Introduction to 60 GHz Millimeter Wave Multi-Gigabit Wireless Networks

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These slides and Video recordings of this class lecture are at:
http://www.cse.wustl.edu/~jain/cse574-24/

Student Questions

Q on 7-17c

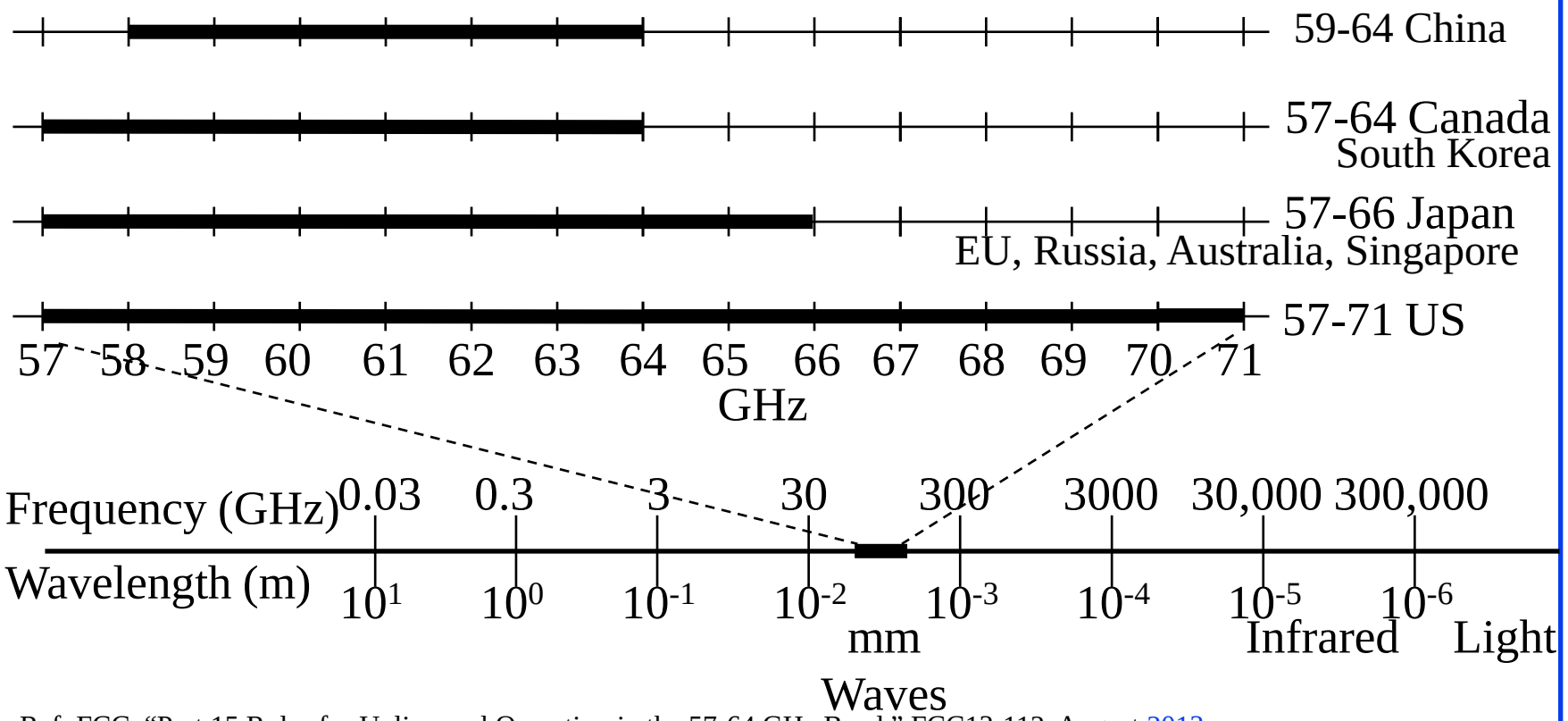
Overview

1. 60 GHz Frequency Allocations and characteristics
2. 60 GHz Wireless Standards
3. IEEE 802.11ad
4. WirelessHD
5. WirelessHD HRP OFDM Parameters

Student Questions

60 GHz Frequency Allocations

- 7-14 GHz in 57-71 GHz (**millimeter** waves 30 GHz-300 GHz)
- 6 Channels of ~ 2.16 GHz
- Significant activity after FCC made 57-66 GHz license-exempt and then extended it to 57-71 GHz.



