Wireless LANs
Part II: 802.11a/b/g/n/ac

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Audio/Video recordings of this class lecture are available at:
http://www.cse.wustl.edu/~jain/cse574-22/

Student Questions

Q on 10,11c,12a,15,16,17b,20,22,24,26,29b,30,40

1. IEEE 802.11 Amendments
2. Protocol Data Units (PDUs)
3. IEEE 802.11abgn
4. 802.11e: Enhanced DCF, Frame Bursting, Direct Link
5. IEEE 802.11n: STBC, Bonding, Aggregation
6. IEEE 802.11ac: Beamforming, Multi-User MIMO

Note: This is 2nd in a series of class lectures on Wireless LANs.

Student Questions

IEEE 802.11 Amendments

- **802.11a-1999**: Higher Speed PHY Extension in the 5 GHz Band
- **802.11b-1999**: Higher Speed PHY Extension in the 2.5 GHz Band
- 802.11c: Bridge Operation (Added to IEEE 802.1D)
- 802.11d-2001: Global Harmonization (PHYs for other countries.)
- **802.11e-2005**: Quality of Service.
- 802.11F: Inter-Access Point Protocol (Withdrawn)
- **802.11g-2003**: Higher data rate extension in the 2.4 GHz band
- 802.11h-2003: Dynamic Frequency Selection and transmit power control to satisfy 5 GHz band operation in Europe.

Student Questions

- Can you please explain what we should remember regarding protocols in bold? Does it mean which year, what frequency range, and what's new?

What's new? The year is not important since it changes.

IEEE 802.11 Amendments (Cont)

- **802.11i-2004**: MAC Enhancements for Enhanced Security.
- 802.11j-2004: 4.9-5 GHz operation in Japan.
- 802.11k-2008: Radio Resource Measurement interface to higher layers.
- 802.11m: Maintenance. Correct editorial and technical issues in 802.11a/b/d/g/h.
- **802.11n-2009**: Enhancements for higher throughput (100+ Mbps)
- **802.11p-2010**: Inter-vehicle and vehicle-road side communication at 5.8GHz.
- 802.11r-2008: Fast Roaming
- **802.11s-2011**: Extended Service Set (ESS) Mesh Networks.

Student Questions

IEEE 802.11 Amendments (Cont)

- 802.11T: Performance Metrics
- 802.11u-2011: Inter-working with External Networks.
- 802.11v-2011: Wireless Network Management enhancements for interface to upper layers. Extension to 802.11k.
- 802.11w-2009: Protected Management Frames
- 802.11y-2008: 2650-3700 MHz operation in the USA
- 802.11z-2010: Direct Datalink Setup (DLS) mechanism w Power Save.
- 802.11aa-2012: Video Transport Streams
- **802.11ac-2013**: Very High Throughput <6GHz
- **802.11ad-2012**: Very High Throughput 60 GHz
- 802.11ae-2012: Prioritization of Management Frames

Ref: http://grouper.ieee.org/groups/802/11/Reports/802.11_Timelines.htm

Student Questions

IEEE 802.11 Amendments (Cont)

- 802.11af-2013: TV Whitespaces.
- IEEE Std P802.11-2016: Includes all amendments until 2015.
- 802.11ah-2017: Sub 1 GHz for IoT. OFDM PHY in license-exempt bands below 1 GHz, e.g., 868-868.6 MHz (Europe), 950 MHz -958 MHz (Japan), 314-316 MHz, 430-434 MHz, 470-510 MHz, and 779-787 MHz (China), 917 - 923.5 MHz (Korea) and 902-928 MHz (USA). Coexistence with IEEE 802.15.4 and IEEE P802.15.4g. Transmission range up to 1 km. Data rates > 100 kb/s.
- P802.11ai-2016: Fast initial link set up. Fast AP detection, network discovery, association, authentication, and IP address assignment.

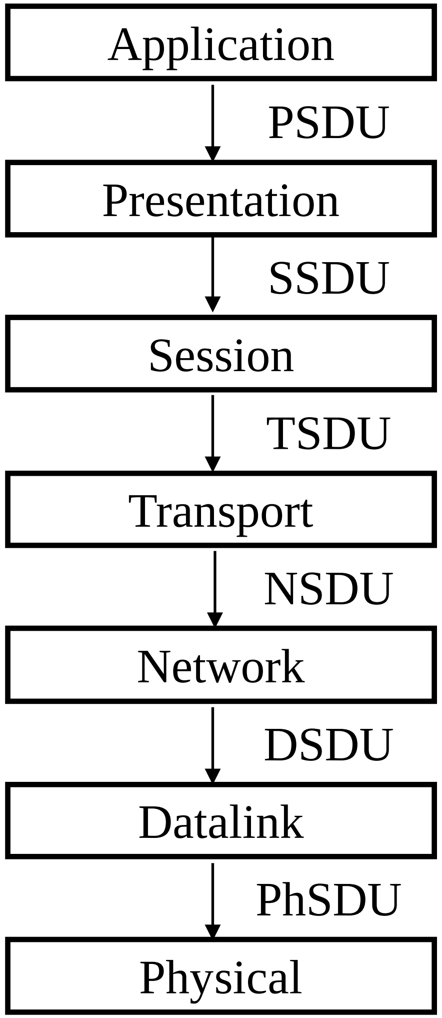
Student Questions

IEEE 802.11 Amendments (Cont)

- P802.11aj-2018: China millimeter wave. 59-64 GHz and 45 GHz.
- P802.11aq-2018: Pre-association discovery of services
- P802.11ak-2018: Enhancements for transit links within bridged networks. High-speed 802.11 links can be used as internal links like Ethernet and access.
- **P802.11ax**: High-Efficiency WLAN. Extension of 802.11ac. Expected Dec 2019.
- **P802.11ay**: Next Generation 60 GHz. Extension of 802.11ad. Expected Dec 2019.
- P802.11az: Next generation positioning. Expected Mar 2021.
- P802.11ba: Wake Up Radio, Expected Sep 2020
- P802.11bb: Light Communications. 300 nm-5000nm band. 10 Mbps to 5 Gbps. Expected Jul 2021

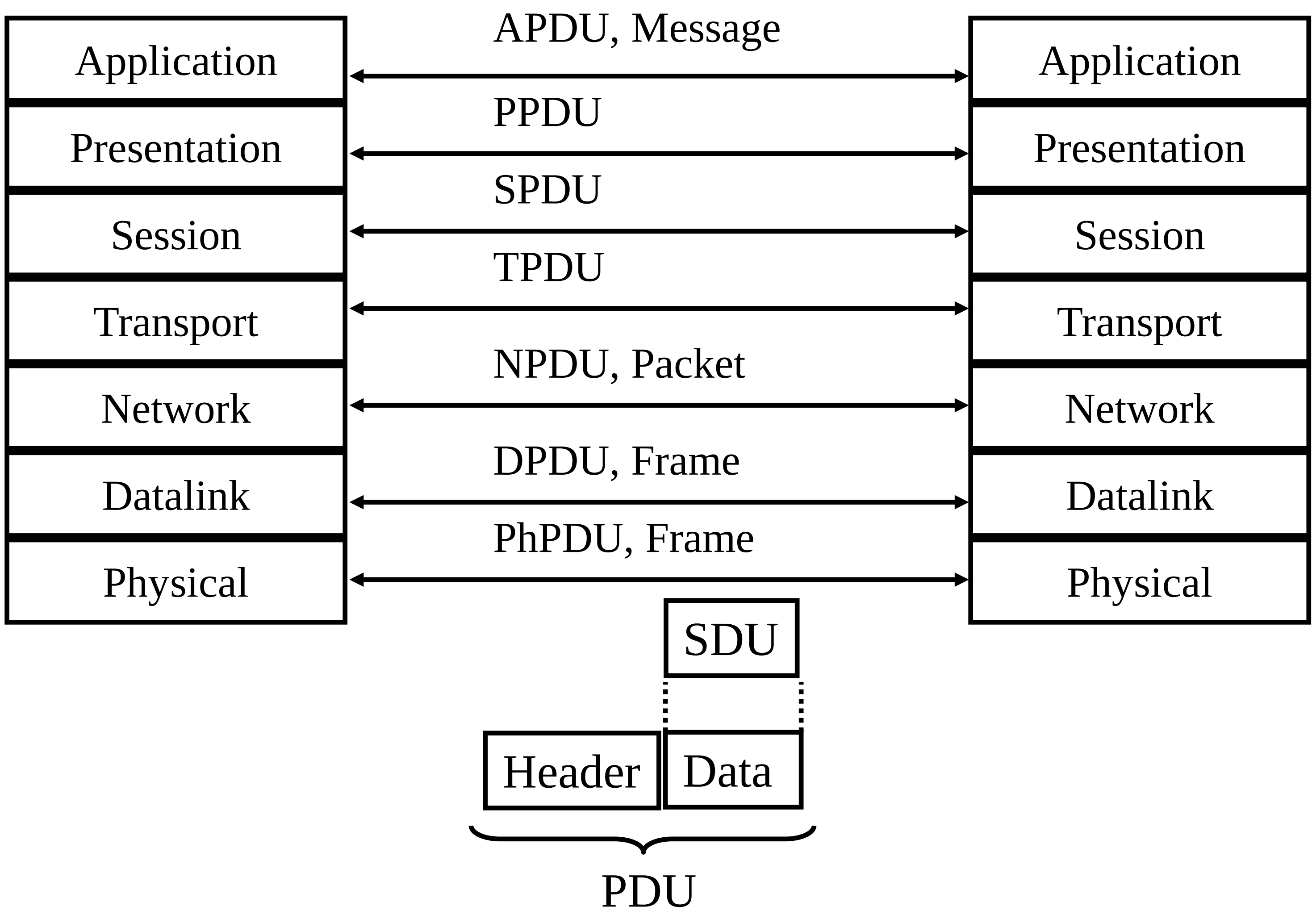
Student Questions

ISO/OSI: Service Data Unit (SDU)



Student Questions

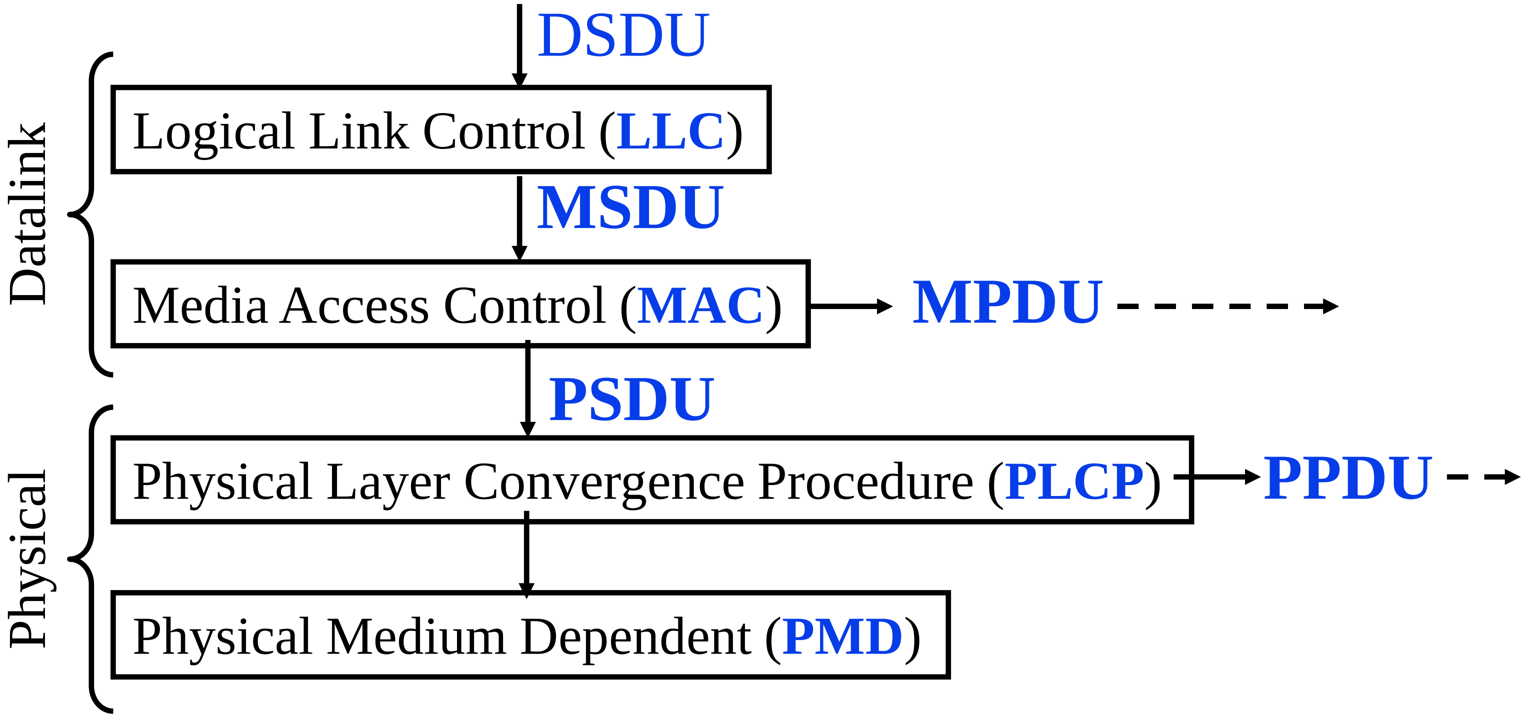
Protocol Data Unit (PDU)



Student Questions

802.11 Protocol Layers

- **Logical Link Control (LLC)**: Bridging
- **Media Access Control (MAC)**: CSMA/CA, Ack
- **Physical Layer Convergence Procedure (PLCP)**: Framing
- **Physical Medium Dependent (PMD)**: Modulation



Student Questions

- What does "S" mean in MSDU and PSDU?

S=Service
SDU=Service Data Unit
PDU=Protocol Data Unit

- Do MSDU and MPDU mean received and sent data units?

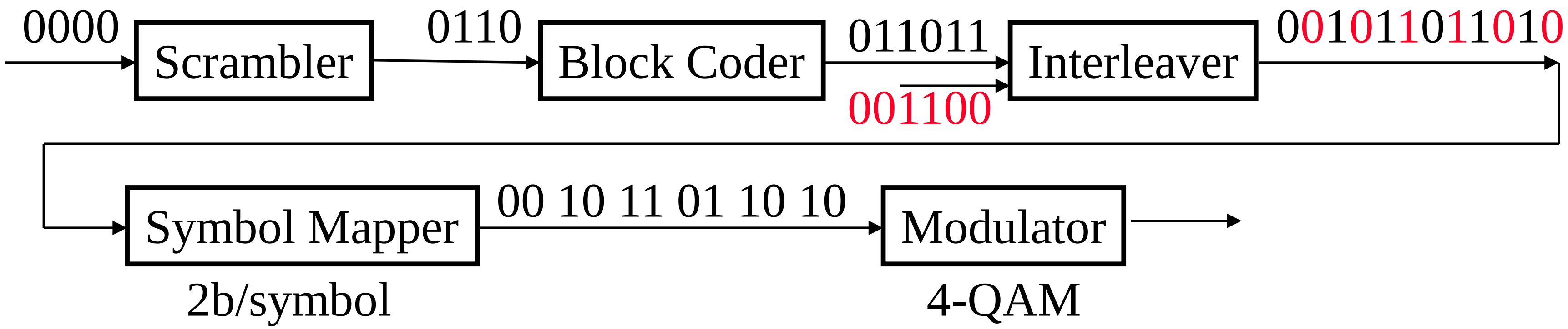
Service Data Unit = Input from the upper layer
PDU=Packets exchanged between two entities in the same layer.

