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/cse574-20/

Student Questions

Overview

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- 802.11F: Inter-Access Point Protocol (Withdrawn)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 2.4GHz band
- 802.11h-2003: Dynamic Frequency Selection and transmit power control to satisfy 5GHz band operation in Europe.

Student Questions

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 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.

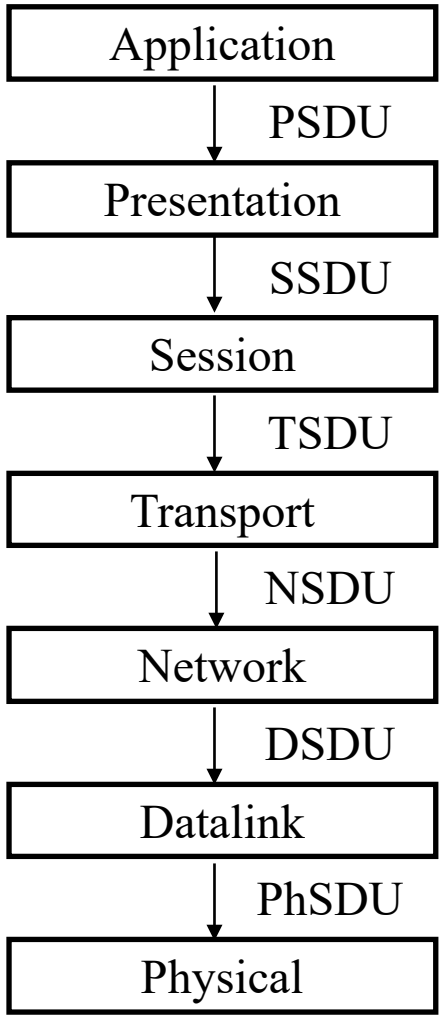
Student Questions

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 just like Ethernet in addition to 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

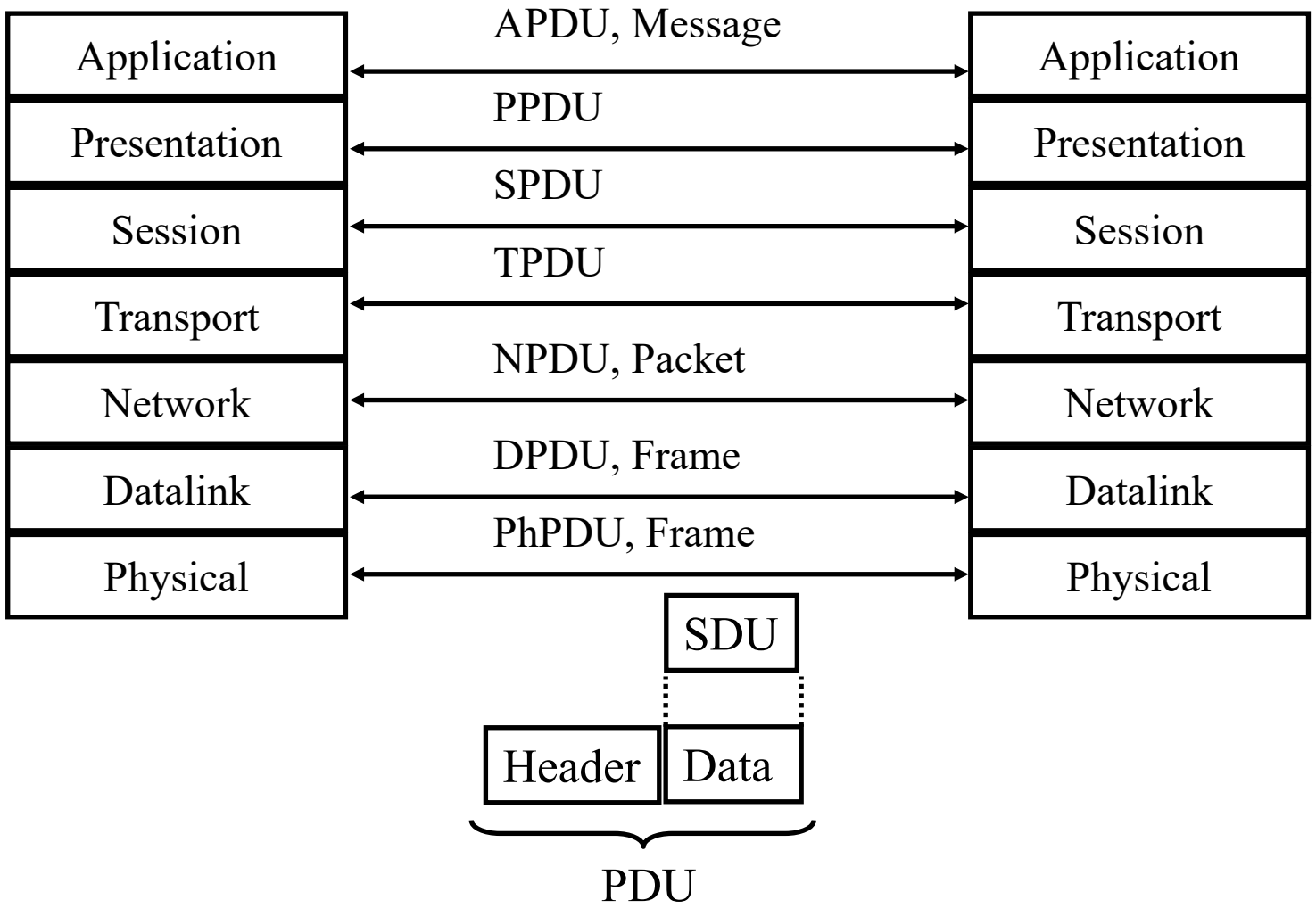
Student Questions

ISO/OSI: Service Data Unit (SDU)



