel (out of the total of 79 channels) at least every 400milliseconds
- DSSS (802.11b)
  - DBPSK & DQPSK
  - Uses one of 11 overlapping channels (22 MHz)
  - 1 and 2 Mbps: multiply the data by an 11-chip spreading code (Barker sequence)
  - 5.5 and 11 Mbps: uses Complementary Code Keying (CCK) to generate spreading sequences that support the higher data rates
    - Spreading code is calculated based on the data bits

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7

7

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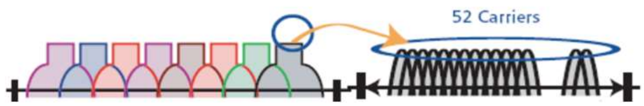
8

802.11a Overview

- First WiFi version in the 5 GHz band
- Use OFDM to divide each physical channel (20 MHz) into 52 subcarriers (20M/64=312.5 KHz each)
  - 48 data, 4 pilot



- Adaptive modulation
  - BPSK: 6, 9 Mbps
  - QPSK: 12, 18 Mbps
  - 16-QAM: 24, 36 Mbps
  - 64-QAM: 48, 54 Mbps
- Also used in the 2.4 GHz as 802.11g
  - Same PHY layer as 802.11a
  - But has the benefits and drawbacks of the 2.4 GHz band compared to 5 GHz

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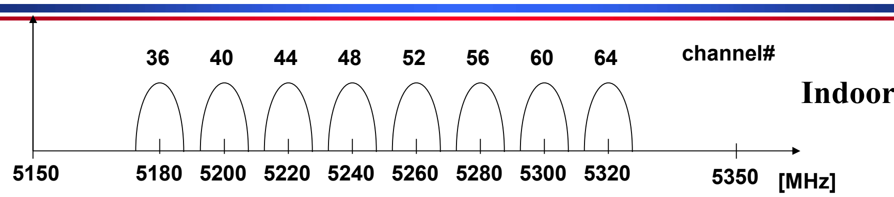
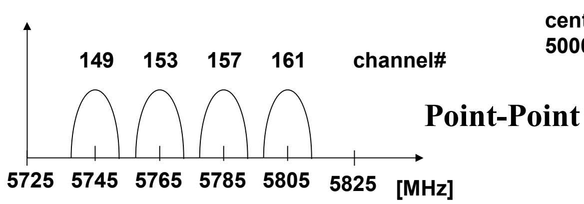
9

9

802.11a Physical Channels



center frequency =
5000 + 5*channel number [MHz]



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10

10

802.11a Discussion

- Uses OFDM in the 5 GHz band
  - » Also used by 802.11g in 2.4 GHz (next slides)
- What are the benefits of 802.11a compared with 802.11b/g?
  - » Greater bandwidth (up to 54Mb)
    - – 54, 48, 36, 24, 18, 12, 9 and 6 Mbs
    - – 802.11g (next slide) offers same benefit
  - » Less potential interference (5GHz)
  - » More non-overlapping channels
- But it does not provide interoperability with 802.11b, as 802.11g does
  - » Cannot fall back to lower rates (not an issue in practice)
  - » Cards typically support a and g

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802.11g and Interoperability

- 802.11g is the same as 802.11a, but in 2.4GHz band
  - » Falls back to 802.11b for the lower rates (1,2, 5.5, 11 MHz)
  - » Uses 802.11a OFDM technology for new rates (6 Mbs and up)
- This creates an interoperability challenge!
- We have two standards, b and g, that are incompatible at the physical layer!
  - » OFDM versus spread spectrum + CKK
- Let us consider two cases
  - » Upgrading of devices
  - » Upgrading of access points

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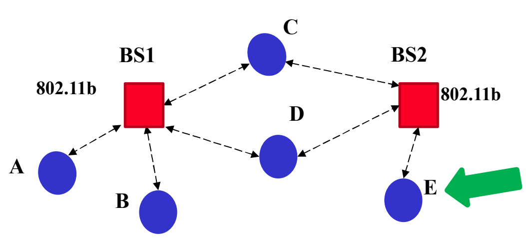
13

13

Upgrading Client Devices

- Starting point is an 802.11b only network
- User E buys a new laptop 802.11b/g WiFi
- Exciting .. oops: incompatible with APs!
- Solution?