- Is MPDU equal to PSDU?

Yes.

PLCP PDUs

- PMD includes scrambling (Randomization), coding (FEC), Interleaving, symbol mapping and modulation. For Example:



- PLCP adds a preamble and a header that helps receiving Phy to correctly decode the stream. For example:

Sync 010101…	Start of Frame Delimiter (**SFD**) 0000 1100 1011 1101	Signal	Service	Length	Header Error Check (**HEC**)
128b	16b	8b	8b	16b	16b
Preamble		Header			

Ref: P. Roshan and J. Leary, "802.11 Wireless LAN Fundamentals," Cisco Press, 2003, ISBN:1587050773, Safari book
V. Holla, "802.11b PLCP Frame Format," https://www.hitchhikersguidetolearning.com/2017/09/17/802-11b-plcp-frame-format/

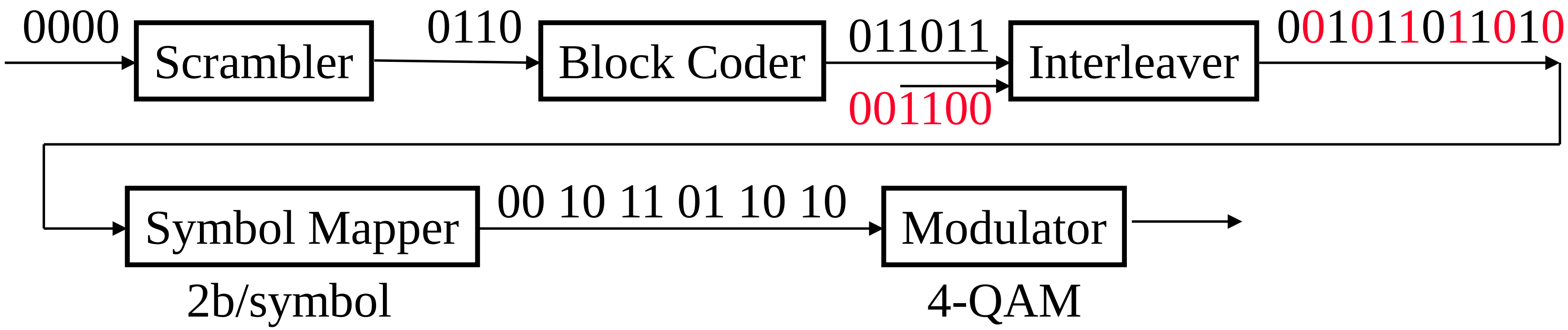
Student Questions

- "What is the purpose of the Interleaving step?
To avoid burst errors. Multi-bit errors may result in 1 bit error in multiple frames.
- Why do we need the Data rate/Signaling section if we have the Sync bits in the preamble? Don't the Sync bits define the data rate?
Signal bits indicate the modulation used and so determine the data rate. Service bits indicate further info about the oscillators used. Length indicates the size in microseconds.
- How many blocks can be interleaved together?
A small number (2-16)

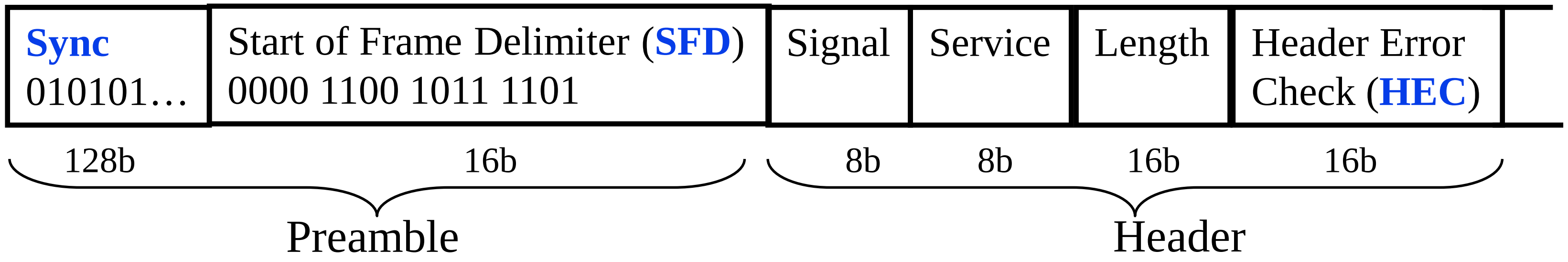
- Why do we need a scrambler?
Removes a long series of 0s and 1s.
https://www.rfwireless-world.com/Terminology/Advantages-and-Disadvantages-of-Scrambling-in-data-communication.html

PLCP PDUs

- PMD includes scrambling (Randomization), coding (FEC), Interleaving, symbol mapping, and modulation. For Example:



- PLCP adds a preamble and a header that helps to receive Phy to decode the stream correctly. For example:



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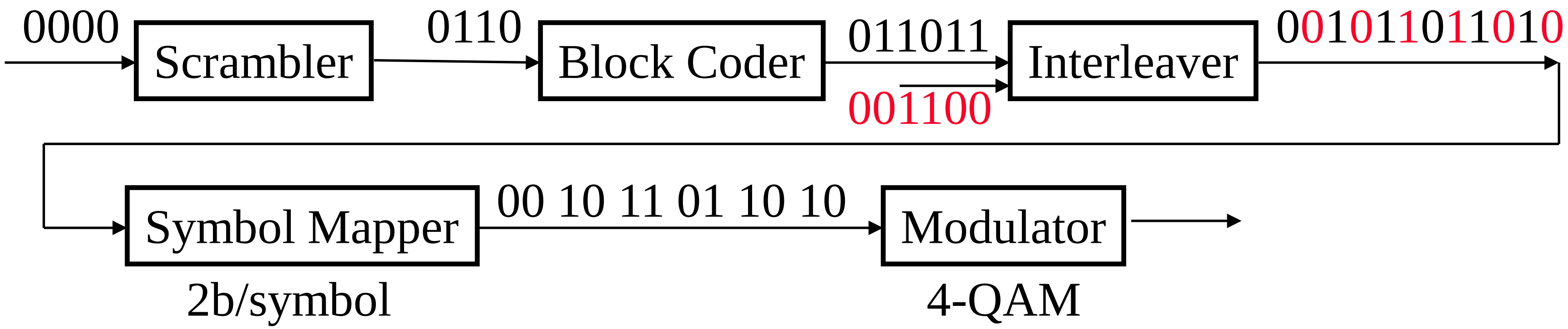
Student Questions

- In the video, you say 80 b for the sync, but the slide says 128 b. Which is the correct one?
  Although the standard specifies different lengths (possibly at different speeds), 128 b is sufficient for this class.
- Does the scramble, coding, inter, and leaving pipeline work with a single packet or multiple packets? If it works with multiple packets, this process introduces a significant amount of latency compared to Ethernet.
  It works on every packet. This causes complexity. Transmission delay is the same as Ethernet at the same speed.

PLCP PDUs

- PMD includes scrambling (Randomization), coding (FEC), Interleaving, symbol mapping, and modulation. For Example:



- PLCP adds a preamble and a header that helps to receive Phy to decode the stream correctly. For example:

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128b	16b	8b	8b	16b	16b
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V. Holla, "802.11b PLCP Frame Format," https://www.hitchhikersguidetolearning.com/2017/09/17/802-11b-plcp-frame-format/

Student Questions

- Could you clarify how exactly PMD and PLCP work together?

See Slide 6-10.

- What section of the frame does the "length " refer to?

Length = microseconds to transmit

- What are signal and service?

Signal = Data rate => Modulation
Service = implementation detai,ls e.g., oscillators used

- For which sections are HEC calculated?

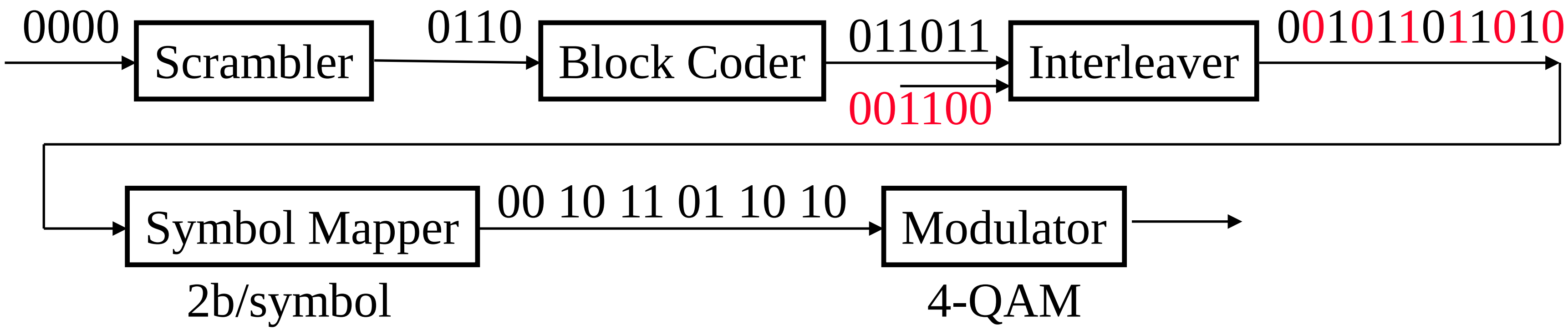
Header

- ❖ Why is the coding rate here 2/3?

The block coder is sending out 6 bits for 4 bits.
4/6=2/3

PLCP PDUs

- PMD includes scrambling (Randomization), coding (FEC), Interleaving, symbol mapping, and modulation. For Example:



- PLCP adds a preamble and a header that helps to receive Phy to decode the stream correctly. For example:

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V. Holla, "802.11b PLCP Frame Format," https://www.hitchhikersguidetolearning.com/2017/09/17/802-11b-plcp-frame-format/

Student Questions

- The video says that PLCP adds a header, but the 1st quiz says L2 PDU has the header. I wonder whether it's PPDU or MPDU that has the header.

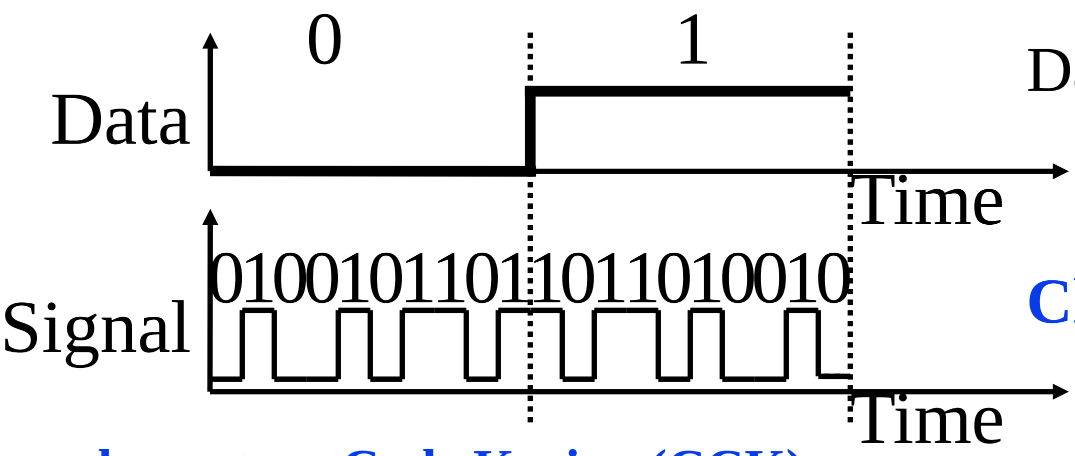
Each layer has its header. PLCP adds its header. L2 adds its header too.

- Can the block coder change the first 4 bits?

Yes.

IEEE 802.11b-1999

- Direct Sequence Spread Spectrum:



Data **Bits**

Chips = Code bits

- **Complementary Code Keying (CCK)**: Multi-bit symbols with appropriate code to minimize errors
- IEEE 802.11-1997: ½ rate binary convolution encoder, 1 bit/symbol, 11 chips/symbol, DQPSK (2 b/Hz) = ½ ×1 × 1/11 × 2 × 22 = 2 Mb/s using 22 MHz
- IEEE 802.11b-1999: ½ rate binary convolution encoder, 8 bit/symbol, 8 chips/symbol, CCK (1 b/Hz) = ½ ×8 × 1/8 × 1 × 22 = 11 Mb/s using 22 MHz

Ref: P. Roshan and J. Leary, "802.11 Wireless LAN Fundamentals," Cisco Press, 2003, ISBN:1587050773, Safari book

Student Questions

- Could you go over the equations on slide again and explain where the numbers are coming from?

The variables are indicated just before the equal sign.

- Can you go over what are the Chips are again?

Each data bit is encoded as multiple code bits, called chips.

- Can you explain the multiplication to get 11 Mb/s for 802.11b?

The variables are indicated just before the equal sign.

- Can you please explain the numbers in point 4?

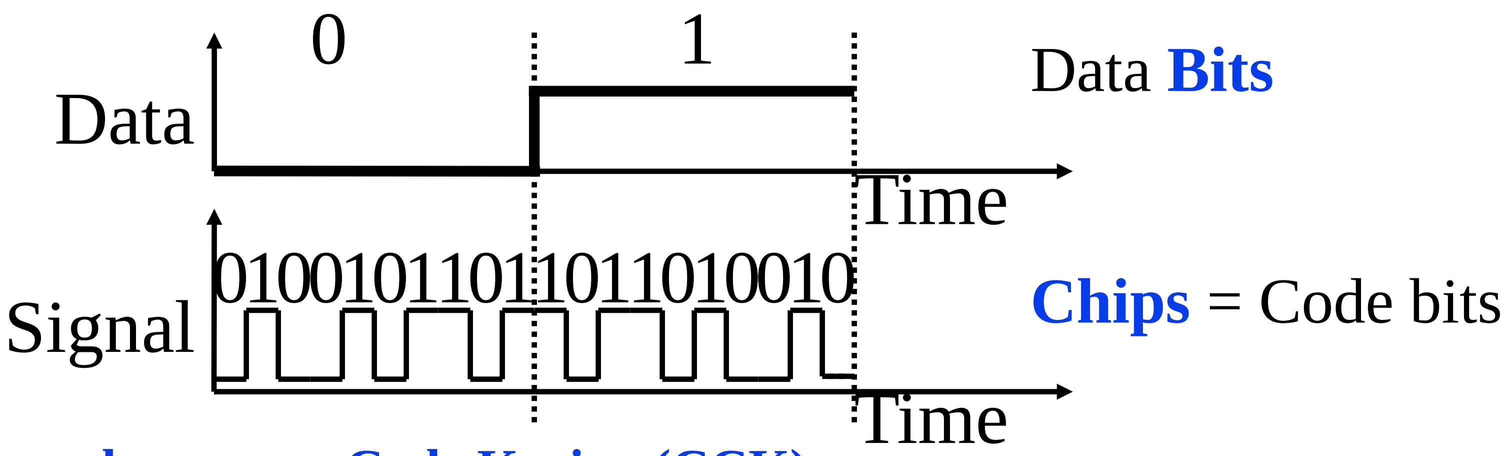
Sure.