Student Questions

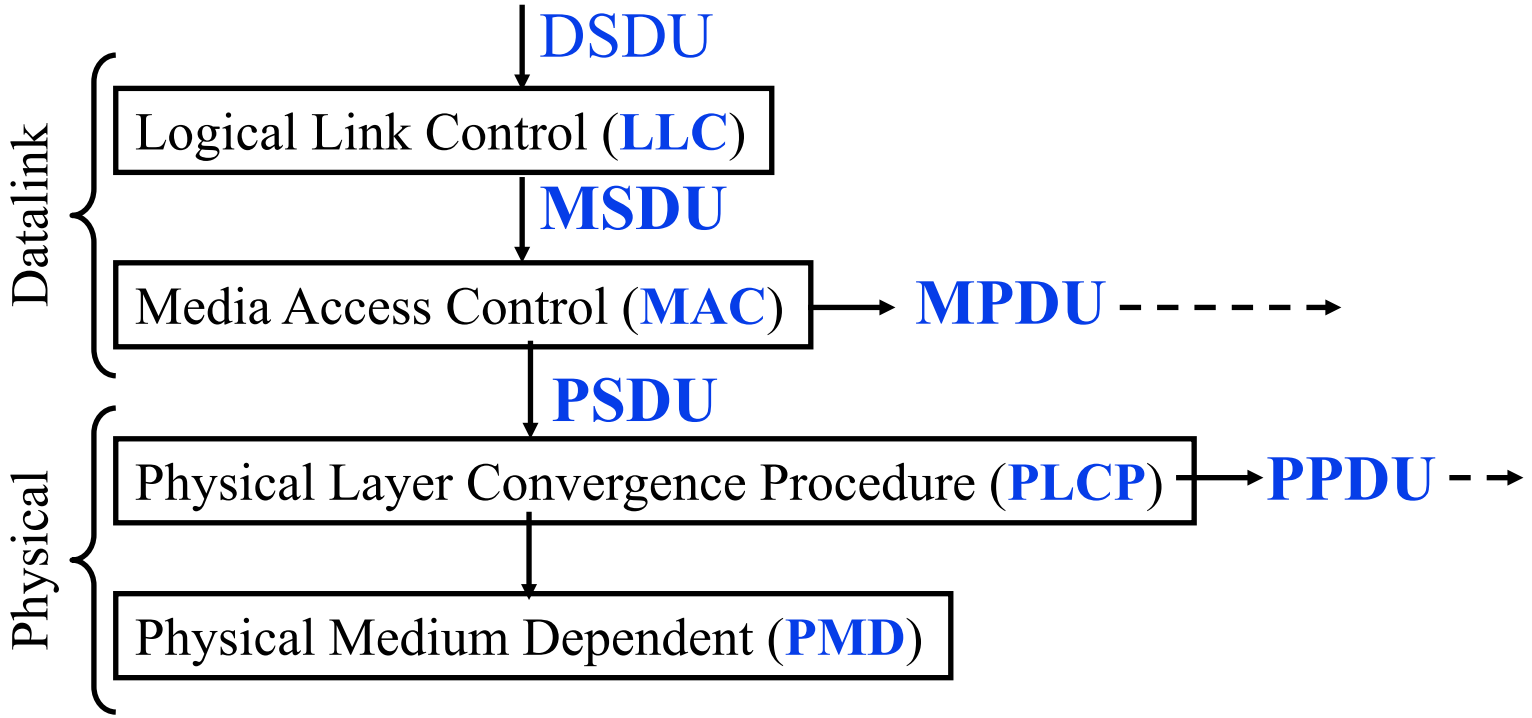
Protocol Data Unit (PDU)



Student Questions

802.11 Protocol Layers

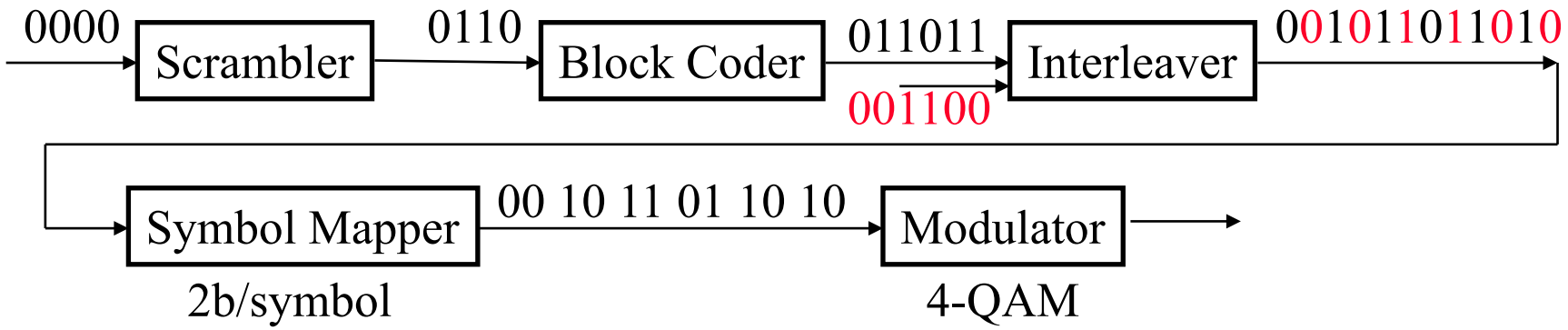
- **Logical Link Control (LLC)**: Bridging
- **Media Access Control (MAC)**: CSMA/CA, Ack
- **Physical Layer Convergence Procedure (PLCP)**: Framing
- **Physical Medium Dependent (PMD)**: Modulation



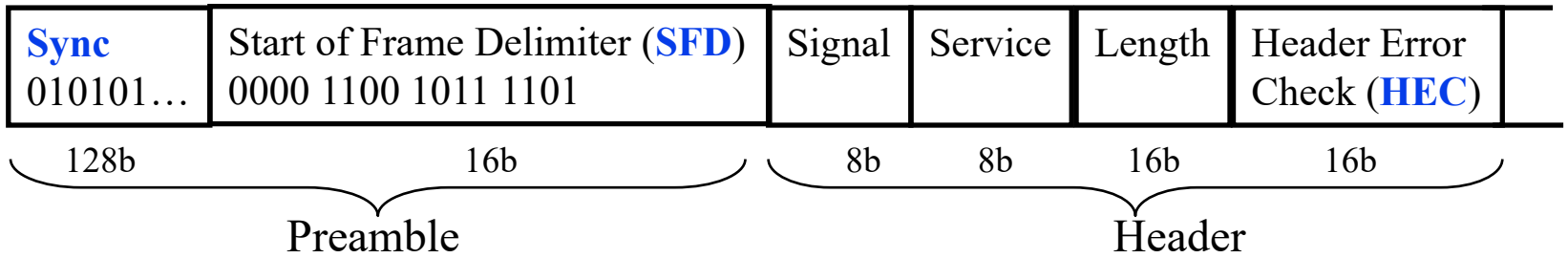
Student Questions

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:



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?