Ref: FCC, "Part 15 Rules for Unlicensed Operation in the 57-64 GHz Band," FCC13-112, August 2013, http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-13-112A1.pdf

Student Questions

- So it is 7-9 GHz bandwidth in 57-66 GHz band?

Yes

- Why if I am at 60Ghz, do I get more bandwidth than 2.4GHz?

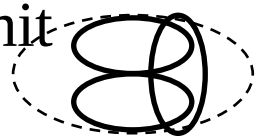
The total band available at 2.4GHz is 60 MHz. At, 60 GHz, it is 7-9 GHz.

- Does that means 30GHz is 1 millimetres and 300 GHz is 10 millimetres?

No. $\lambda = \frac{c}{f}$

60 GHz Power Limits

- **Equivalent Isotropically Radiated Power (EIRP):**
  The power that an isotropic antenna would have to emit to match the directional reception



Region	GHz	Transmit dBm	EIRP dBm	Antenna Gain dBi
US/Canada	7	27	43	33 if 10dBm Transmit
Japan	7	10	58	47
Korea	7	10	27	17
Australia	3.5	10	51.7	41.8
Europe	9	13	57	30

Ref: S. Yong, P. Xia, A. Valdes-Garcia, "60 GHz Technology for Gbps WLAN and WPAN: From Theory to Practice," Wiley, Aug. 2011, 296 pp., ISBN:0470747706, Safari Book

Student Questions

- You mean 16 dBm of antenna gain?

Yes, if you transmit 27 dBm then maximum antenna gain you can have is 16 dBm. However, if you transmit less, then you can have a higher gain antenna as long as EIRP is still below 43 dBm.

- What is the relation between dBi and dBm?

dBi=Power ratio with an isotropic antenna
dBm=Power Ratio with one mW

- So, the directional antenna consumes less energy to deliver the same power as the isotropic antenna?

Yes.

60 GHz Power Limits

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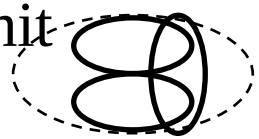

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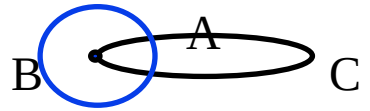
Student Questions

- how to convert transmit power to EIRP, e.g., 27 dBm to 43 dBm EIRP?

You do not compute. You measure. A highly directional antenna will have a high gain and a high EIRP.



Isotropic B will have to transmit 43 dBm to have the same power at point A as Antenna A will have with 27 dBm of transmit power.

- How could you add dBi and dBm? they have different units.

dB is a ratio, which is a difference in log scale:
dB = dBm – dBm
dB + dBm = dBm
dBi = dB with respect to isotropic

60 GHz Power Limits

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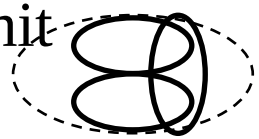

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Student Questions

- Is it correct that I can transmit at a maximum power of 43 dBm omni-directional and 27 dBm directional in the US region?

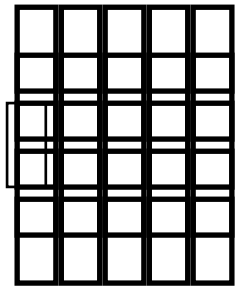
No. Transmit Power ≤27 dBm

- What is the difference between the Transmit dBm and the EIRP dBm?

Transmit is maximum allowed in all directions. EIRP is what a receiver will receive if the transmitter antenna is directional.

Advantages of 60 GHz Band

1. **Large spectrum**: 7 GHz
   - 7 Gbps requires only one b/Hz (BPSK ok).
   - Complex 256-QAM not needed
2. **Small Antenna Separation**:
   5 mm wavelength. ÷4=1.25 mm
3. **Easy Beamforming**: Antenna arrays on a chip.
4. **Low Interference**: Does not cross walls.
   Good for urban neighbors
5. **Directional antennae**: Spatial reuse is easy
6. **Inherent security**: Difficult to intercept
7. **Higher power transmission:**
   - FCC allows up to 27 dBm at 60 GHz, but amplifiers difficult
   - 60 GHz: 10 dBm+30 dBi Antenna gain = 40 dBm EIRP
   - 802.11n: 22 dBm+3 dBi Antenna gain = 25 dBm EIRP



Student Questions

- Why we divided the wavelength in point 2 by 4?