- What is the relation between DSSS, CDMA, CCK, and QPSK?

CCK and QPSK are modulation methods. CDMS and DSSS are multiple access methods. There are many ways to do DSSS. CDMA is one of them.

IEEE 802.11b-1999

- Direct Sequence Spread Spectrum:



- **Complementary Code Keying (CCK)**: Multi-bit symbols with appropriate code to minimize errors
- IEEE 802.11-1997: ½ rate binary convolution encoder, 1 data bit/symbol, 11 chips/symbol, DQPSK (2 Code bits/Hz) = ½ ×1 × 1/11 × 2 × 22 = 2 Mb/s using 22 MHz
- IEEE 802.11b-1999: ½ rate binary convolution encoder, 8 data bit/symbol, 8 chips/symbol, CCK (1 Code bit/Hz) = ½ ×8 × 1/8 × 1 × 22 = 11 Mb/s using 22 MHz

Ref: P. Roshan and J. Leary, "802.11 Wireless LAN Fundamentals," Cisco Press, 2003, ISBN:1587050773, Safari book

Student Questions

- Why is DQPSK's unit bit/Hz instead of bit/symbol?

Modulation works with code bits. It takes two code bits and produces one cycle (Hz).

- Why is DQPSK not indicating 2 bits/symbol?

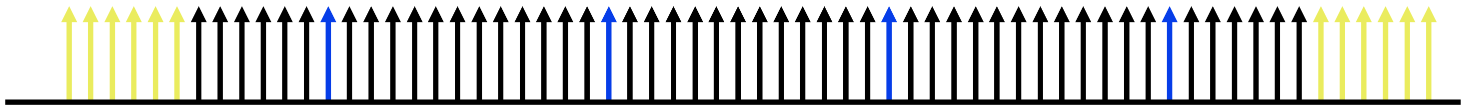
Symbols for DQPSK are different from symbols for DSSS.

- Why is chip rate 11 chips/symbol instead of chips/bit? If we use these units, it cannot get b/s units.

DSSS in 11b works with a group of 8 bits.

IEEE802.11a-1999

- OFDM: 64 subcarriers in 20 MHz. 6 subcarriers at each end are used as guard (i.e., not used), 4 as pilots, leaving 48 for data ⇒ 12 MHz for data



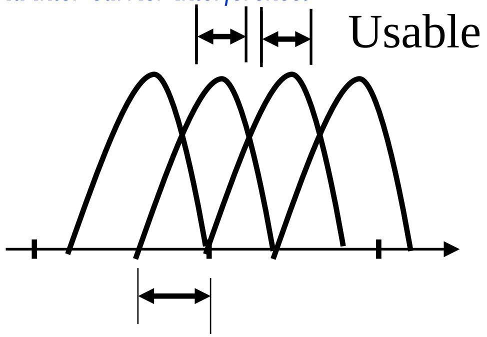
Coding	b/Hz	Mb/s	FEC	Net
BPSK	1	12	1/2	6 Mb/s
BPSK	1	12	3/4	9 Mb/s
QPSK	2	24	1/2	12 Mb/s
QPSK	2	24	3/4	18 Mb/s
16-QAM	4	48	1/2	24 Mb/s
16-QAM	4	48	3/4	36 Mb/s
64-QAM	6	72	2/3	48 Mb/s
64-QAM	6	72	3/4	54 Mb/s

- 5 GHz band ⇒ Expensive at that time

Student Questions

- How did we get 12 MHz? Shouldn't it be 15 MHz?

20/64 MHz/subcarrier
× 48 subcarriers
= 15 MHz
However, subcarriers may use only part of the width to avoid inter-carrier interference.



- 5.4 GHz band or 5.8GHz Band?

5 GHz band

IEEE 802.11g-2003

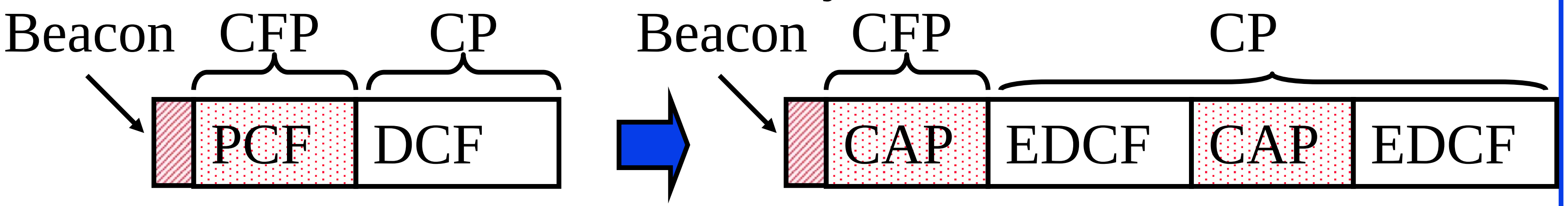
- OFDM – Same as 802.11a ⇒ 54 Mbps
- 2.4 GHz band ⇒ Cheaper than 802.11a
- Fall back to 802.11b CCK

Student Questions

IEEE 802.11e-2005 (Enhanced QoS)

- Backward compatible:
  $\Rightarrow$ Non-802.11e terminals can receive QoS-enabled streams

1. Hybrid Coordination Function (**HCF**) w two components
   a. Controlled Access Phase (CAP)
      = Contention Free Access and Hybrid Polling
   b. Contention-based Access: Enhanced DCF (**EDCF**)
2. **Direct Link**: Traffic sent directly between two stations
3. **Frame bursting** and Group Acknowledge
4. Multiple **Priority** levels
5. Automatic Power Save Delivery



Student Questions

- How does hybrid polling differ from what we already learned about the contention-free period? What is new?

Four classes of service inside the station.

- HCF has two components: Hybrid polling and EDCF. So, why did you substitute PCF with HCF in the figure?

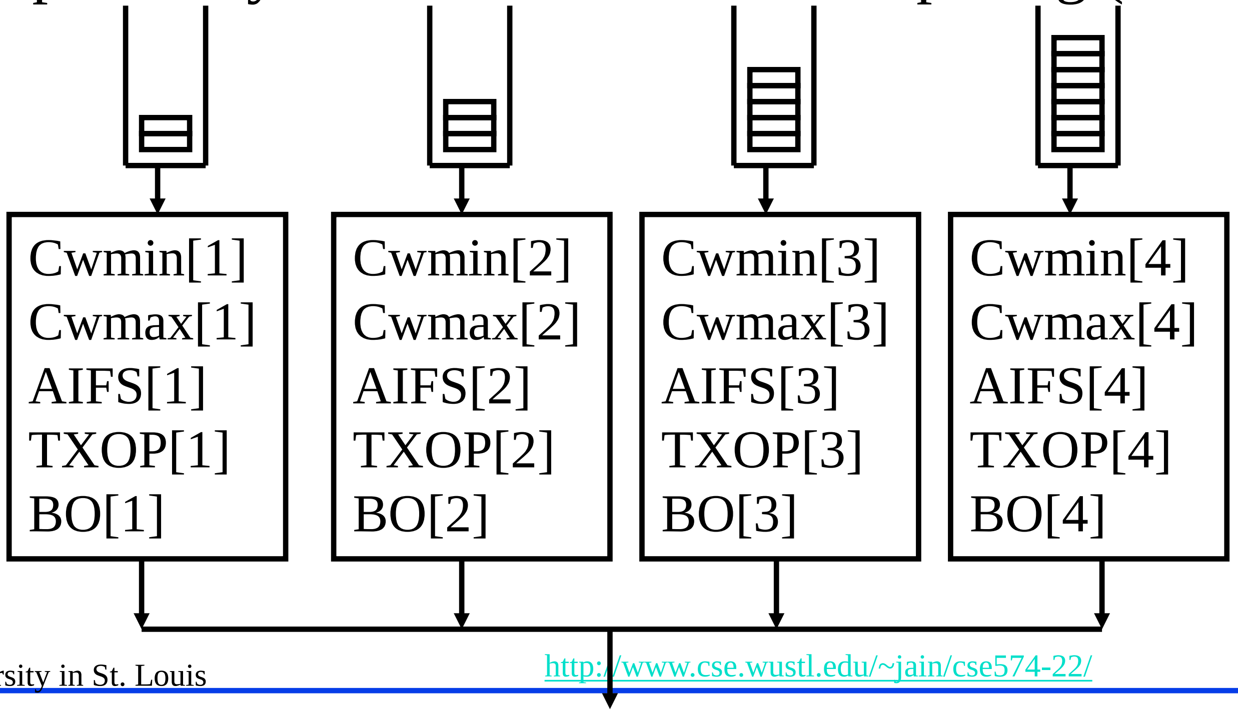
The figure and text have been corrected.

- What is the difference between classes of service and priority levels?

Priorities imply an order. One comes before two. Classes of service are unordered.

Enhanced DCF

- Up to 4 queues. Each Q gets a different set of four Parameters:
  - CW_{min}/CW_{max}
  - Arbitrated Inter-Frame Spacing (**AIFS**) = DIFS
  - Transmit Opportunity (**TXOP**) duration
- DIFS replaced by Arbitrated Inter-frame Spacing (AIFS)



Student Questions

- So are AIFS values different per queues? also, does EDCF mean we randomize which queue each transmission is going to use?

No. Each packet comes with the queue # indicated in the transmission request.

- Why higher priority only can transmit fewer frames?

So that space is left for lower class frames.

- What is BO?

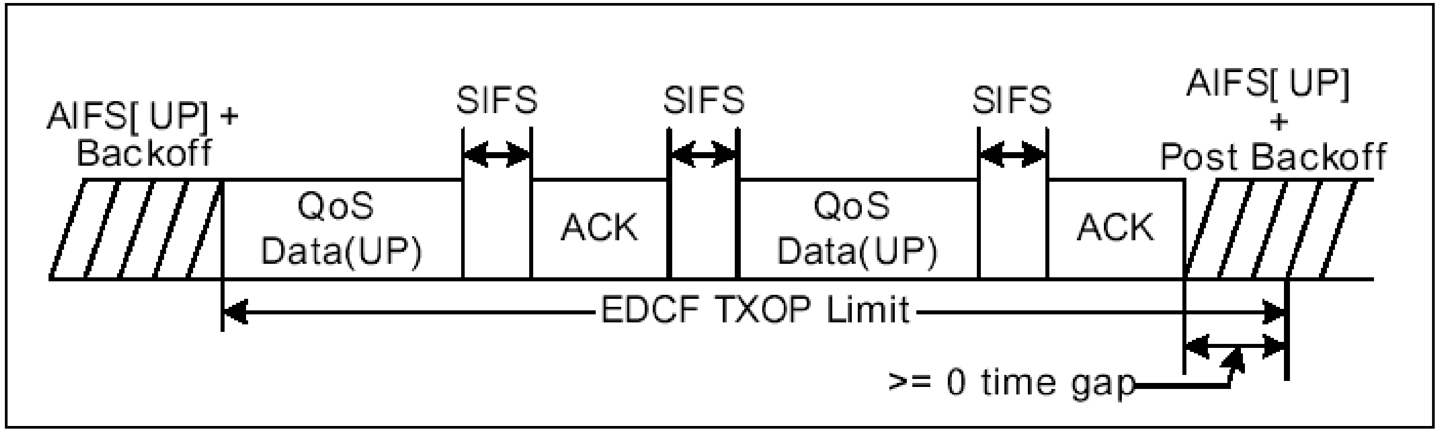
Backoff

- Each Q gets 4 or 5 different parameters.

Yes.

Frame Bursting

- EDCF parameters announced by the access point in beacon
- Can not overbook higher priorities ⇒ Need admission control
- EDCF allows multiple frame transmission
- Max time = Transmission Opportunity (TXOP)
- Voice/gaming has high priority but small burst size
- Video/audio has lower priority but large burst size



Student Questions

- What happens if a frame is dropped during frame bursting? Will you have to send the whole burst again?

No. Each frame is acked as indicated in the diagram. Only the lost frame will be retransmitted.

- The quiz in the video mentioned that enhanced DCF allows multiple classes of service, and the slide shows that EDCF allows multiple frame transmission. Is there any relationship between them?

EDCF allows both multiple classes of service and frame bursting.

Frame Bursting

- EDCF parameters announced by the access point in beacon
- Can not overbook higher priorities $\Rightarrow$ Need admission control
- EDCF allows multiple frame transmission
- Max time = Transmission Opportunity (TXOP)
- Voice/gaming has high priority but small burst size
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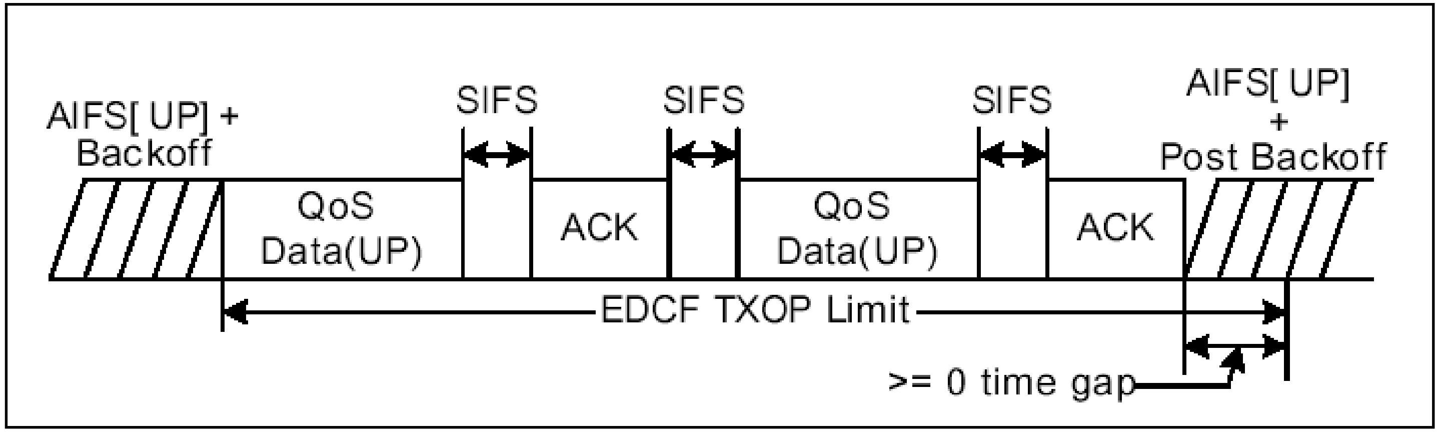


Student Questions

- In the diagram, does QoS mean the quality of service?

Yes.

- What is AIFS, and how long is it?

See Slide 6-16. AIFS replaces DIFS.

- Why does the voice have a small burst size? I wonder if it should be voice/audio and video/gaming.