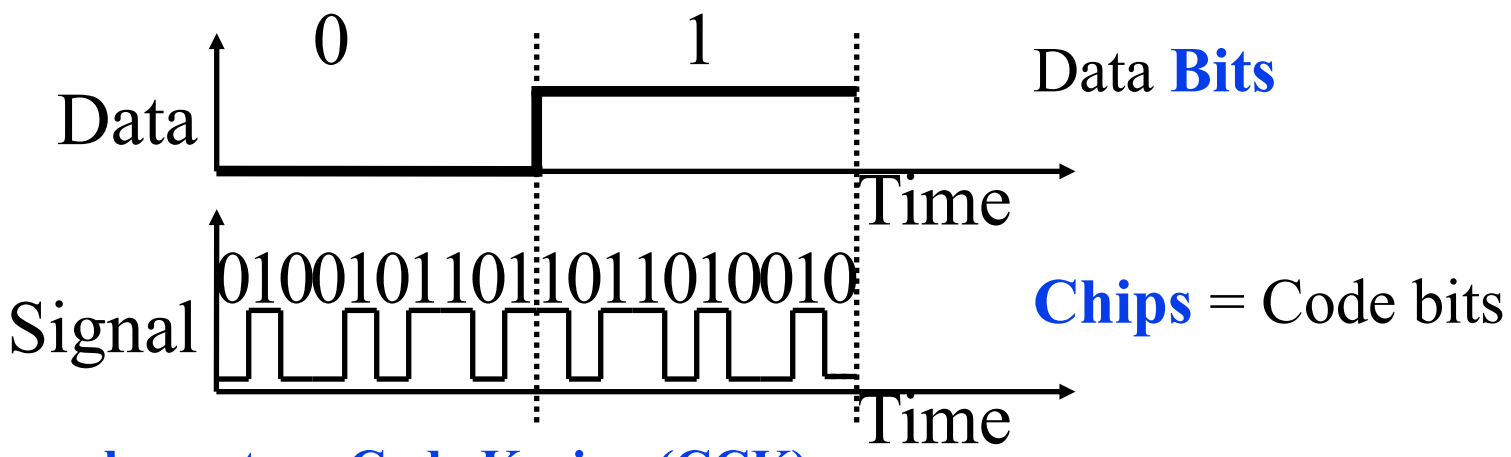
Signal bits indicate the modulation used and so determine the data rate. Service bits indicate further info about the oscillators used. Length indicates the size in microseconds.

- How many blocks can be interleaved together?

A small number (2-16)

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 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

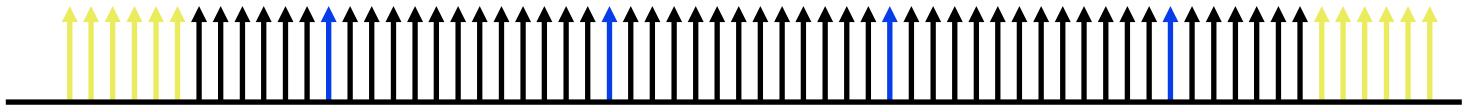
Student Questions

- 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.

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

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



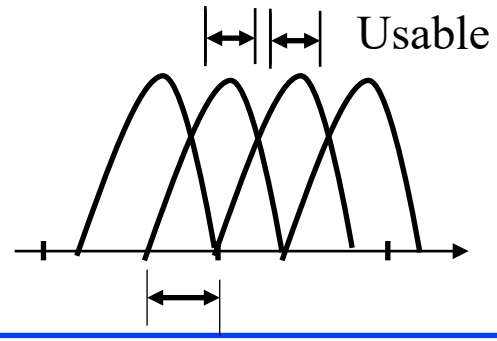
Coding	b/Hz	Mb/s	FEC	Net
BPSK	1	12	1/2	6 Mb/s
BPSK	1	12	3/4	9 Mb/s
QPSK	2	24	1/2	12 Mb/s
QPSK	2	24	3/4	18 Mb/s
16-QAM	4	48	1/2	24 Mb/s
16-QAM	4	48	3/4	36 Mb/s
64-QAM	6	72	2/3	48 Mb/s
64-QAM	6	72	3/4	54 Mb/s

- 5.4 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.



IEEE 802.11g-2003

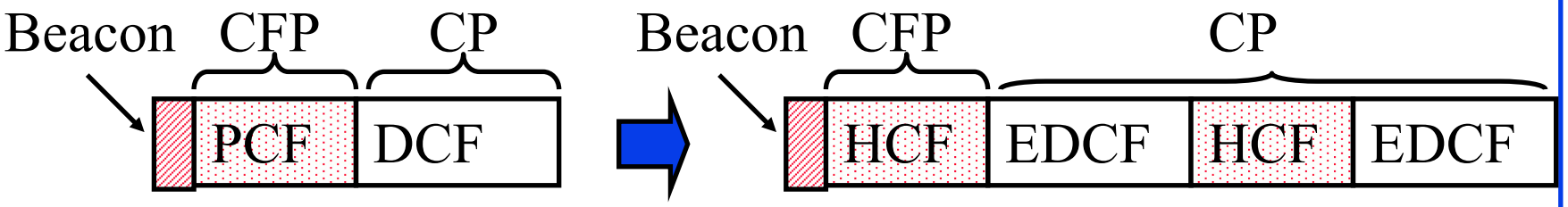
- OFDM – Same as 802.11a ⇒ 54 Mbps
- 2.4 GHz band ⇒ Cheaper than 802.11a
- Fall back to 802.11b CCK

Student Questions

IEEE 802.11e-2005 (Enhanced QoS)