The antenna size is related to the wavelength and how it is placed. A standard dipole antenna is generally l/2. However, it is possible to cut it down to l/4 by using the printed circuit board as the other half.
Ref: https://www.digikey.com/en/articles/understanding-antenna-specifications-and-operation

- Because 60Ghz has such a low interference, does that mean we would need more relays?

Yes. It is meant for a small area only. Every room in the house may need an access point.

- Why could it be "many antennae array on one chip"?

Antennae are tiny.

- Does the picture mean there are many small antennae like an array? Is it a similar idea to MIMO, or is it different?

Yes, it could be used for MIMO.

- Why do we need a higher antenna gain than 802.11n? Does this mean that we need to have better antennas? We could increase transmit power instead of it.

The better design will save battery.

- Why are amplifiers difficult? Difficult to enable high transmit power?

Analog circuits are challenging to design and make.

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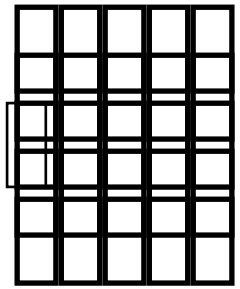


Student Questions

- What's the meaning of 5 mm wavelength/4=1.25mm? Why 4?

Antenna Separation ≥ ¼ λ

Disadvantages of 60 GHz Band

1. **Large Attenuation**: Attenuation α frequency^2
   - Strong absorption by Oxygen
   - Need larger transmit power: 10W allowed in 60GHz
   - Need high antenna gain $\Rightarrow$ directional antennae
   - Short Distance ~ 10m
2. **Directional Deafness**: Can't hear unless aligned
   - Carrier sense not possible
   - RTS/CTS does not work
   - Multicast Difficult
3. **Easily Blocked**: By a human/dog
   Need a relay

Student Questions

- ❑ Does 60 GHz band require a significantly greater amount of antennae? If so, what are the implications in terms of chip size & cost?

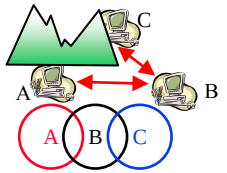
Higher power and directionality is achieved by using many antennae. The cost is negligible.

- ❑ Would some of these issues be solved with a mesh network similar to google home?

Mesh networks are simply multiple access points connected via a wireless backhaul.

- ❑ Why do CTS and RTS work for the hidden node problem and don't work with directional deafness?

With Hidden nodes, B's CTS is heard by both A and C. With directional deafness, C will not hear B's CTS.



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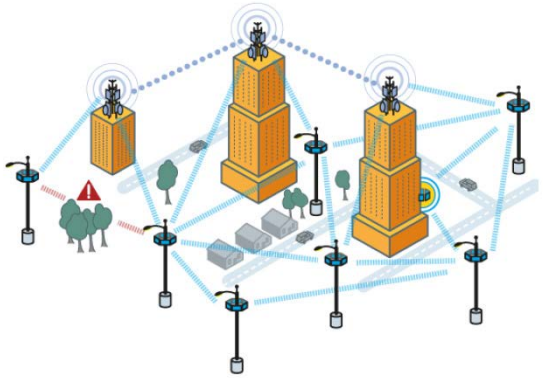
Student Questions

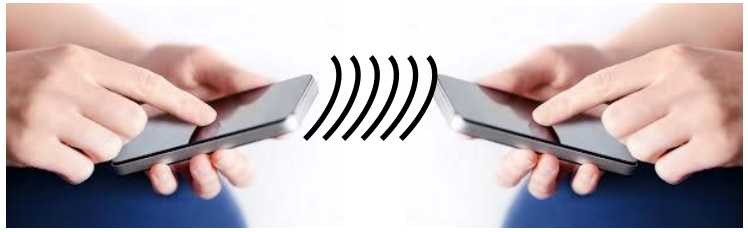
- As 60 GHz suffer significant attenuation, how can networks ensure reliable communication over distances longer than 30 meters?