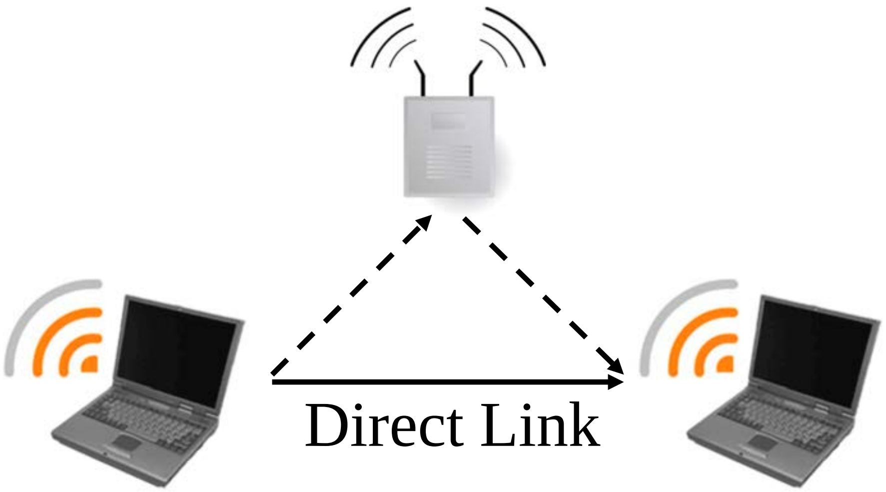
Gaming, e.g., shooting a gun, has a high priority.

- How is TXOP determined?

Programmed the administrator. Default values by the manufacturer, or standards.

Direct Link

- Any station can transmit to any other station in the same BSS ⇒ No need to go through AP



Student Questions

- For direct links, do the clients also send a beacon to announce a start?

There is no beacon. The 4-way handshake is still there. All other stations hear it.

Automatic Power Save Delivery (APSD)

- Unscheduled APSD (U-APSD):
  - AP announces waiting frames in the beacon
  - When stations wake up, they listen to the beacon.
  - Send a polling frame to AP.
  - AP sends frames.
- Scheduled APSD (S-APSD):
  - Station tells AP its wakeup schedule
  - AP sends a frame on schedule. No need for polling.
- Pre-802.11e: AP announces in Beacon. STA polls. AP sends one frame with more bits. STA polls. AP sends the next frame…

Student Questions

Homework 6A

Fill in the blanks:

1. 802.11a uses ________________ in ________________ GHz band.
2. 802.11b uses ________________ in ________________ GHz band.
3. 802.11g uses ________________ in ________________ GHz band.
4. 802.11n is a ________________ band technology.
5. ________________ specification deals with quality of service in 802.11 networks.
6. The key new concept that 802.11ac introduced is that of ________________.
7. IP packets constitute ________________ for 802.11 MAC layer without LLC.
8. MPDUs from MAC layer are used to form ________________ and ________________ in the PHY layer.
9. ________________ is used to randomize bit stream before ECC coding.
10. ________________ combines the bits from several symbols to overcome burst errors.
11. The code bits obtained by Direct Sequence Spread Spectrum are called ________________.
12. IEEE 802.11e replaced DCF with ________________ and PCF with ________________.

Student Questions

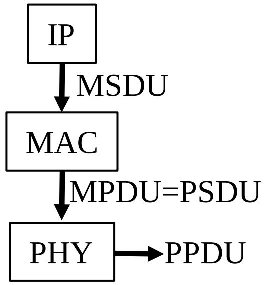
- Should ECC be FEC in point 9?

ECC = Error Correction Code
FEC =Forward Error Connection
Both are equivalent. In storage, they use ECC. In networking, we use FEC.

- Can you please review the solutions for homework 6A and 6B?

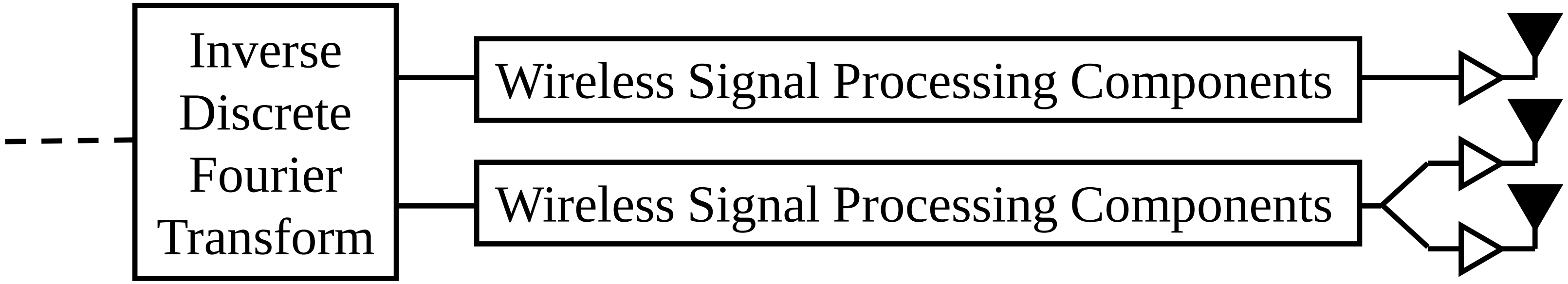
Sure.

- How the MPDU relates to the PHY layer? Isn't PDU provided horizontally?



IEEE 802.11n-2009

1. **MIMO** (Multi-input Multi-Output):
   $n \times m:k \Rightarrow n$ transmitters, m receivers, k streams
   k is the number of parallel radio chains inside $\leq$ # of Antennas
   $\Rightarrow k$ times more throughput
   E.g., 2×2:2, 2×3:2, 3×2:2, 4×4:4
2. **Diversity**: More receive antennas than the number of streams. Select the best subset of antennas.
3. **Beam Forming**: Focus the beam directly on the target antenna
4. **MIMO Power Save**: Use multiple antennas only when needed



Student Questions

- Just to clarify, for 3x2:2 we are using only 2 streams out of 6 possible streams, right?

Yes, this saves the cost of the electronics required to process all 6 streams.

- Why 3x2:2 instead of 2x2:2 if they have the same throughput = 2?

Each stream requires internal hardware.

- Do the different antennas broadcast at different frequency bands in MIMO?

No.

IEEE 802.11n-2009 (Cont)

5. **Frame Aggregation**: Pack multiple input frames in side a frame ⇒ Less overhead ⇒ More throughput
6. **Lower FEC Overhead**: 5/6 instead of ¾
7. **Reduced Guard Interval**: 400 ns instead of 800 ns
8. **Reduced Inter-Frame Spacing** (SIFS=2 us, instead of 10 us)
9. **Greenfield Mode**: Optionally eliminate support for a/b/g (shorter and higher rate preamble)
10. **Dual Band**: 2.4 and 5.8 GHz
11. **Space-Time Block Code**
12. **Channel Bonding**: Use two adjacent 20 MHz channels
13. **More subcarriers**: 52+4 instead of 48+4 with 20 MHz, 108+6 with 40MHz

- 54 Mbps with 64-QAM ¾ for 3200 Data+800 GI for a/g

4 Streams × 64-QAM × 5/6 FEC × 40 MHz w 400 ns ⇒ 600 Mbps

$4\times(6/6)\times[(5/6)/(3/4)]\times(108/48)\times[(3200+800)/(3200+400)]\times54$

Student Questions

- "How do we not lose data from frame aggregation?

Aggregation ≠ Less Loss
Aggregation = Less overhead

- "As per the quiz, could you answer ""What is the bandwidth of the wireless channel (in MHz) used in IEEE 802.11b""? Why is 2.4 Mhz = 2400 MHz wrong?

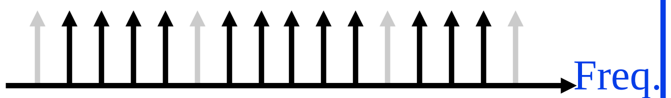
Band ≠ Bandwidth
Bandwidth of each channel is only 20 MHz. The band may be 2.4 GHz or 5.8 GHz.

- Could you please explain the calculation at the bottom of the slide?

Sure.

- Why 48+4? We had 48 subcarriers for data.

4 for pilot and guards.



- Greenfield vs. Brownfield?

Green=New install, Brown=Update

IEEE 802.11n-2009 (Cont)

5. **Frame Aggregation**: Pack multiple input frames in side a frame ⇒ Less overhead ⇒ More throughput
6. **Lower FEC Overhead**: 5/6 instead of ¾
7. **Reduced Guard Interval**: 400 ns instead of 800 ns
8. **Reduced Inter-Frame Spacing** (SIFS=2 us, instead of 10 us)
9. **Greenfield Mode**: Optionally eliminate support for a/b/g (shorter and higher rate preamble)
10. **Dual Band**: 2.4 and 5.8 GHz
11. **Space-Time Block Code**
12. **Channel Bonding**: Use two adjacent 20 MHz channels
13. **More subcarriers**: 52+4 instead of 48+4 with 20 MHz, 108+6 with 40MHz

- 54 Mbps with 64-QAM ¾ for 3200 Data+800 GI for a/g

4 Streams × 64-QAM × 5/6 FEC × 40 MHz w 400 ns ⇒ 600 Mbps
4×(6/6)×[(5/6)/(3/4)]×(108/48)×[(3200+800)/(3200+400)]×54

Student Questions

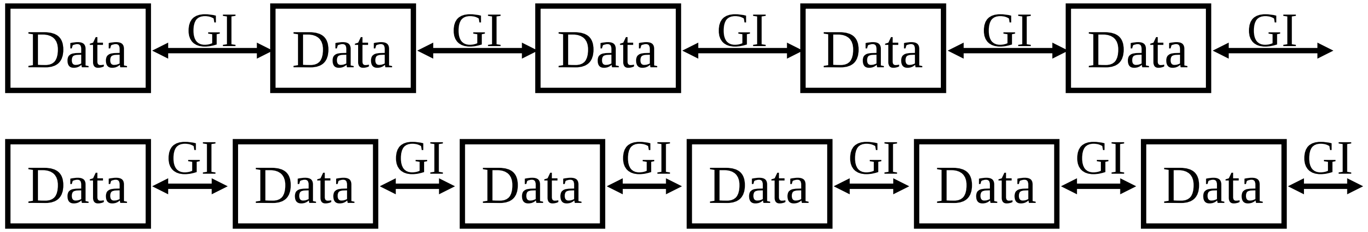
- Why is the last line not [(3200+400)/(3200+800)]?

Because GI is inversely related to throughput.

- How can we calculate the usable bandwidth if we have the number of carriers, and guard interval length in seconds?

Covered in a later module.

Guard Interval



- Rule of Thumb: Guard Interval = 4 × Multi-path delay spread
- Initial 802.11a design assumed 200 ns delay spread
  ⇒ 800 ns GI + 3200 ns data ⇒20% overhead
- Most indoor environments have smaller 50-75 ns
- So if both sides agree, 400 ns can be used in 802.11n
  ⇒ 400 ns GI + 3200 ns data ⇒11% overhead

Ref: M. Gast, "802.11n: A Survival Guide," O'Reilly, 2012, ISBN:978-1449312046, Safari Book

Student Questions

- How would the modification work? If both sides agree, will it change by calculation, or is it written in the standard? Is this automatic or manual?

The standard specifies GI values. Value adjusted based on error rate.

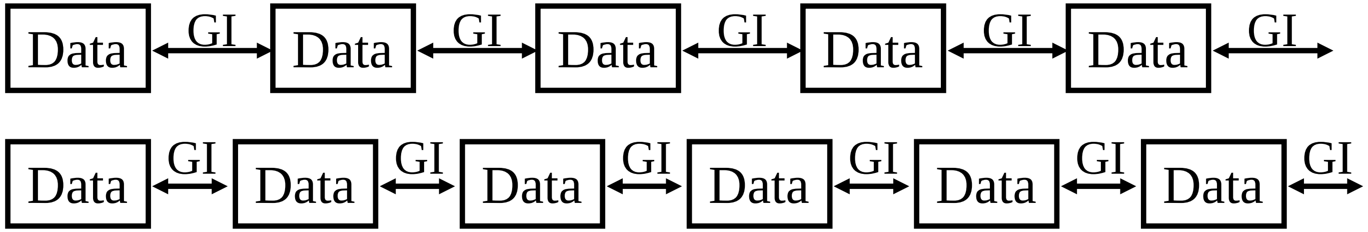
- Is the primary purpose of guard interval to avoid interference?

To avoid inter-symbol interference.

- Are guard intervals in place when transmitting any data at any time? Or is it only implemented for a particular design?

Any data at any time. It applies to all bits.

Guard Interval



- Rule of Thumb: Guard Interval = 4 × Multi-path delay spread
- Initial 802.11a design assumed 200ns delay spread
  ⇒800 ns GI + 3200 ns data ⇒20% overhead
- Most indoor environments have smaller 50-75 ns
- So if both sides agree, 400 ns can be used in 802.11n
  ⇒ 400 ns GI + 3200 ns data ⇒11% overhead

Student Questions

- How do you determine the correct length of the guard interval? It would make sense to be shorter, but that could lead to a high packet error rate.

Standard covers a high percentage of cases.

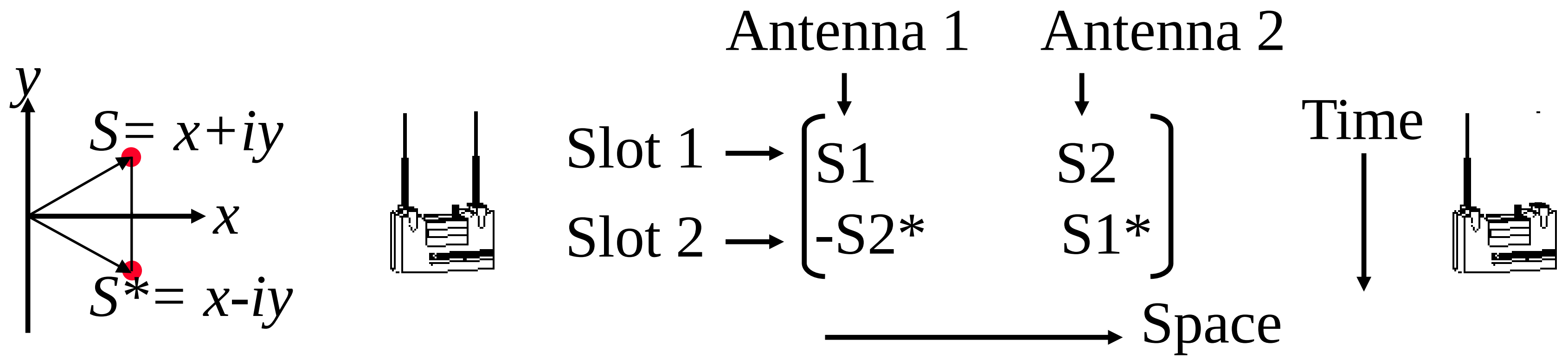
- The multipath spread delay. Is it the difference between the first received symbol and the last received duplicate of the symbol?