- Backward compatible:
  ⇒ Non-802.11e terminals can receive QoS enabled streams

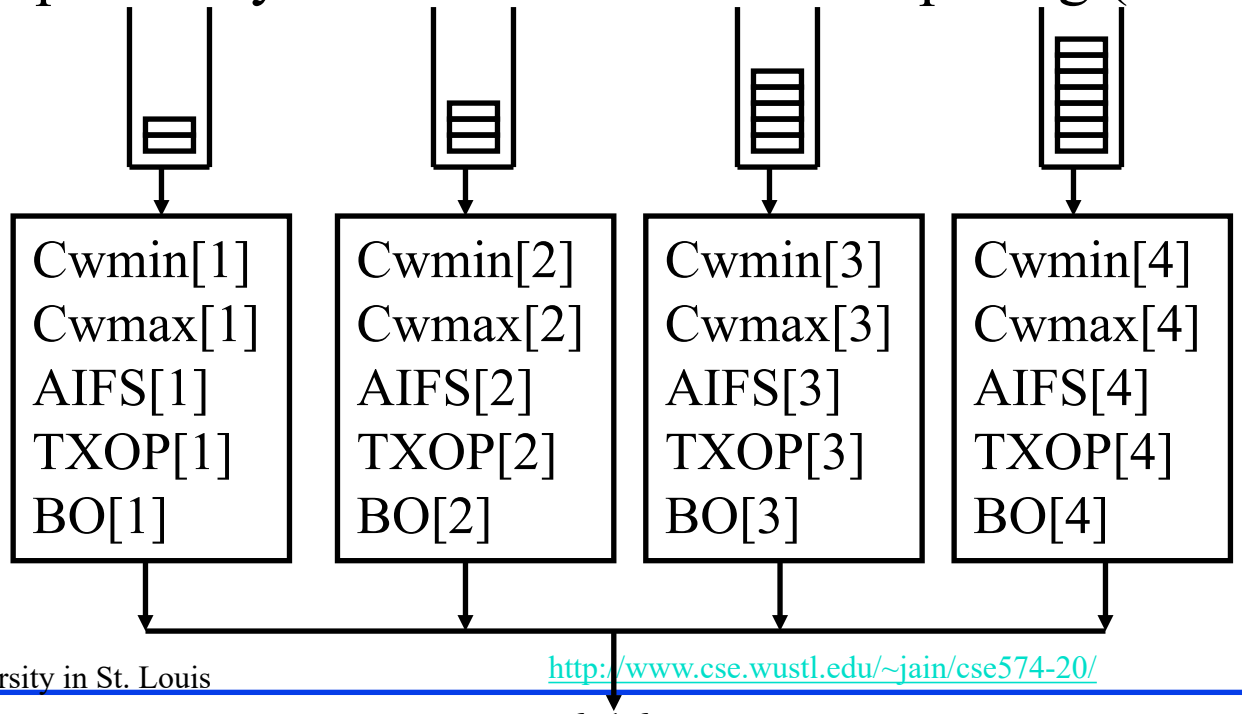
1. Hybrid Coordination Function (**HCF**) w two components
   a. Contention Free Access: Hybrid Polling
   b. Contention-based Access: Enhanced DCF (**EDCF**)
2. **Direct Link**: Traffic sent directly between two stations
3. **Frame bursting** and Group Acknowledge
4. Multiple **Priority** levels
5.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



Student Questions

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)



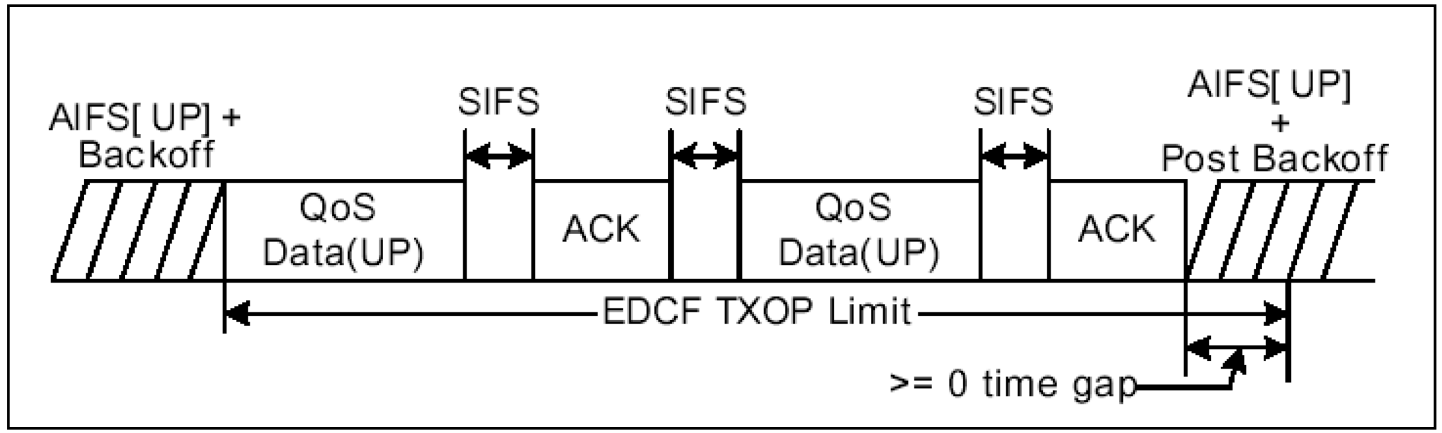
Student Questions

- 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.

Frame Bursting

- EDCF parameters announced by access point in beacon frames
- 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



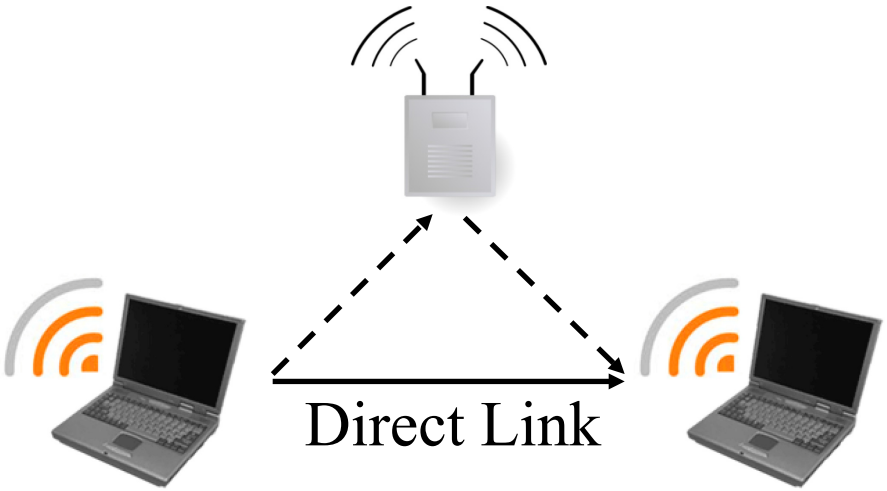
Student Questions

- 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.