Can't do longer distance without complexity.

Multi-Gigabit Wireless Applications

- **Cable Replacement**: High-Definition Uncompressed streaming video
- Interactive **gaming**
- High-speed file transfer
- Wireless Mesh **Backhaul** (200-400m)





Student Questions

- To what degree does the wireless mesh backhaul mitigate the signal being easily blocked? Can the signal still be blocked?

Yes, the signal will be blocked for some locations. Some places could still be in the shadow.

- Why is mmWave suitable for wireless backhaul specifically, not mid-haul?

Front-Haul = RAN
Back-Haul = Core
Mid-Haul = Core edge
You can use mmWave for both Back-haul and mid-Haul.

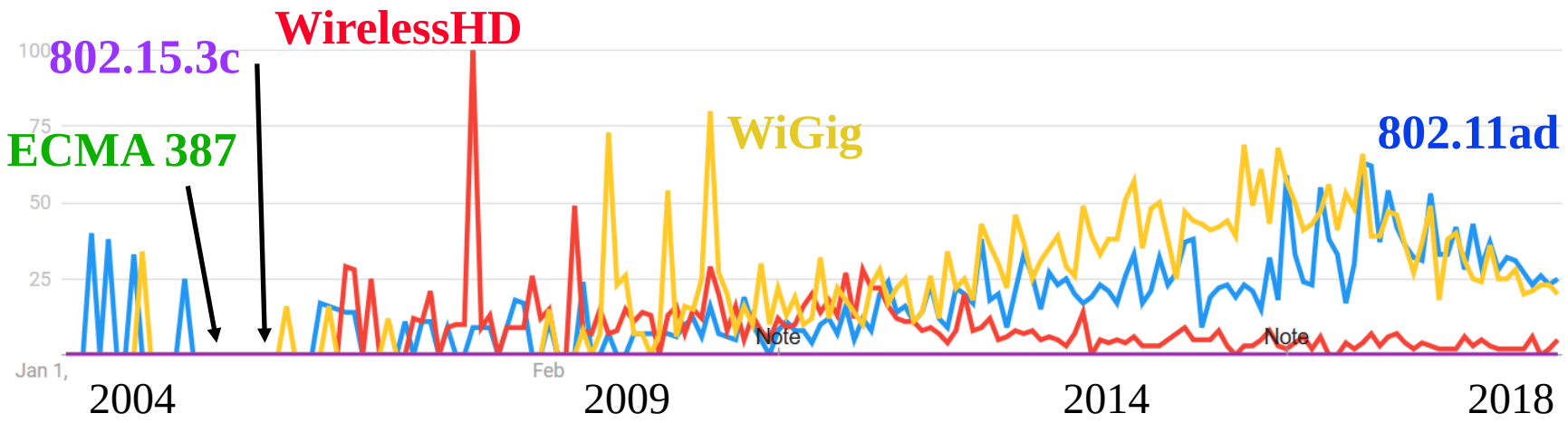
60 GHz Wireless Standards

1. **IEEE 802.11ad-2014**
2. **ECMA-387-2009** (European Computer Manufacturers Association). Second Edition 2010.
3. **IEEE 802.15.3c-2009**
4. **WirelessHD 2010**
5. **WiMAX 802.16-2001** used 10-66 GHz licensed bands for fixed broadband wireless access (WirelessMAN-SC) but was not widely deployed.
6. **ARIB STD-T69** (2005): Millimeter Wave Video Transmission Equipment for Specified Low Power Radio Stations. Association of Radio Industries and Business (ARIB), Japan
7. **ARIB STD-T74** (2005): Millimeter Wave Data Transmission Equipment for Specified Low Power Radio Stations (Ultra High-Speed Wireless LAN System)

Student Questions

Google Trends

- Google trends show the number of searches over time
  - No one is interested in ECMA 387 or 802.15.3c
  - WirelessHD was hot in 2008-2009 but is now being taken over by 802.11ad
- Amazon Search:
  - Four pages of products on WirelessHD on Amazon
  - Nine pages of products on WiGig on Amazon



Student Questions

- What is the y-axis on the Google Trends graph?