Spread = Received width-Sent width

Ref: M. Gast, "802.11n: A Survival Guide," O'Reilly, 2012, ISBN:978-1449312046, Safari Book

Space Time Block Codes (STBC)

- Invented 1998 by Vahid Tarokh.
- Transmit multiple redundant copies from multiple antennas
- Precisely coordinate distribution of symbols in space and time.
- Receiver combines multiple copies of the received signals optimally to overcome multipath.
- Example: Two antennas: Two symbols in two slots ⇒ Rate 1



S1* is complex conjugate of S1 ⇒ columns are orthogonal

Student Questions

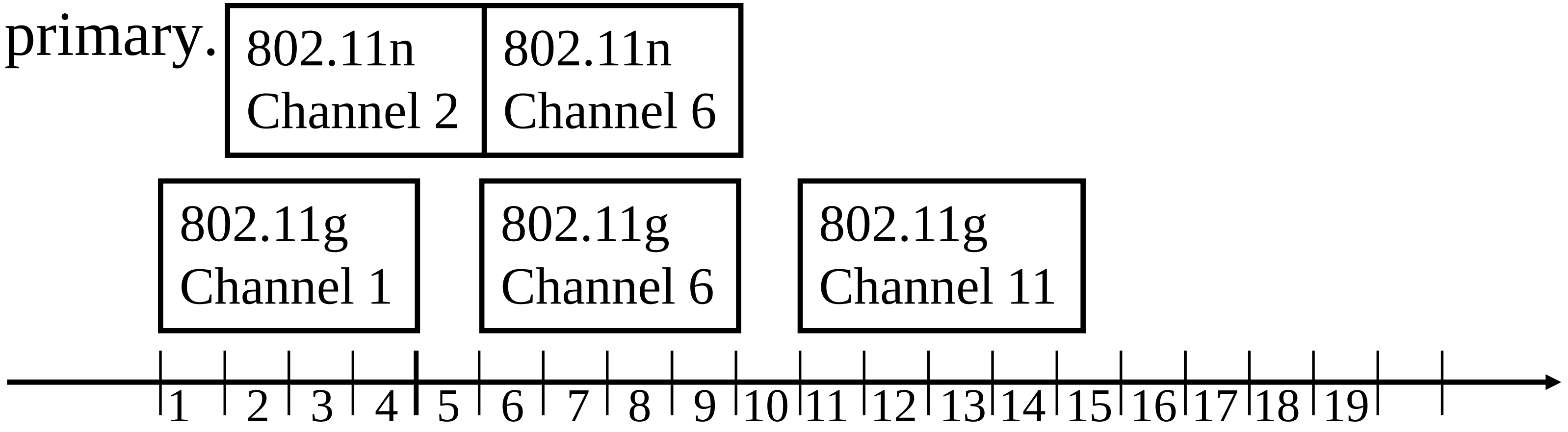
- Can you explain the diagram at the bottom?
  1. *There are two antennas (left and right in space). Shown horizontally.*
  2. *We take two consecutive slots in time (Slot 1 and Slot 2). Shown vertically.*
  3. *We take two symbols that we need to transmit (S1 and S2)*
  4. *In Slot 1: on Antenna 1, we transmit S1. On Antenna 2, we transmit S2*
  5. *In Slot 2: on Antenna 1, we transmit -S2*, where * is complex conjugate. On Antenna 2, we transmit S1*.*
  6. *This way we transmitted two symbols in two slots. Although the throughput rate is the same as that with one antenna. The effective throughput is higher since the noise can be canceled out after reception.*

❖ In the previous student question, it said, "In Slot 1 Antenna 2, we transmit -S2*, In Slot 2, Antenna 1, we transmit S2." However, from the diagram, it seems like transmit s2 in slot 1 antenna2 and transmit -s2* in slot 2 antenna 1.

Error corrected. Thank you.

802.11n Channel Bonding

- Two adjacent 20 MHz channels used
- OFDM: 52+4 instead of 48+4 with 20 MHz, 108+6 with 40MHz (No guard subcarriers between two bands)
- **Primary 20 MHz channel**: Used with stations not capable of channel bonding
- **Secondary 20 MHz channel**: Just below or just above primary.



Ref: M. Gast, "802.11n: A Survival Guide," O'Reilly, 2012, ISBN:978-1449312046, Safari Book

Student Questions

- Which are the primary and secondary channels in the diagram?

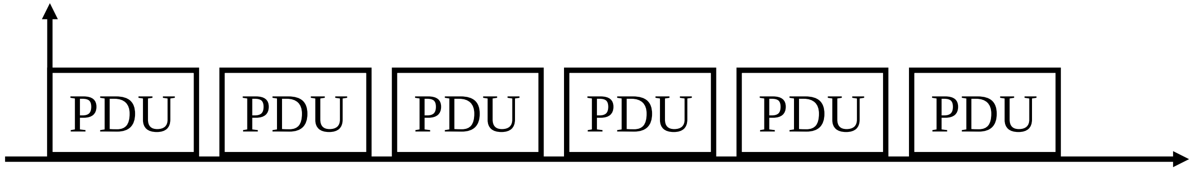
On the top row, two channels are bonded together. Either one can be primary.
On the 2nd row, none of the channels are bonded. So each user has only one (primary) channel.

- I wonder why we bond specifically channels 2 and 6.

The band is divided into 5 MHz channels. We use 20 MHz by combining 4 consecutive channels.
Channel 2 = 2,3,4,5
Channel 6 = 6,7,8,9

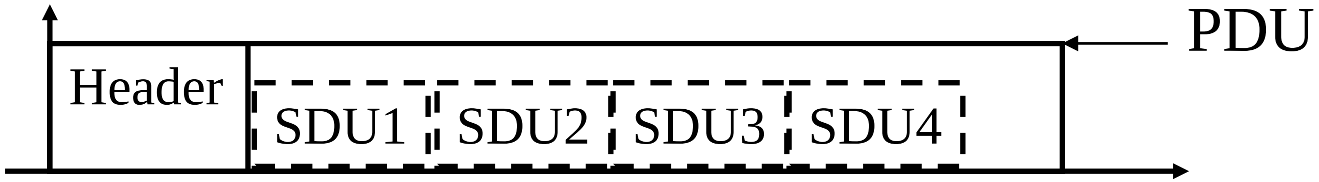
Frame Aggregation

- **Frame Bursting**: Transmit multiple PDUs together



- **Frame Fragmentation**: SDU fragment in a PDU

- **Frame Aggregation**: Multiple SDUs in one PDU
  All SDUs must have the same transmitter and receiver address



- Can combine any 2 or all of the above

Student Questions

- What is the difference between Frame Fragmentation and Frame Aggregation?

Fragmentation = n out of 1
Aggregation = 1 out of n

- Can you please explain Frame Fragmentation again?

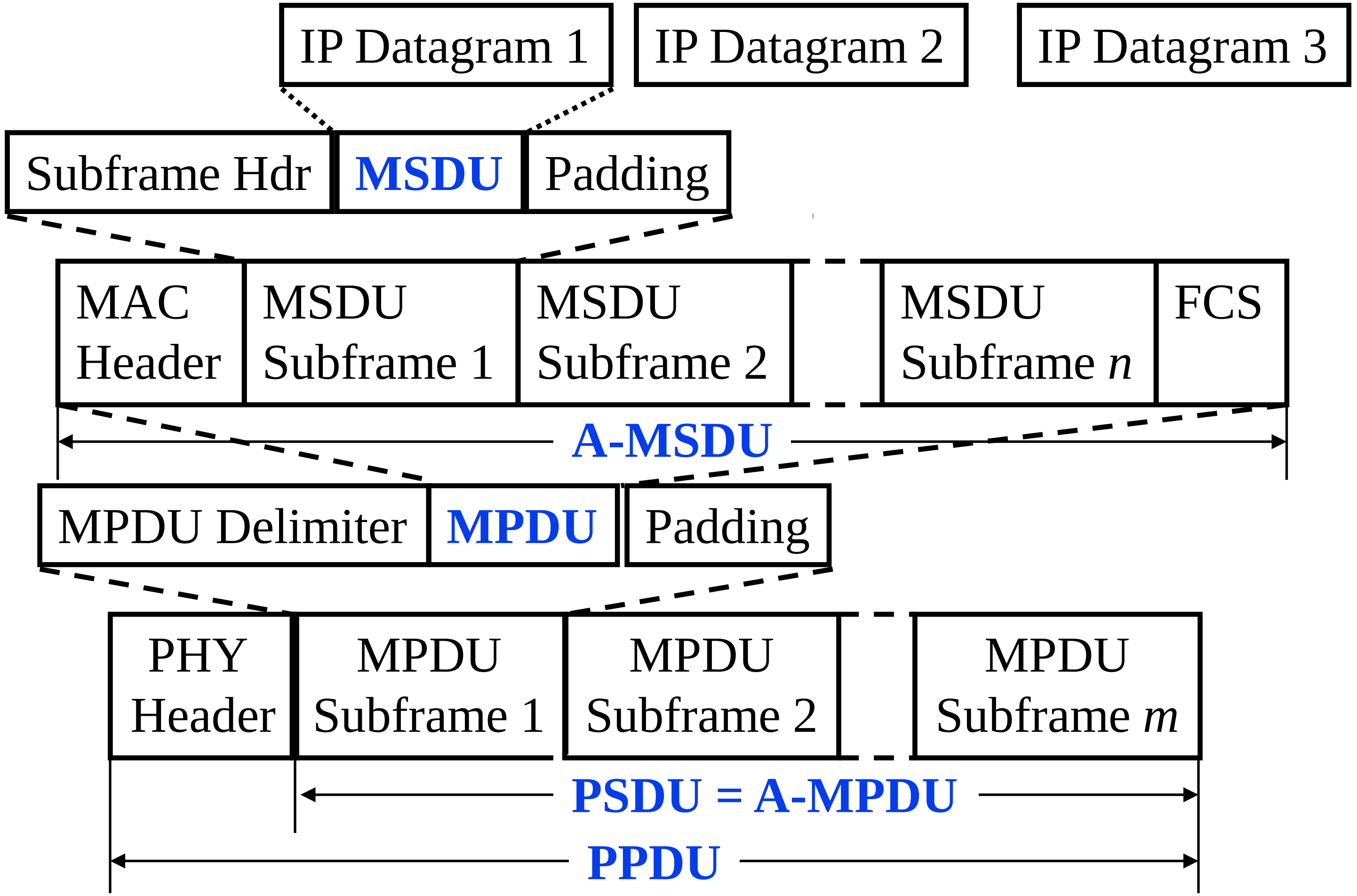
Sure.

- How many RTSs are used in each of the 3 cases?

One 4-way handshake per PDU. 6, 3, and 1 PDUs, respectively, in the three cases.

End of Part 1

802.11n Frame Aggregation



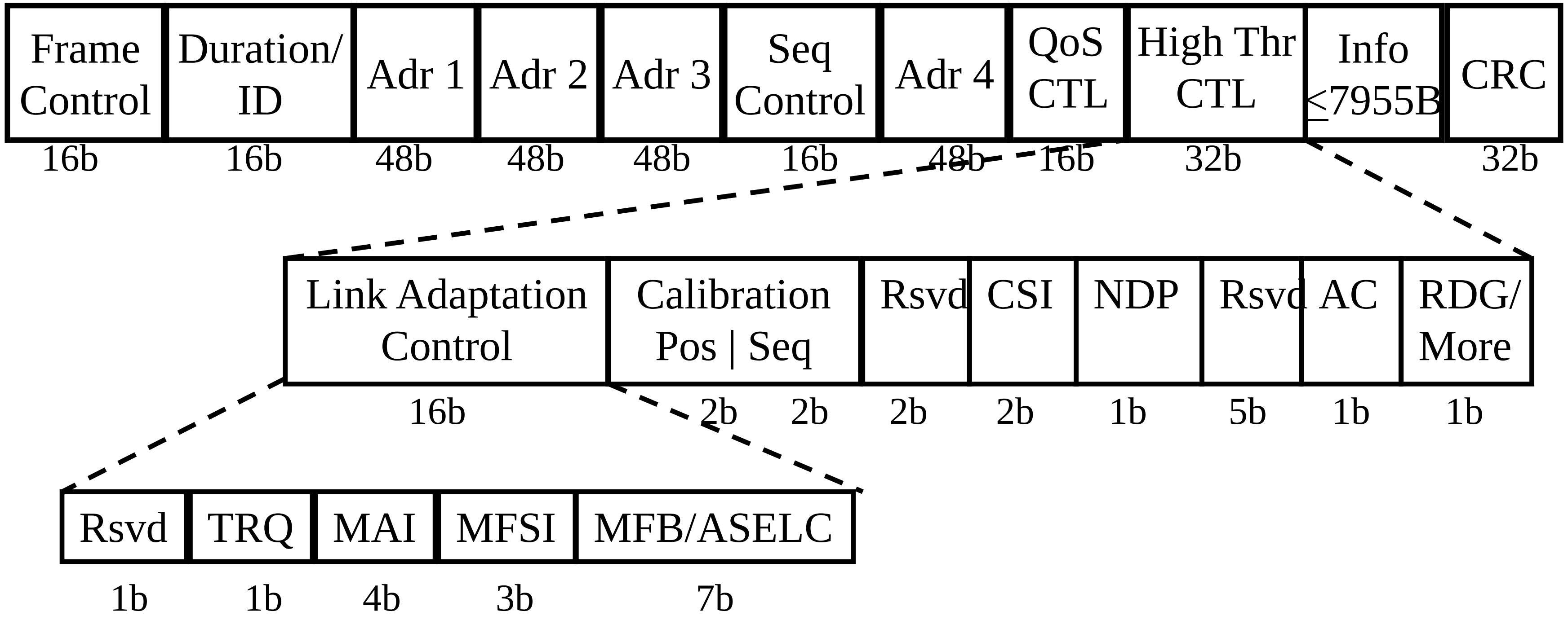
Ref: D. Skordoulis, et al., "IEEE 802.11n MAC Frame Aggregation Mechanisms for Next-Generation High-Throughput WLANs," IEEE Wireless Magazine, February 2008, http://tinyurl.com/k2gvl2g

Student Questions

- Can you aggregate frames other than MAC and PHY?

Frame/packet aggregation can be done at any layer provided the protocol being used at that layer allows it. For example, some applications do packet aggregation at Layer 5.

802.11n MAC Frame



- For first RTS, SIFS is used in stead of DIFS. Thus, 11n stations have priority over 11abg
- 802.11n introduced a “High Throughput Control” field to exchange channel state information

Student Questions

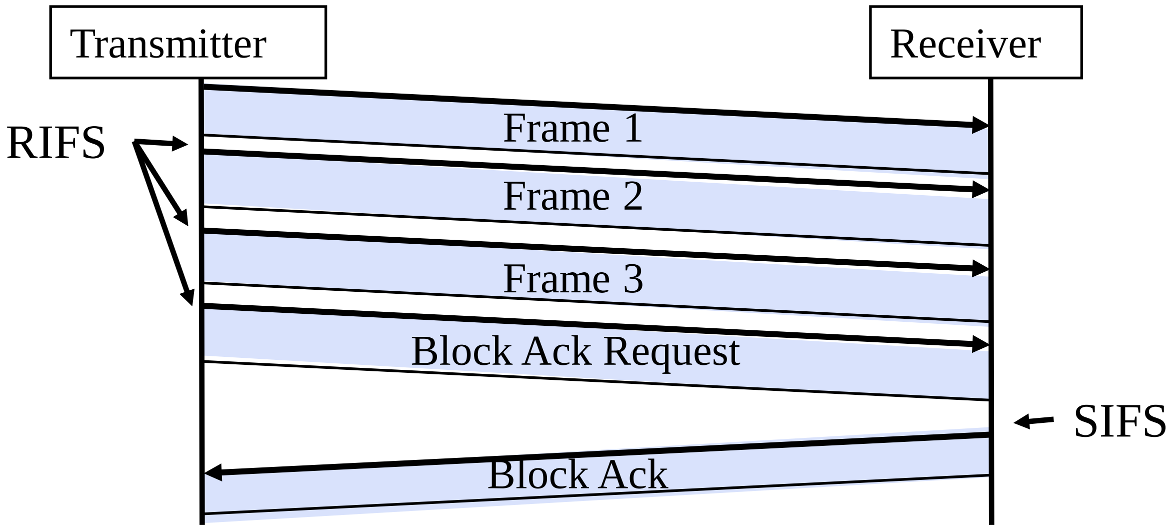
- Only the first RTS after connecting to the network?