Direct Link

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



Student Questions

Automatic Power Save Delivery (APSD)

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

Student Questions

Homework 6A

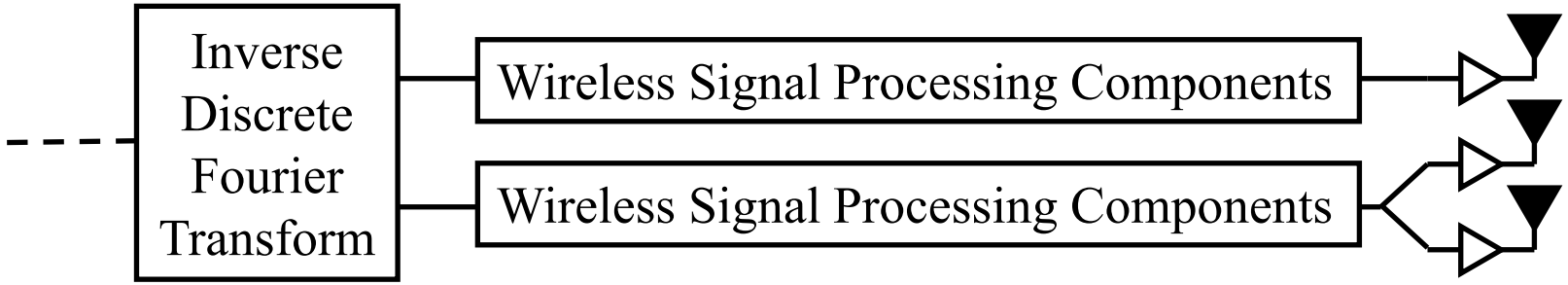
Fill in the blanks:

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

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 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.

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

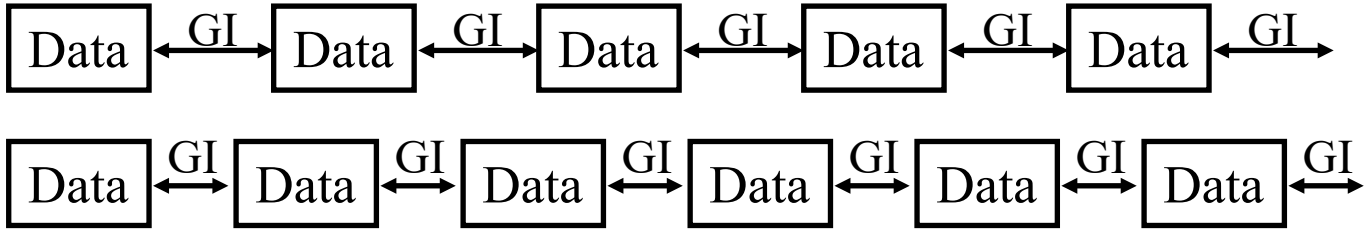
- "How do we not lose data from frame aggregation?

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.

Guard Interval



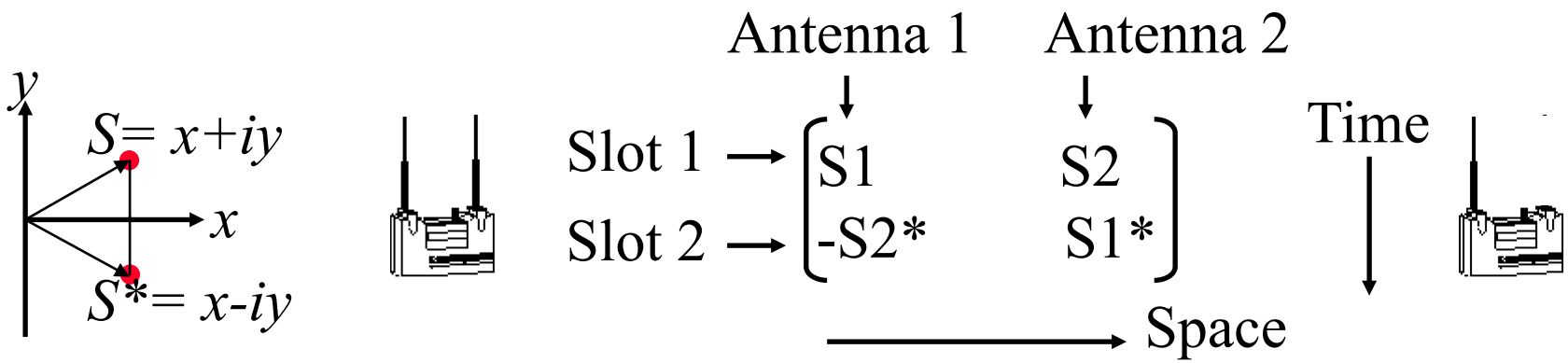
- Rule of Thumb: Guard Interval = 4 × Multi-path delay spread
- Initial 802.11a design assumed 200ns delay spread
  ⇒800 ns GI + 3200 ns data ⇒20% overhead
- Most indoor environment have smaller 50-75 ns
- So if both sides agree, 400 ns can be used in 802.11n
  ⇒400 ns GI + 3200 ns data ⇒11% overhead

Student Questions

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

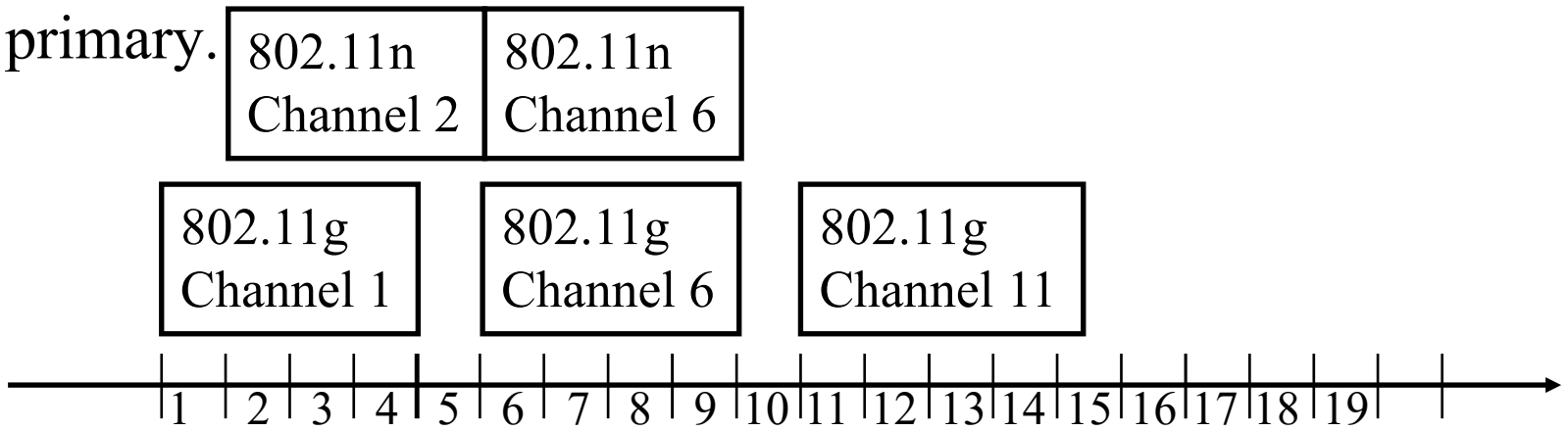
Student Questions

- 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* where * is complex conjugate.*
5. *In Slot 2: on Antenna 1, we transmit S2. On Antenna 2, we transmit S1*.*
6. *This way we transmitted two symbols in two slots. Although the throughput rate is same as that with one antenna. The effective throughput is higher since the noise can be canceled out after reception.*

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.