WiFi devices must support latest <u>and older</u> standards



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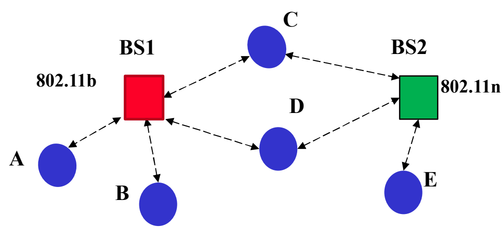
14

14

Upgrading Endpoints

- CMU decides to upgrade its WiFi network
  - » Option 1: one AP at a time
  - » Option 2: all APs (entire network) at the same time
- Solution: APs must support multiple versions



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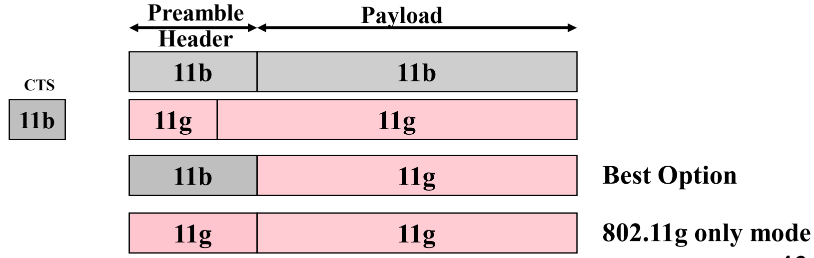
15

Interoperability 802.11b and 802.11g Devices

- Clients must know WiFi versions the AP supports
  - » Part of the association process – pick "best" protocol
- Interoperability mode for hybrid networks:
  - » Send CCK CTS before OFDM packets or use (optional) hybrid packet
- AP knows the Wifi version of its associated devices
  - » It uses OFDM for all traffic if all devices speak 802.11g



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16

16

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802.11n Overview

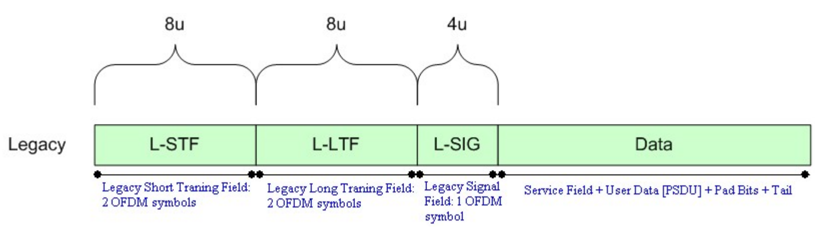
- 802.11n extends 802.11a for MIMO
  - » Supports up to 4x4 MIMO – downstream only
  - » Preamble that includes high throughput training field
- Standardization was completed in Oct 2009, but early products had long been available
  - » WiFi alliance started certification using draft in mid-2007
- Supported in both the 2.4 and 5 GHz bands
  - » Goal: typical indoor rates of 100-200 Mbps; max 600 Mbps
- Use either 1 or 2 non-overlapping channels
  - » Uses either 20 or 40 MHz - interoperability problems!
- Supports frame aggregation to amortize overheads over multiple frames
  - » Optimized version of 802.11e

802.11n
Backwards Compatibility

- 802.11n can create interoperability problems for existing 802.11 devices (abg)
  - » 802.11n does not sense their presence
  - » Legacy devices end up deferring and dropping in rate
- Mixes Mode Format protection embeds an "n" frame in a "g" or "a" frame
  - » Preamble is structured so legacy systems can decode header, but MIMO can achieve higher speed (training, cod/mod info)
  - » Works only for 20 MHz 802.11n use
  - » Only deals with interoperability with a and g – still need CTS protection for b
- For 40 MHz 802.11n, we need CTS protection on both the 20 MHz channels – similar to g vs. b
  - » Amortize over multiple transmissions

Interoperability Uses PLCP
Legacy

- Legacy mode: use 802.11a/g OFDM format
  - » The L-SIG field contains rate and length information
  - » Loses all the benefits of 802.11n!