See Reduced IFS in updated Slide 6-28b

802.11n MAC Frame

Frame Control	Duration/ ID	Adr 1	Adr 2	Adr 3	Seq Control	Adr 4	QoS CTL	High Thr CTL	Info ≤7955B	CRC
16b	16b	48b	48b	48b	16b	48b	16b	32b		32b

- IEEE 802.11n introduced Reduced Interframe Spacing (RIFS) for use inside a frame burst. Its effect was small compared to block ack. So, it was removed in 11ac and not implemented.



- 802.11n introduced a “High Throughput Control” field to exchange channel state information

Ref: Interframe Space (RIFS, SIFS, PIFS, DIFS< AIFS, EIFS)), https://wifisharks.com/2020/11/14/interframe-space/

Student Questions

- Can you please explain what channel state information is exchanged in the "High Throughput Control" field?

The information is related to MIMO antennas and MCS (modulation and control scheme). The details have now been removed.

- Is there a different MAC frame for every 802.11 design?

Yes. All protocols at all layers have fields added in newer versions.

IEEE 802.11ac

- Supports 80 MHz and 80+80 MHz channels
- 5 GHz only. No 2.4 GHz.
- 256-QAM 3/4 and 5/6: 8/6 times 64-QAM ⇒ 1.33X
- 8 Spatial streams: 2X
- **Multi-User MIMO**
- Null Data Packet (NDP) explicit beamforming only
- Less pilots: 52+4 (20 MHz), 108+6 (40 MHz), 234+8 (80 MHz), 468+16 (160 MHz). Note 468/52 = 9X
- MAC enhancements for high-speed. HT Control field redefined
- 96.3 Mbps for one stream, 20 MHz, 256-QAM, 5/6, Short GI
- 8 streams and 160 MHz = 8×9×96.3Mbps = 6.9333 Gbps

Ref: M. Gast, "802.11ac: A Survival Guide," O'Reilly, July 2013, ISBN:978-1449343149, Safari Book

Student Questions

- Why aren't proportionally more pilots needed for 802.11ac?

The designers allowed lower reliability for higher throughput. Someone may have argued that we have too many pilots in previous versions.

- Can you explain the numbers in the bullet point with Less pilots? I get that with ac we can use less pilots, but how did you get those numbers?

The numbers were selected after some study and are now in the IEEE standard.

- In IEEE 802.11ac, is it "always" 8 streams with 160MHz channel? In another word, will we always consider 8 streams for calculating the rate for 160MHz channel?

Yes, each stream is 20 MHz. So wider channels are used only when the internal electronics allow processing more streams.

- Why do we only need 16 pilots for 468 carriers? 468/52 is 9. Why do we not need 9*4=36 pilots?

Pilots are overhead. There is a tradeoff between throughput and performance (noise level measurement).

IEEE 802.11ac

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Student Questions

- Under what circumstances can 802.11ac support 80MHz vs. 80+80MHz?

Bandwidth availability and configuration by the administrator.

❖How did we get 96.3Mbps?

Given in the previous line.

Beamforming

- Direct energy towards the receiver
- Requires an antenna array to alter direction per frame
  $\Rightarrow$ A.k.a. Smart Antenna
- Implicit: Channel estimation using packet loss
- Explicit: Transmitter and receiver collaborate for channel estimation

Student Questions

- Is this why ac routers tend to have 4+ antennas?

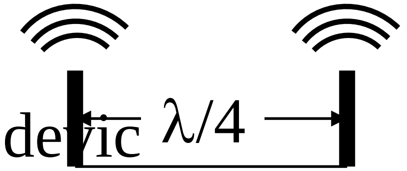
Yes. MIMO requires multiple antennas.

- How do smart antennas form multiple beams simultaneously in MU-MIMO?

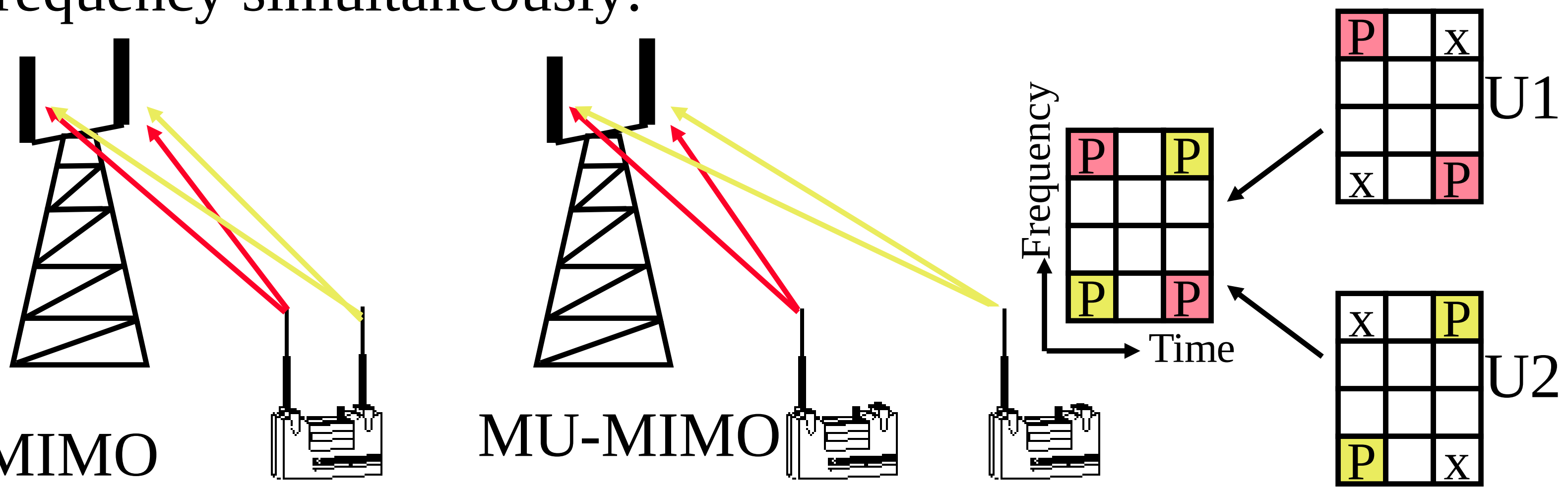
Beyond this course.

Multi-User MIMO

- **MIMO**: Multiple uncorrelated spatial beams
  Multiple antennae's separated by λ/4
  You cannot put too many antennas on a small devic



- **MU-MIMO**: Two single-antenna users can act as one multi-antenna device. The users do not need to know each other.
- Simultaneous communication with two users on the same frequency simultaneously.



Student Questions

- Could you go over the diagrams again? Is the yellow line the receiver?

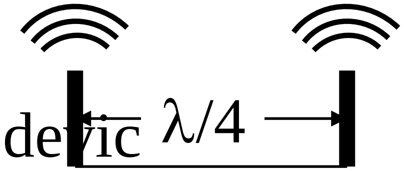
Bottom Right: User 1 is told to send pilots in red slots as indicated and not use slots marked x. User 2 is told to send pilots in yellow slots and not use the slots marked x. Using these different pilots, the signals can be separated at the receiver by correlating each square with the corresponding pilots.
Thus, two users can transmit in the same time-frequency slot and be separated out.

- Is multi-user MIMO just for the "input" side? It is hard to imagine that multiple users could send data while acting as a single source with multiple antennae.

MIMO works on both sides. The tower enables it by proper assignment of OFDMA slots.

Multi-User MIMO

- **MIMO**: Multiple uncorrelated spatial beams
  Multiple antennae's separated by λ/4
  You cannot put too many antennas on a small devic



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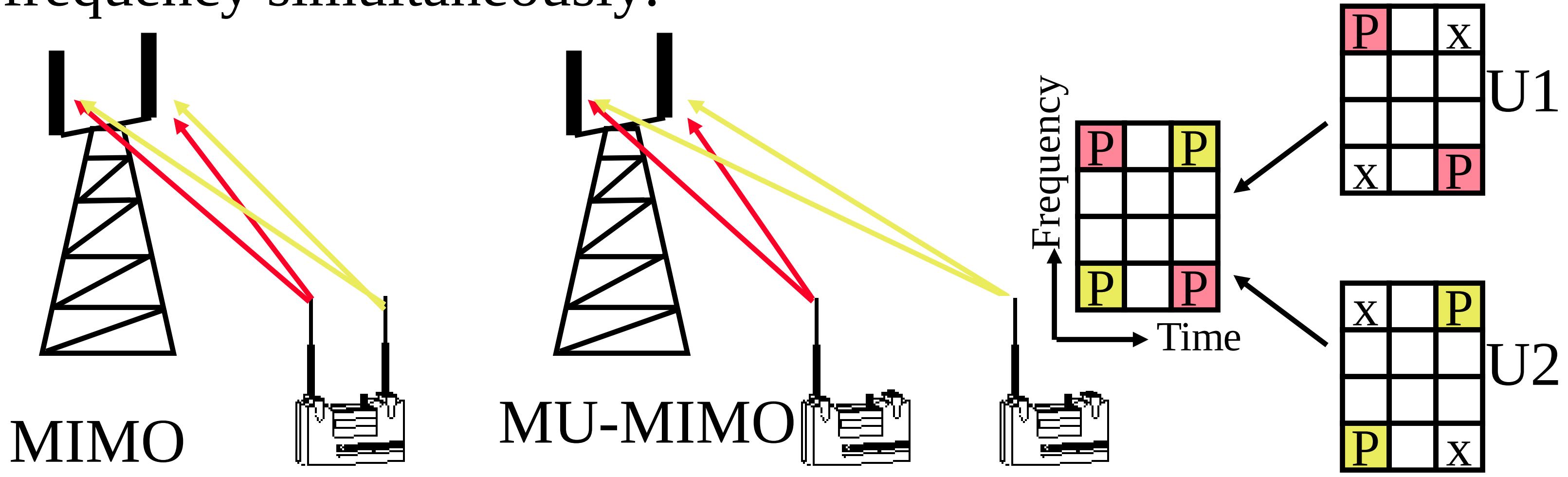


Student Questions

- When can we regard multiple single-antenna users as MU-MIMO?

When the tower enables it.

- In MIMO, we send the same data through all antennas. Here these two stations do not send the same data. Is this correct?

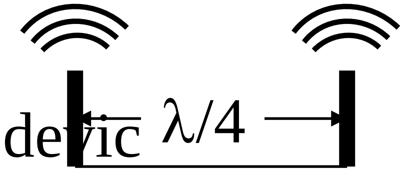
Even in single-user MIMO, different antennae send signals with different phases.

- What is the role of two pilots?

Each user puts its pilots as indicated.

Multi-User MIMO

- **MIMO**: Multiple uncorrelated spatial beams
  Multiple antennae's separated by λ/4
  You cannot put too many antennas on a small devic



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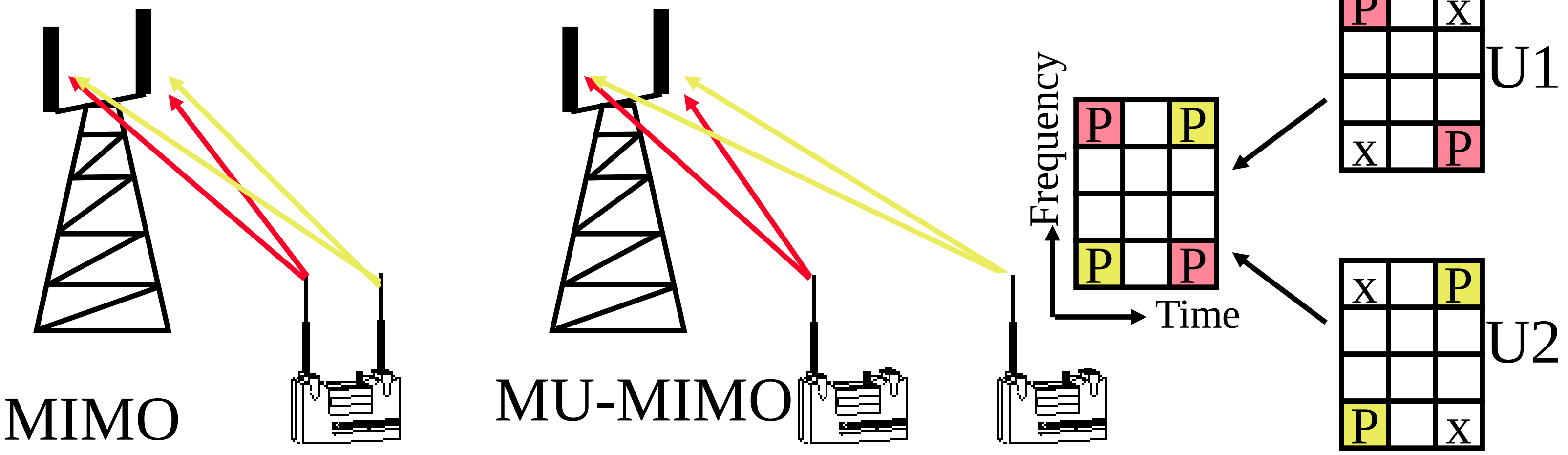


Student Questions

- We could always use OFDMA. What does MU-MIMO here? Does this mean that AP uses one frequency for one of its antennae and a different frequency for another antenna to send data to two different stations simultaneously?

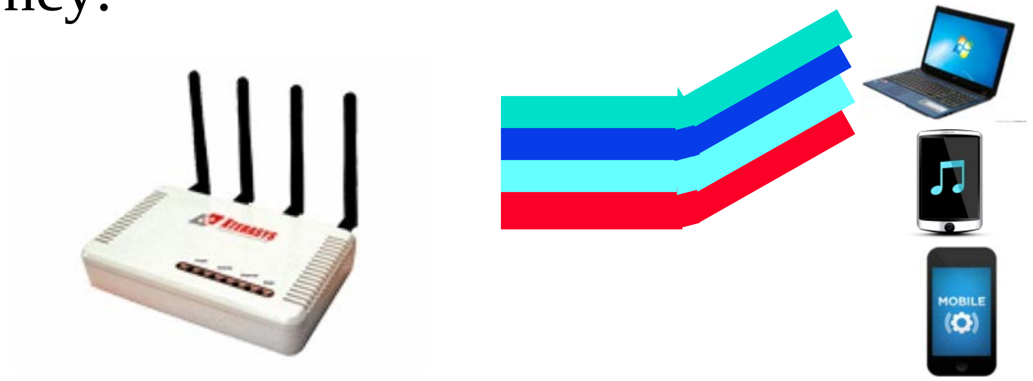
We can use most of the same time-frequency slots simultaneously for multiple users.

- What are the disadvantages of using MU MIMO?