Student Questions

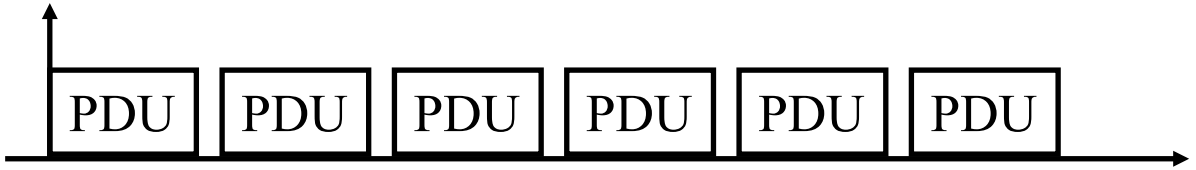
- Which are the primary and secondary channels in the diagram?

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.

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

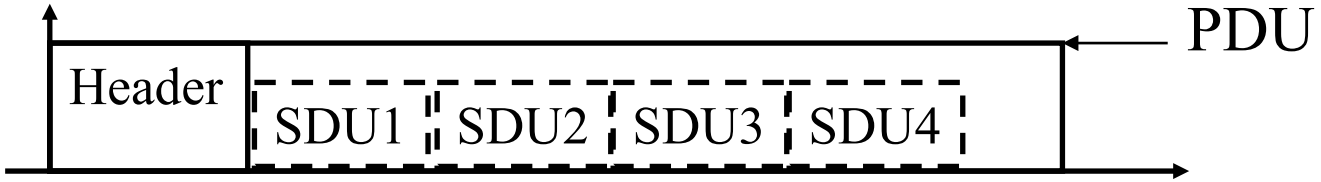
Frame Aggregation

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



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

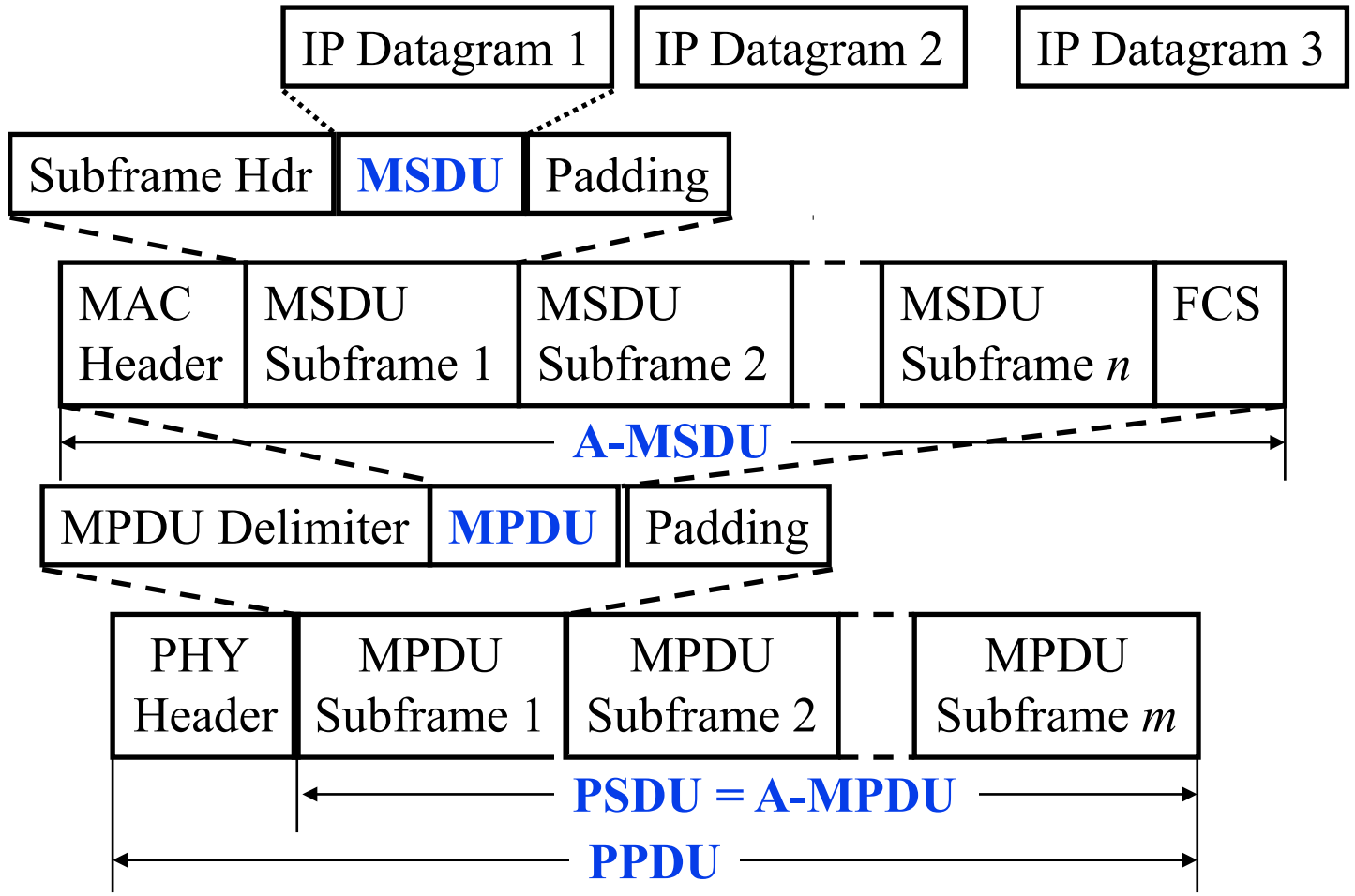
- **Frame Aggregation**: Multiple SDUs in one PDU
  All SDUs must have the same transmitter and receiver address