- Mixed mode:
  - » Include both an 802.11a/g and 802.11n PLC header- next slide
  - » 802.11ag devices can interpret green fields, which includes the L-SIG field (rate and length information)

PLC – PHY Layer Convergence protocol
http://rfmw.em.keysight.com/wireless/helpfiles/n7617a/mimo_ofdm_signal_structure.htm

Interoperability: Mixed Mode

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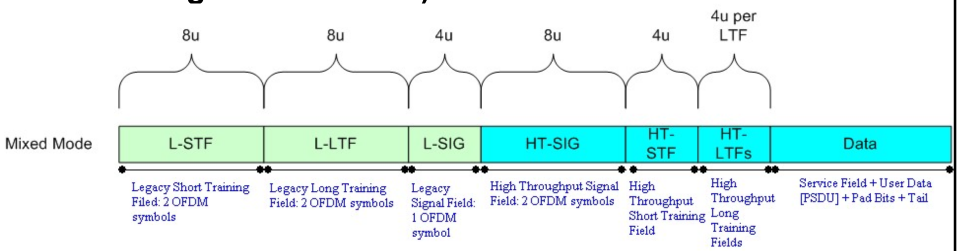
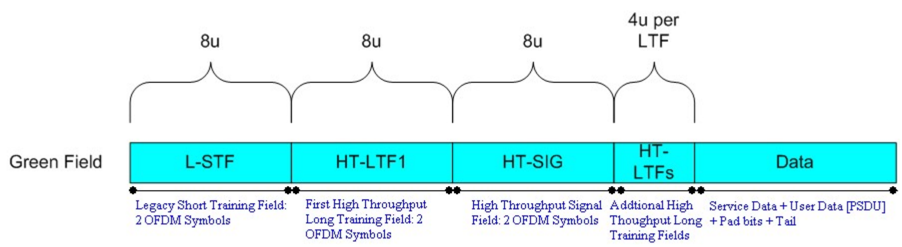


Interoperability: Greenfield Mode

- All devices support 802.11n
- Green field mode or High Throughput Mode



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802.11ac Multi-user MIMO

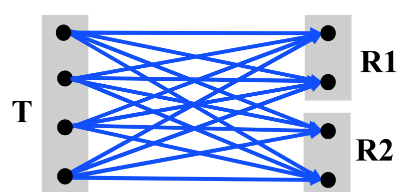
- Extends beyond 802.11n
  - » MIMO: up to 8 x 8 channels (vs. 4 x 4)
  - » More bandwidth: up to 160 MHz by bonding up to 8 channels (vs. 40 MHz)
  - » More aggressive signal coding: up to 256 QAM (vs. 64 QAM); both use 5/6 coding rate (data vs. total bits)
  - » Uses RTS-CTS for clear channel assessment
  - » Multi-gigabit rates (depends on configuration)
- Support for multi-user MIMO on the downlink
  - » Can support different frames to multiple clients at the same time
  - » Especially useful for smaller devices, e.g., smartphones
- Also supports beam forming to target signal to device – increases SNR

Multi-User MIMO
Up versus Down Link

- Assume one AP with multiple clients
- Downlink: Broadcast Channel (BC)
  - » Consistent with the traditional WiFi model of having each client receive a packet from the base station independently (except that it is at the same time!)
- Uplink: Multiple Access Channel (MAC)
  - » Multiple clients transmit simultaneously to a single base station
  - » WiFi is designed to avoid this!
    - – Simultaneous transmissions = collision
  - » MU-MIMO would require some changes to the standard
  - » Also requires fine grain clock coordination among clients on packet transmission – protocol support!