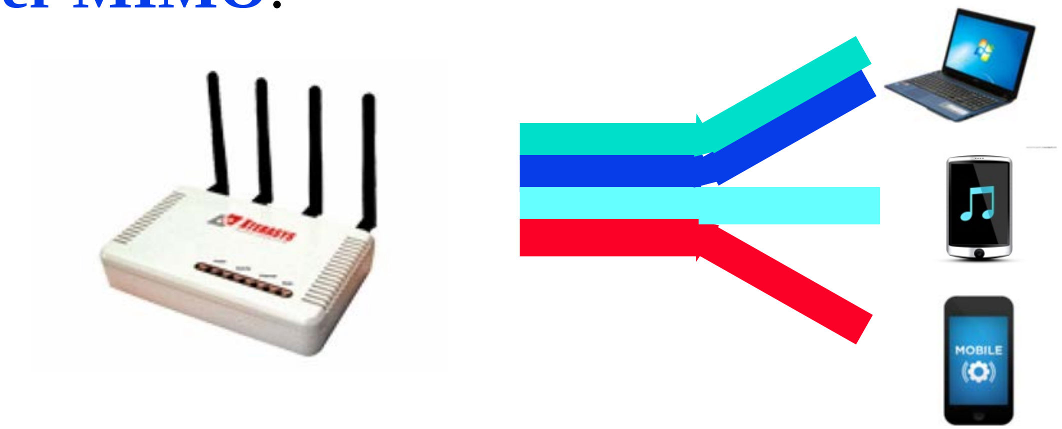
Complexity/cost at the tower.

Beamforming with Multi-User MIMO

- **Single User MIMO**: Colors represent transmission signals, not frequency.



- **Multi User MIMO**:



Student Questions

- So with Single User MIMO, does it mean only one system can receive data at any given time?

This applies in both directions. With single user MIMO, only one user can transmit/receive. With multi-user MIMO, multiple users can transmit/receive simultaneously.

- What is the speed gain of MU-MIMO (what makes it faster than transmitting to users individually)?

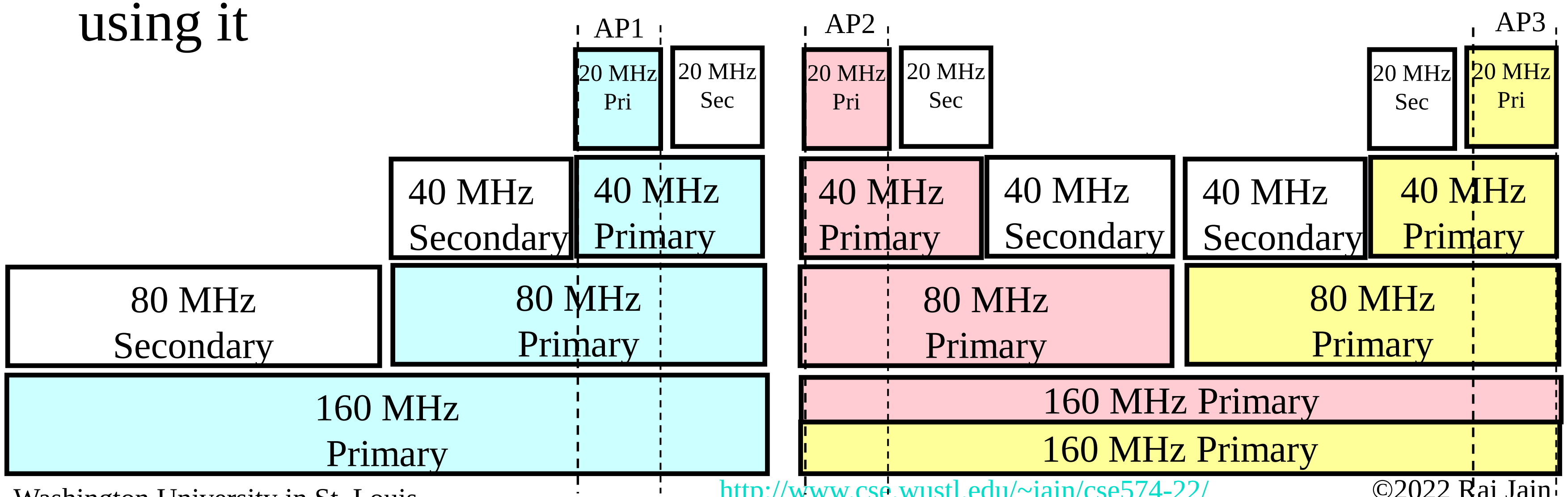
$n \times m$ MIMO can potentially give nm times more throughput than no MIMO.

- Do the different colors represent different carrier frequencies?

Different signals at the same frequency. Different in phases.

Primary and Non-Primary Channels

- Beacons on the primary channel
- AP supports a mixture of single-band and multi-band stations
  ⇒ AP can change channel width on a frame-by-frame basis
- Stations need 160 MHz only some time
  ⇒ Two networks can share the same 160 MHz (e.g., AP2 and AP3 below)
- Stations check that the entire bandwidth is available before using it



Student Questions

- The two graphics on the bottom aren't very clear to me- What is the 40Mhz primary/secondary, and why is everything besides the blue 40MHz a primary?

The primary can be lower or higher than the secondary. Some standards allow non-contiguous channels to be bonded. Most don't. IEEE 802.11n and 11ac require adjacent primary/secondary.
Primary 20 MHz should completely overlap with primary 40 MHz. Similarly, primary 40 MHz should completely overlap with primary 80 MHz, and so on. Three different examples of overlap are shown in the figure. This allows all stations to hear beacons which are in the primary 20 MHz channel.

- When two stations are sharing the same 160Mhz channel, how do they know when the channel is free to be used? Do they listen to the traffic and wait for a chance to transmit?

AP decides when a multi-band station can transmit and in what band.

Primary and Non-Primary Channels

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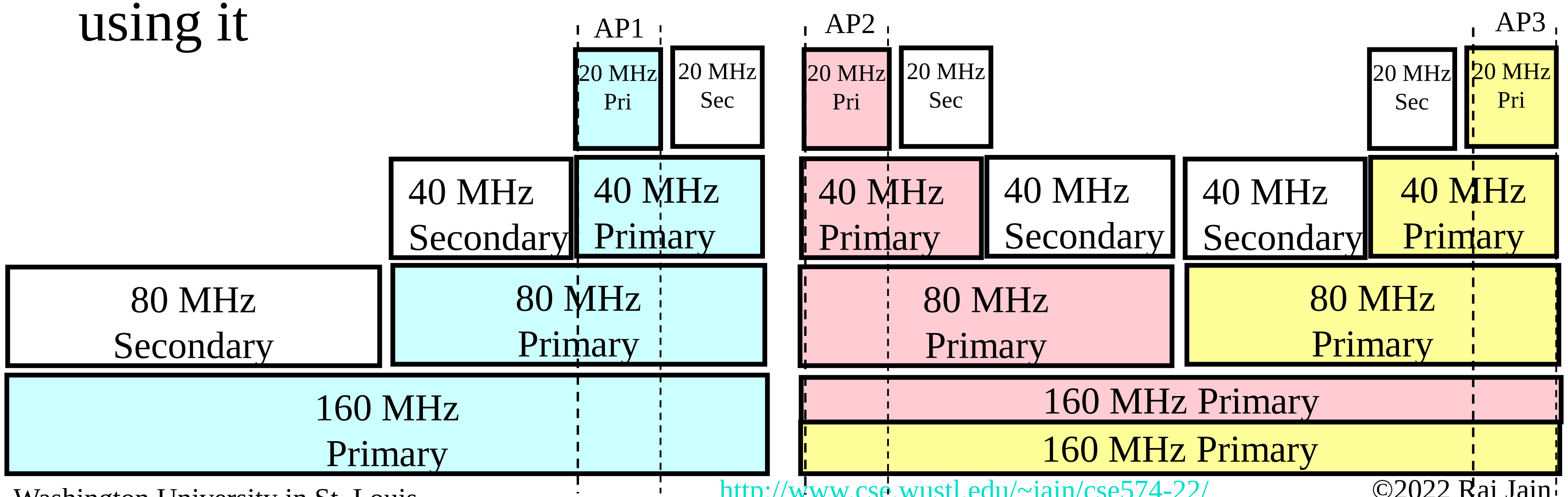

Student Questions

- What is the difference between the left and suitable diagram? Does each block mean one possible AP?

Each color represents one AP. There are three APs in the figure.

- Is the Max number of APs = 160/20 = 8 in this case? How do neighboring APs (say, all of them working at 5GHz) share the spectrum?

There is no limit to the number of AP. Two APs using the same band interfere and work at lower throughput. You can see all this using InSSIDer V3, which is free.

Primary and Non-Primary Channels

- Beacons on the primary channel
- AP supports a mixture of single-band and multi-band stations
  ⇒ AP can change channel width on a frame-by-frame basis
- Stations need 160 MHz only some time
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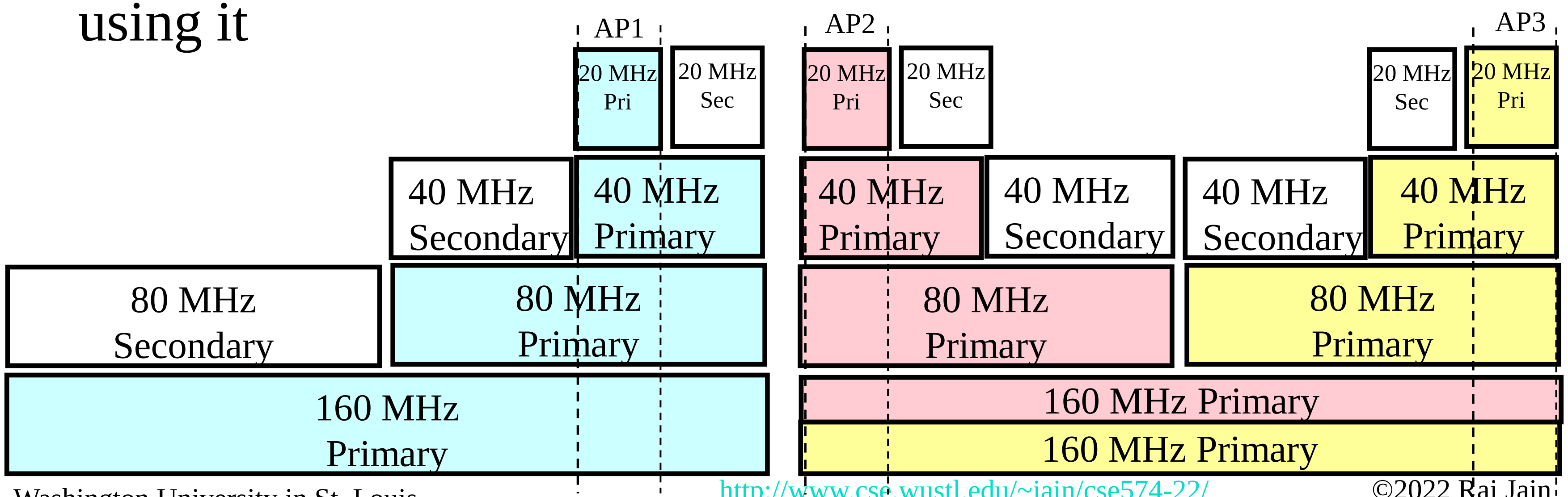


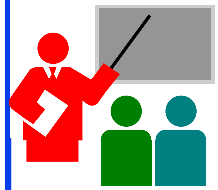
Student Questions

- What does "AP can change channel width on a frame-by-frame basis"?

AP tells each station which band(s) to use.

- So, AP sends its beacons and announces that it listens and uses the whole 160 MHz (might send beacons on different frequencies?), and we might have a station that uses only 20 MHz, but the AP still operates on the whole 160 MHz for possible stations?

Yes. Single-band stations operate in the primary band. The Beacon is sent only on the primary channel but has all channels' info.



Summary

1. Each layer has SDU, and PDU, which can be Aggregated, Fragmented or transmitted in Burst.
2. 802.11a/g use OFDM with 64 subcarriers in 20 MHz. 48 Data, 4 Pilot, 12 guards.
3. 802.11e adds frame bursting, direct link, APSD, and four queues with different AIFS and TXOP durations. QoS field in frames.
4. 802.11n adds MIMO, aggregation, dual-band, STBC, and channel bonding. HT Control field in frames.
5. IEEE 802.11ac supports multi-user MIMO with 80+80 MHz channels with 256-QAM and eight streams to give 6.9 Gbps
6. Multi-User MIMO allows several users to be combined in a MIMO pool.

Student Questions

- ❑ Can you explain the purpose of guard and pilot subcarriers?

Pilot subcarriers are used to measure the quality of signal by sending a known signal, e.g., 0101010…
The receiver can measure the error rate and report it to the transmitter. The transmitter can then adjust the coding rate in nearby subcarriers.
There are many pilots distributed uniformly throughout the channel.
Guard subcarriers represent the subcarriers at both ends that are not used to avoid interference with signals on the adjacent channels.

- ❑ What is in the QoS field in the MAC frame?

See Slides 6-15 through 6-17 on 802.11e.

Homework 6B

- A. Given that the 802.11ac Phy rate for 20MHz BPSK 1/2 channel with short GI is 7.22 Mbps, what would be the rate for 160 MHz 256-QAM ¾ with short GI? In both cases, the number of streams is 8.

Student Questions

Recent Developments in Wi-Fi

1. Wi-Fi Generations
2. Wi-Fi 6
3. White-Fi or Super Wi-Fi
4. Wi-Fi HaLow
5. Other upcoming standards

Note: This and the following slides are a supplement to Modules 5 and 6 on Wi-Fi. All modules are available on the course URL below.

Student Questions

Wi-Fi Generations

- 802.11n vs. 802.11ac
- General public has no idea which one of these is superior
- Wi-Fi Alliance: Wi-Fi Interoperability and Marketing organization solved it by assigning generations 1=2 Mbps, 2=11 Mbps, 3=56 Mbps, …
- Wi-Fi Alliance renamed 802.11n and 802.11ac retroactively as Wi-Fi 4, Wi-Fi 5
- Similar to 4G/5G, Bluetooth 4.0/Bluetooth 5.0, …
- **Wi-Fi 4**: IEEE 802.11n **Wi-Fi 5**: IEEE 802.11ac
- Easier for the public to remember when comparing products with different versions of Wi-Fi
- Most products were developed before the name Wi-Fi 5 was announced. So all products still say 802.11n and 802.11ac

Ref: https://www.duckware.com/tech/wifi-in-the-us.html

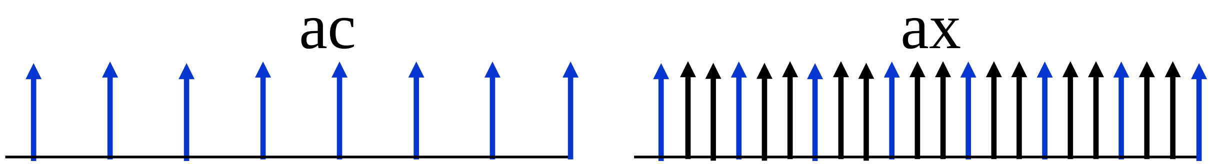
Student Questions

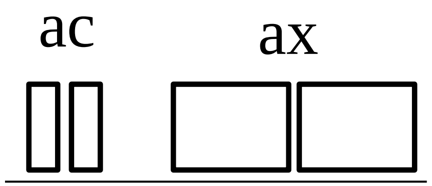
- Is something marketed as "gigabit Wi-Fi" 802.11ac?