- Can combine any 2 or all of the above

Student Questions

802.11n Frame Aggregation



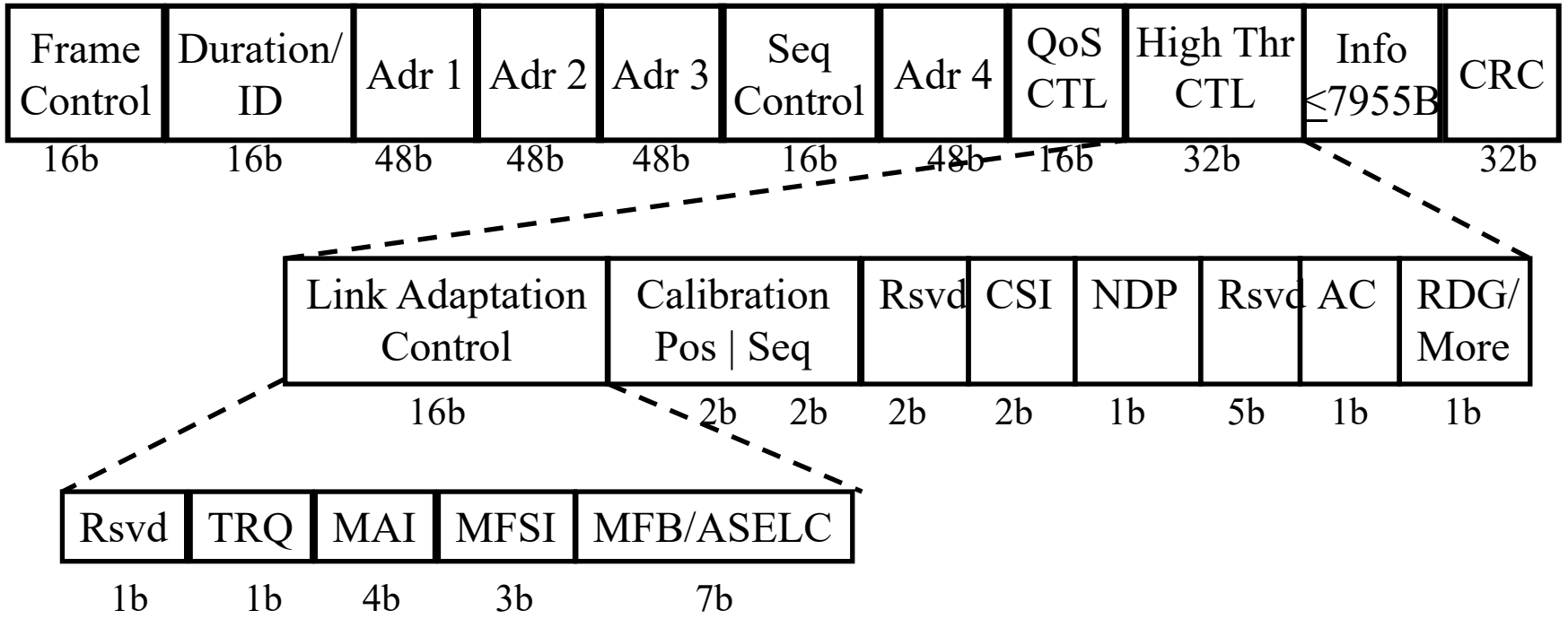
Ref: D. Skordoulis, et al., "IEEE 802.11n MAC Frame Aggregation Mechanisms for Next-Generation High-Throughput WLANs," IEEE Wireless Magazine, February 2008, http://tinyurl.com/k2gvl2g

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

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 1 stream, 20 MHz, 256-QAM, 5/6, Short GI
- 8 streams and 160 MHz = 8×9×96.3Mbps = 6.9333 Gbps

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.

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

Beamforming

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

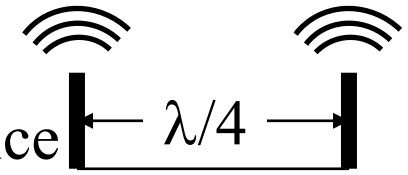
Student Questions

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

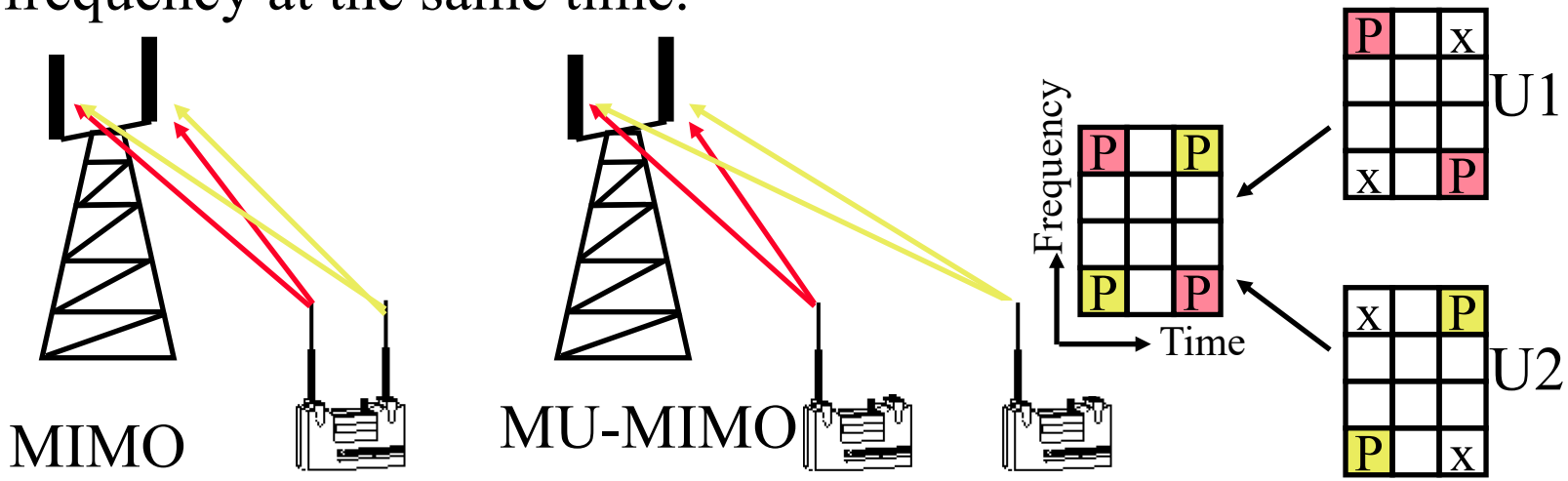
Yes. MIMO requires multiple antennas.