Challenges MU-MIMO
in 802.11ac

- You must have traffic for multiple receivers!
- Channels to the receivers are ideally "orthogonal"



$$R1: \quad O_1 = P_{R1} * H_1 * P_T * I + P_{R1} * N$$
$$R2: \quad O_2 = P_{R2} * H_2 * P_T * I + P_{R2} * N$$

  - » The signal that you create with the packet for one destination should have a "null" for the other destination(s)
  - » Important since the other receivers cannot cancel out that signal
- Becomes a scheduling problem: for each "packet" transmission, identify the destinations that have traffic waiting and that are "the most" orthogonal

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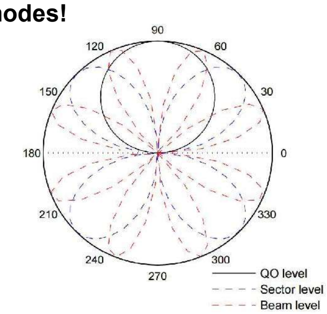
802.11ad 60 GHz WiFi

- Uses a new physical layer definition specifically for 60 GHz band
  - Very different signal propagation properties
  - Does not penetrate walls, but does work with reflections
  - Shorter distances; up to 7 Gbps
  - 6 channels of 2.16 GHz
- "Compatible" with 802.11 in 2.4 / 5 GHz bands
  - Backwards compatible MAC (not PHY!)
  - Not surprising! It is an 802 standard
- The technology had been in use for point-point links for a while
  - Set top box to TV,
  - Connect a WiFi AP to wired network (remote)

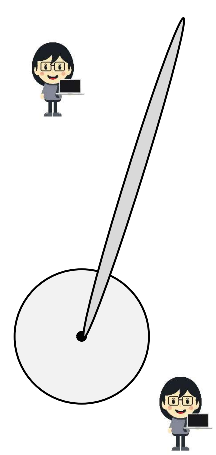
Optimizing Communication in 802.11ad

- Transmission range in 60 GHz is very limited
- Must use directionality to direct energy to the receiver
  - » Increases range and throughput (high signal strength)
  - » Also reduces interference at other nodes!
- Good news: antenna size scales with wave length
  - » Small antennas and narrow beams
- Bad news: how do nodes find each other?
  - » Use iterative algorithm, starting with wider beams



WiFi mmWave in the Real World

- Fundamental challenge:
- Long range requires narrow beams
  - » But that is only possible if you know the device location
  - » What about mobile devices?
  - » How do you find devices?
- Omni-directional provides broad coverage
  - » But range is short!
  - » You can only "sense" nearby devices



Some Possible Solutions (Research)

- Start with omnidirectional beacons and iteratively make beams more narrow
  - » In part leverages that fact that control packets use lower bit rates – provides a longer range
- Track mobile users
  - » Mobile users move smoothly in a horizontal plane
  - » Can predict location/direction based on history
- Use information about the physical environment
  - » Cars are challenging: move fast!
  - » But they drive on roads so their movement is predictable
  - » Example: “point” narrow beam up/down a straight road

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31

31

What Happens in Practice?

- mmWave WiFi is not widely used
- Its primary use is in stationary scenarios
  - » Connect remote devices to a LAN
  - » Wireless links in a local area networks, e.g., WiFi access point to a remote ethernet backbone
- Remote: device or AP is not close to the wired infrastructure

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32

32

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802.11ax versus ac

- Operates in both 2.4 and 5 GHz band
- Low level modulation differences
  - » Up to 1024 QAM compared to 256 QAM
  - » Tighter packing of subcarriers and longer symbol duration
  - » Shorter gaps between symbols
- Use of OFDMA (next slide)
- MU-MIMO uplink and downlink
  - » With UL MU-MIMO AP coordinates clients using a "trigger" control packet
  - » Easy example: ACKs after a DL MU-MIMO transmission
- Support for IoT devices
  - » Power saving techniques targeting IoT, OFDMA, …

Orthogonal Frequency Division Multiple Access (OFDMA)

- Remember Spread Spectrum?
  - Allows multiple users to share the spectrum band
  - Provides time and frequency diversity
  - Use different spreading codes/hopping sequences
- Can we do this for OFDM as well?
  - As discussed so far, OFDM allows just two devices to communicate
- Yes – OFDMA!