Both. Even 600 MHz is marketed as Gigabit.

Wi-Fi 6

- IEEE P802.11ax: Named Wi-Fi 6 by Wi-Fi Alliance
- Approved by IEEE in September 2020
- More efficient 802.11ac ⇒ 4× Throughput
- 1/4th subcarrier spacing ⇒ 4 × subcarriers
  - 20 MHz = 4 × 64 = 256 subcarriers
  - 40 MHz = 4 × 128 = 512 subcarriers
  - 80 MHz = 4 × 256 = 1024 subcarriers
  - 160 MHz = 4 × 512 = 2048 subcarriers
- 1/4th subcarrier spacing ⇒ 4 × symbol size (in time)
  - 4 × 32. μs = 12.8 μs ⇒ More inter-symbol interference





Ref: E. Khorov, A. Kiryanov, A. Lyakhov and G. Bianchi, "A Tutorial on IEEE 802.11ax High Efficiency WLANs," in *IEEE Communications Surveys & Tutorials*, vol. 21, no. 1, pp. 197-216, Firstquarter 2019, https://ieeexplore.ieee.org/document/8468986

Student Questions

- Can you please explain the time domain vs. frequency domain and its effect on inter-symbol interference?
- Thinner spectrum in the frequency domain translates to a wider pulse in the time domain and vice versa. An impulse in the frequency domain translates to a uniform function in the time domain.
  Wider symbols are more prone to inter-symbol interference.

Wi-Fi 6E

- Wi-Fi 6 extended to 6 GHz band
- More contiguous Spectrum: FCC approved all 1200 MHz spectrum at 6 GHz for unlicensed use
  ⇒ 14 additional 80 MHz channels
  or 7 160 MHz channels
- Wider Channels ⇒ Less queueing ⇒ Low latency
- Shorter range ⇒ Less Interference

Ref: https://www.wi-fi.org/discover-wi-fi/wi-fi-certified-6

Student Questions

White-Fi or Super Wi-Fi

- IEEE 802.11af-2014
- Operates in TV white spaces in 54 and 790 MHz.
- Uses cognitive radio technology
- Stations determine their position using GPS to determine what bands are available in that location and use it while the TV station is not transmitting
- Lower frequency ⇒ Longer range than 11-11ax
- 26.7 Mbps to 568.9 Mbps
- Significant market confusion with popular 802.3af power over Ethernet capability
- Spectrum in the USA but not globally ⇒ No products so far

Ref: https://www.mwrf.com/technologies/active-components/article/21846205/whats-the-difference-between-ieee-80211af-and-80211ah

https://en.wikipedia.org/wiki/IEEE_802.11af

Student Questions

- How do stations know what TV channels are available in a certain location? Is there a database?

Yes, there are national databases.

Wi-Fi HaLow

- IEEE 802.11ah-2016
- Wi-Fi for Internet of Things (IoT)
- Designed for 900 MHz spectrum
- Can reach three times longer than 2.6 GHz
- 900 MHz is available in the USA but not globally
  - No global standard
  - US and proprietary products

Ref: https://en.wikipedia.org/wiki/IEEE_802.11ah

Student Questions

Wi-Fi 7

- Extremely High Throughput
- Bands between 1 and 7.125 GHz
- **Study group** approved in July 2018
- IEEE 802.11be Extremely High Throughput (EHT)
- Final standard expected in early 2024.

Ref: E. Khorov, I. Levitsky and I. F. Akyildiz, "Current Status and Directions of IEEE 802.11be, the Future Wi-Fi 7," in *IEEE Access*, vol. 8, pp. 88664-88688, 2020, https://ieeexplore.ieee.org/document/9090146

Student Questions

- Has there been a Task Group for Wi-Fi 7 made since 2018? Also, with that wide range in frequency bands, what might that antenna array look like?

Yes. IEEE 802.11be is the task group. A separate antenna covers each band in that range.

- I wonder which one comes out first, the IEEE standards or the Wi-Fi generations, e.g., Wi-Fi 1, 2, by Wi-Fi alliance?

The IEEE Standards group starts discussing first. Wi-Fi Alliance starts working in parallel.

- What is the study group?

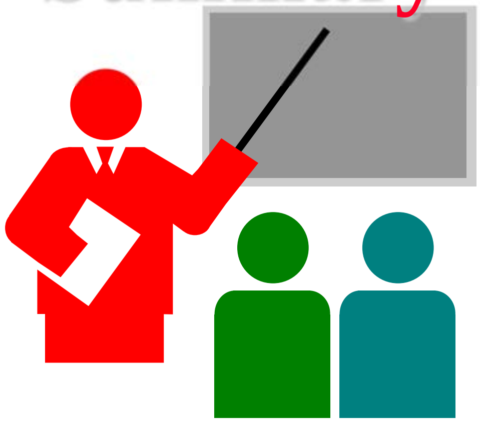
The IEEE standards group forms a study group, then a task group. The study group is like a state-of-the-art survey.

IEEE 802.11 Activities

- **P802.11ay**: Increase the data rate in 60 GHz band Enhancement of 802.11ad
- **P802.11az**: Next generation positioning with improved accuracy, scalability, and directionality
- **P802.11ba**: Low power control stations
- **P802.11bb**: Light Communications
- **P802.11bc**: Enhanced broadcase service
- **P802.11bd**: Next Generation Vehicle-to-X
- **Real time applications**: Latency and stability issues with mobile and multiplayer games, robotics and industrial automation

Student Questions

Summary



1. Wi-Fi Generations: 1=802.11, 2=11b, 3=11a/11g, 4=11n, 5=11ac, 6=11ax
2. Wi-Fi 6 is here. 6E is coming.
3. Wi-Fi 7 is in works.
4. White-Fi or Super Wi-Fi uses TV spectrum, but may not come.
5. Wi-Fi HaLow is designed for IoT but may not come.

Student Questions

- If two Wi-Fi networks are in the same room, will they potentially be slower than if there was only one because all channels could get used up?

Slower iff they use overlapping channels or adjacent channels.

Reading List

1. M. Gast, "802.11n: A Survival Guide," O'Reilly, 2012, ISBN:978-1449312046, Safari Book
2. M. Gast, “802.11ac: A Survival Guide,” O’Reilly, July 2013, ISBN:978-1449343149, Safari Book
3. P. Roshan and J. Leary, "802.11 Wireless LAN Fundamentals," Cisco Press, 2003, ISBN:1587050773, Safari book

Student Questions

Reading List (Cont)

- E. Khorov, A. Kiryanov, A. Lyakhov and G. Bianchi, "A Tutorial on IEEE 802.11ax High Efficiency WLANs," in *IEEE Communications Surveys & Tutorials*, vol. 21, no. 1, pp. 197-216, Firstquarter 2019, https://ieeexplore.ieee.org/document/8468986
- E. Khorov, I. Levitsky and I. F. Akyildiz, "Current Status and Directions of IEEE 802.11be, the Future Wi-Fi 7," in *IEEE Access*, vol. 8, pp. 88664-88688, 2020, https://ieeexplore.ieee.org/document/9090146

Student Questions

Wikipedia Links

- http://en.wikipedia.org/wiki/IEEE_802.11
- http://en.wikipedia.org/wiki/IEEE_802.11a-1999
- http://en.wikipedia.org/wiki/IEEE_802.11b-1999
- http://en.wikipedia.org/wiki/IEEE_802.11e-2005
- http://en.wikipedia.org/wiki/IEEE_802.11g-2003
- http://en.wikipedia.org/wiki/IEEE_802.11n-2009
- http://en.wikipedia.org/wiki/Adaptive_beamformer
- http://en.wikipedia.org/wiki/Beamforming
- http://en.wikipedia.org/wiki/Channel_bonding
- http://en.wikipedia.org/wiki/Complementary_code_keying
- http://en.wikipedia.org/wiki/Cyclic_prefix
- http://en.wikipedia.org/wiki/DCF_Interframe_Space
- http://en.wikipedia.org/wiki/Forward_error_correction
- http://en.wikipedia.org/wiki/Frame-bursting
- http://en.wikipedia.org/wiki/Frame_aggregation

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Wikipedia Links (Cont)

- http://en.wikipedia.org/wiki/Greenfield_project
- http://en.wikipedia.org/wiki/Guard_interval
- http://en.wikipedia.org/wiki/IEEE_802.11_(legacy_mode)
- http://en.wikipedia.org/wiki/Low-density_parity-check_code
- http://en.wikipedia.org/wiki/MIMO
- http://en.wikipedia.org/wiki/Precoding
- http://en.wikipedia.org/wiki/Short_Interframe_Space
- http://en.wikipedia.org/wiki/Smart_antenna
- http://en.wikipedia.org/wiki/IEEE_802.11ac
- http://en.wikipedia.org/wiki/Spatial_multiplexing
- http://en.wikipedia.org/wiki/Multi-user_MIMO
- http://en.wikipedia.org/wiki/STBC

Student Questions

Wikipedia Links

- https://en.wikipedia.org/wiki/IEEE_802.11
- https://en.wikipedia.org/wiki/IEEE_802.11ax
- https://en.wikipedia.org/wiki/Super_Wi-Fi
- https://en.wikipedia.org/wiki/IEEE_802.11ah

Student Questions

References

- D. Skordoulis, et al., "IEEE 802.11n MAC Frame Aggregation Mechanisms for Next-Generation High-Throughput WLANs," IEEE Wireless Magazine, February 2008, http://tinyurl.com/k2gvl2g
- http://grouper.ieee.org/groups/802/11/Reports/802.11_Timelines.htm
- Yang Xiao, "IEEE 802.11e QoS provisioning at the MAC layer", Volume: 11 Issue: 3, Pages: 72-79, IEEE Wireless Communications, 2004, http://ieeexplore.ieee.org/iel5/7742/29047/01308952.pdf
- Yang Xiao, "IEEE 802.11n enhancements for higher throughput in wireless LANs", Volume: 12, Issue: 6, Pages: 82-91, IEEE Wireless Communications, 2005, http://www.cs.mun.ca/~yzchen/papers/papers/mac/80211n_intro_xiao_j2005.pdf
- J. M. Gilbert, Won-Joon Choi and Qinfang Sun, "MIMO technology for advanced wireless local area networks", 42nd Design Automation Conference, 2005, pp. 413-415,

  https://ieeexplore.ieee.org/document/1510364/

Student Questions

References (Cont)

- IEEE 802.11e, "Medium Access Control Enhancements for Quality of Service", http://people.cs.nctu.edu.tw/~yctseng/WirelessNet2010-02-nctu/ieee802-11e.ppt
- Rohde & Schwarz, "IEEE 802.11n/IEEE 802.11ac Digital Standard for R&S Signal Generators: Operating Manual," http://www.rohde-schwarz.de/file/RS_SigGen_IEEE80211n_ac_Operating_en_16.pdf

Student Questions

Acronyms

- AC Access Point Constraint
- AIFS Arbitrated Inter-Frame Spacing
- AP Access Point
- AP Access Point
- APSD Automatic Power Save Delivery
- ASELC Antenna Selection Command/Data
- BCC Binary Convolution Code
- BO Backoff
- BPSK Binary Phase Shift Keying
- BSS Basic Service Set
- CCK Complementary Code Keying
- CFP Contention Free Period
- CP Contention Period
- CRC Cyclic Redundancy Check
- CSD Cyclic Shift Diversity
- CSI Channel State Information

Student Questions

Acronyms (Cont)

- CTL Control
- CTS Clear to send
- CW Contention Window
- CWmax Maximum Contention Window
- CWmin Minimum Contention Window
- DCF Distributed Coordination Function
- DIFS DCF Interframe Spacing
- DLS Direct Datalink Setup
- DQPSK Differential Quadrature Phase Shift Keying
- EDCA Enhanced Distributed Coordination Access
- EDCF Enhanced Distributed Coordination Function
- EOSP End of Service Period
- ESS Extended Service Set
- FCS Frame Check Sequence
- GHz Giga Hertz
- GI Guard Interval

Student Questions

Acronyms (Cont)

❑	HCF	Hybrid Coordination Function
❑	HEC	Header Error Check
❑	HT	High Throughput
❑	ID	Identifier
❑	IDFT	Inverse Discrete Fourier Transform
❑	IEEE	Institution of Electrical and Electronic Engineers
❑	IP	Internet Protocol
❑	LAN	Local Area Network
❑	LDPC	Low Density Parity Check Code
❑	LLC	Logical Link Control
❑	MAC	Media Access Control
❑	MAI	MCS Request/Antenna Selection Indication
❑	MCS	Modulation and Coding Scheme
❑	MFB	MCS Feedback
❑	MFS	MFB Sequence Identifier
❑	MFSI	MFB Sequence Identifier

Student Questions

Acronyms (Cont)

- MHz Mega Hertz
- MIMO Multiple Input Multiple Output
- MPDU MAC Protcol Data Unit
- MRQ MCS feedback request
- MRS MRQ Sequence Identifier
- MSDU MAC Service Data Unit
- MU-MIMO Multi-User MIMO
- NDP Null Data Packet
- OFDM Orthogonal Frequency Division Multiplexing
- PCF Point Coordination Function
- PDU Protocol Data Unit
- PHY Physical Layer
- PLCP Physical Layer Convergence Procedure
- PMD Physical Medium Dependent
- PPDU PLCP Protocol Data Unit
- PSDU PLCP Service Data Unit

Student Questions

Acronyms (Cont)

- QAM	Quadrature Amplitude Modulation
- QoS	Quality of Service
- QPSK	Quadrature Phase Shift Keying
- RDG	Reverse Direction Grant
- RIFS	Reduced Inter-Frame Spacing
- S-APSD	Scheduled Automatic Power Save Delivery
- SDU	Service Data Unit
- SFD	Start of Frame Delimiter
- SIFS	Short Interframe Spacing
- STA	Station
- STBC	Space Time Block Code
- STBC	Space Time Block Codes
- TID	Traffic Identifier
- TRQ	Training Request
- TV	Television
- TXOP	Transmission Opportunity

Student Questions

Acronyms (Cont)

U-APSD	Unscheduled Automatic Power Save Delivery
VHT	Very High Throughput
WLANs	Wireless Local Area Network

Student Questions

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rajjain.com/cse574-18

http://www.cse.wustl.edu/~jain/cse574-22/j_06lan.htm

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Related Modules

CSE567M: Computer Systems Analysis (Spring 2013),
https://www.youtube.com/playlist?list=PLjGG94etKypJEKjNAa1n_1X0bWWNyZcof

CSE473S: Introduction to Computer Networks (Fall 2011),
https://www.youtube.com/playlist?list=PLjGG94etKypJWOSPMh8Azcgy5e_10TiDw

Recent Advances in Networking (Spring 2013),
https://www.youtube.com/playlist?list=PLjGG94etKypLHyBN8mOgwJLHD2FFIMGq5

CSE571S: Network Security (Fall 2011),
https://www.youtube.com/playlist?list=PLjGG94etKypKvzfVtutHcPFJXumyyg93u

Video Podcasts of Prof. Raj Jain's Lectures,
https://www.youtube.com/channel/UCN4-5wzNP9-ruOzQMs-8NUw

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