Multi-User MIMO

- **MIMO**: Multiple uncorrelated spatial beams
  Multiple antenna's separated by λ/4
  Cannot put too many antennas on a small device



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



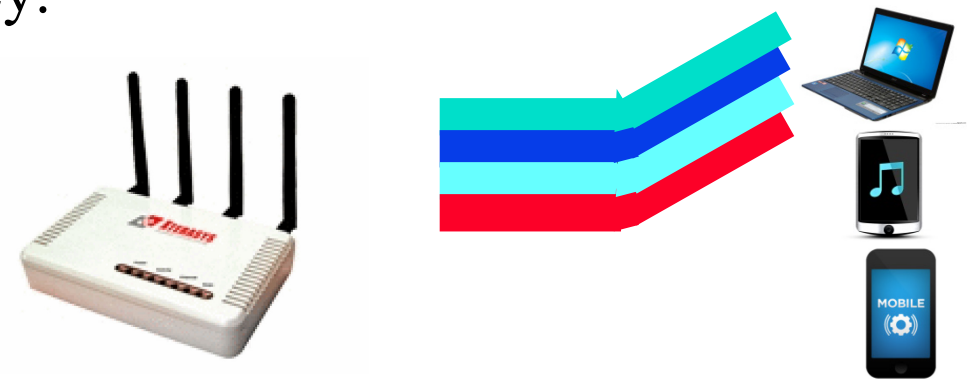
Student Questions

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

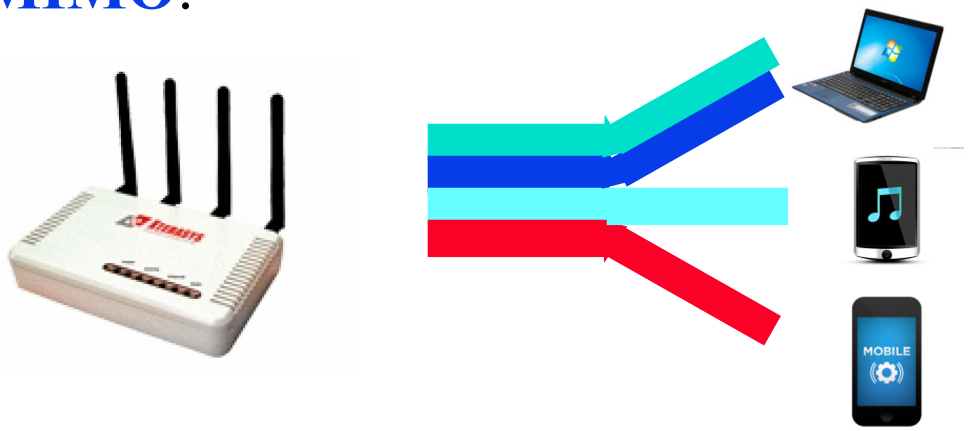
Bottom Right: User 1 is told to send pilots in red slots as indicated and not use slots marked x. User 2 is told to send pilots in yellow slots and not use the slots marked x. Using these different pilots, the signals can be separated at the receiver by correlating each square with the corresponding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

Beamforming with Multi-User MIMO

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



- **Multi User MIMO**:



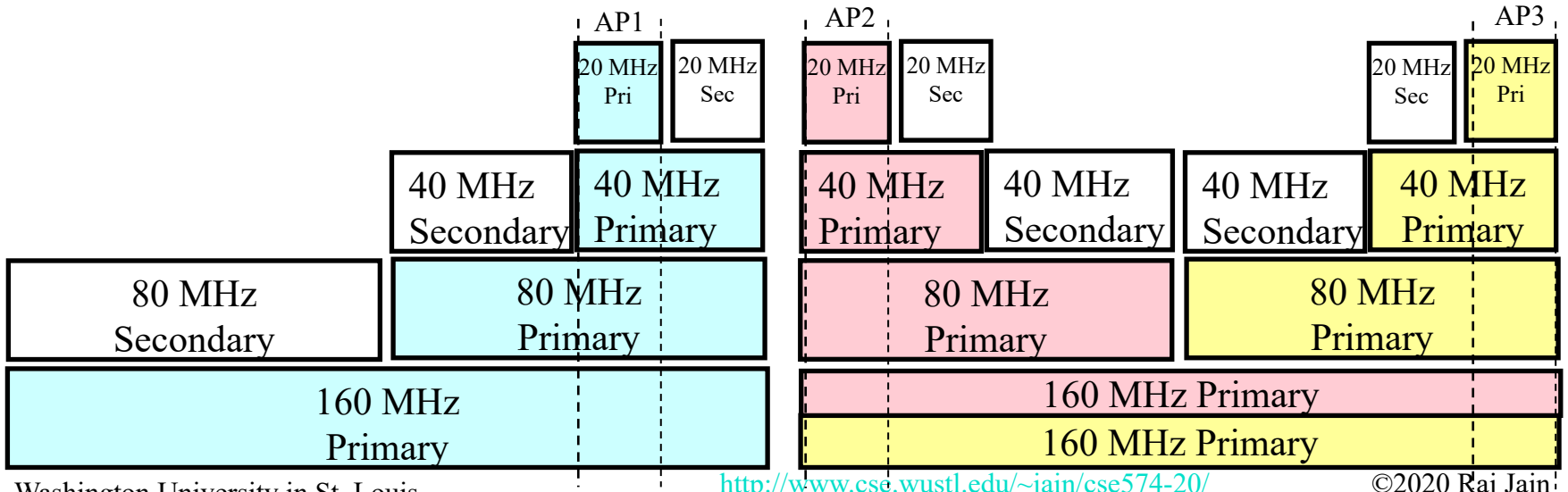
Student Questions

- 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.

Primary and Non-Primary Channels

- Beacons on 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 entire bandwidth is available before using it

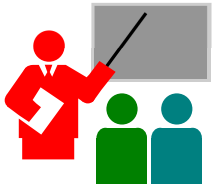


Student Questions

- 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.

Summary



1. Each layer has SDU, 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 guard.
3. 802.11e adds frame bursting, direct link, APSD, and 4 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 8 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.

Homework 6B

- A. Given that 802.11ac Phy rate for 20MHz BPSK 1/2 channel with short GI is 7.22 Mbps, compute 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

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

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

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- 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

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rajjain.com/cse574-18

http://www.cse.wustl.edu/~jain/cse574-20/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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