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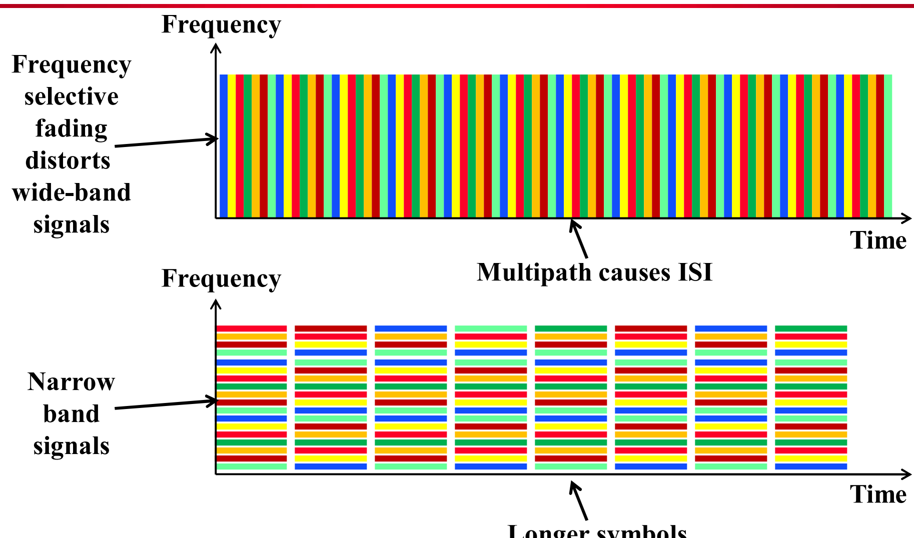
35

35

OFDM Transmission



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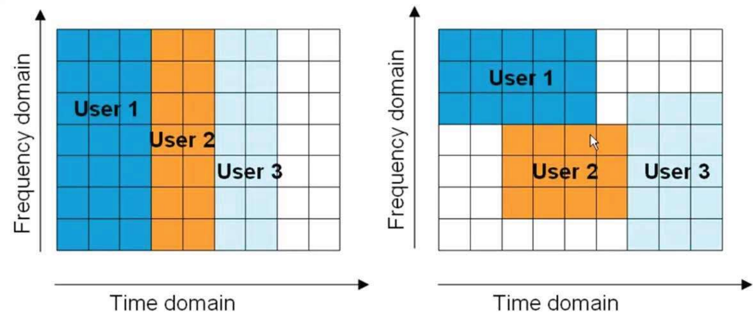
36

36

OFDM versus OFDMA



- Traditional OFDM allows channel sharing by user using TDMA only
- With OFDMA, users can use subsets of subcarriers in each time slot
- Remember: signals travel everywhere!

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37

37

Discussion

- OFDMA allows a base station to transmit data to multiple devices at the same time
  - » Different bit rates can be used for each device
- OFDMA upstream allows multiple devices to the base station at the same time
  - » Requires tight synchronization
  - » Base station controls who uses what “resource blocks”
- It allows multiple clients to efficiently send small amounts of data to an AP
- The cost is that it involves more overhead
  - » The base station and device(s) needs to agree on for each slot what device it is used by

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38

38

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802.11ay versus ad

- Use of MIMO and MU-MIMO instead of beamforming
- Channel bonding: combine up to 4 2.16 GHz channels
- Increased distances to a few 100 m
- Can be used as replacement for Ethernet (indoors) or for backhaul (outdoors)
  - » Reduces the cost of the infrastructure
  - » These are “easy” application: no need to track mobile users