% of searches

Sample WiGiG Products

Netgear 11ac/ad Router

Dell Triband Dock

WiGig USB3 Dongle

Dell Laptop with WiGig

Dell 11 a/b/g/n/ad+Bluetooth
Mini-PCI express card

- Mostly computer industry
- 802.11ad added to other datalinks

Source: All product photos are from Amazon.

Student Questions

- Is there 802.11AD (uppercase) already available?

Error corrected.

Sample WirelessHD Products

IOGEAR Wireless 3D Kit

J-Tech Wireless HDMI Extender

Actiontec Wireless HDMI

Nyrius ARIES Wireless HDMI

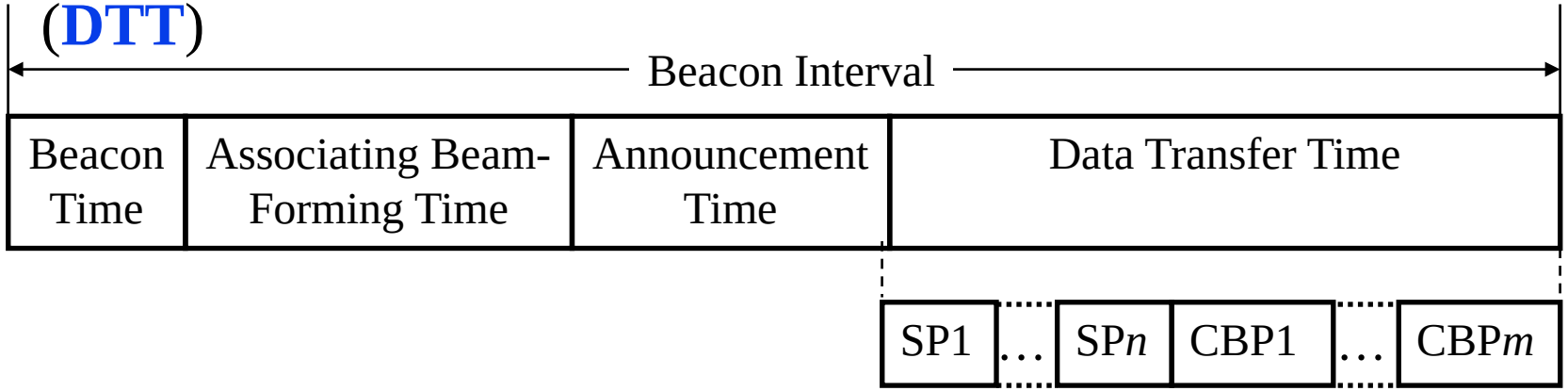
- Mostly Wireless HDMI ⇒ Video Industry
- All come with both ends

Source: All product photos are from Amazon.

Student Questions

IEEE 802.11ad

- **Personal Basic Service Set (PBSS):** Group of stations that communicate
- **PBSS Central Point (PCP)** provides scheduling and timing using beacons
- Each super-frame called "**Beacon Interval**" is divided into: Beacon Time (**BT**), Associating Beamforming Training (**A-BFT**), Announcement Time (**AT**), and Data Transfer Time (**DTT**)



Student Questions

- How does 802.11ad choose one device as PCP?

Based on capability and negotiation.

- How will A-BFT work in the case of mobile stations?

For beamforming, you have to be stationary.

- What is the channel width and the number of channels of 802.11ad?

≈ 12 GHz spectrum,
6 non-overlapping channels of 2GHz,
5 overlapping channels of 4GHz, or
4 overlapping channels of 6GHz, or
3 overlapping channels of 8 GHz.
Ref:
https://en.wikipedia.org/wiki/IEEE_802.11ad

IEEE 802.11ad (Cont)

- Only PCP can send a beacon during beacon time
- In A-BFT, PCP performs antenna training with its members
- In AT, PCP polls members and receives non-data responses
- In DTT, all stations exchange data frames in a dedicated **service period (SP)** or by **contention in a contention-based period (CBP)**
- During DTT, stations use either Distributed Coordination Function (DCF) or Hybrid Coordination Function (HCF)

Student Questions

- Could you please repeat the difference between SP and CBP?

SP is contention free pre-allocated period. CBP is contention based.

- In AT, PCP polls and finds out if stations have data. In DTT, the PCP needs to poll them again to allow them to send data?

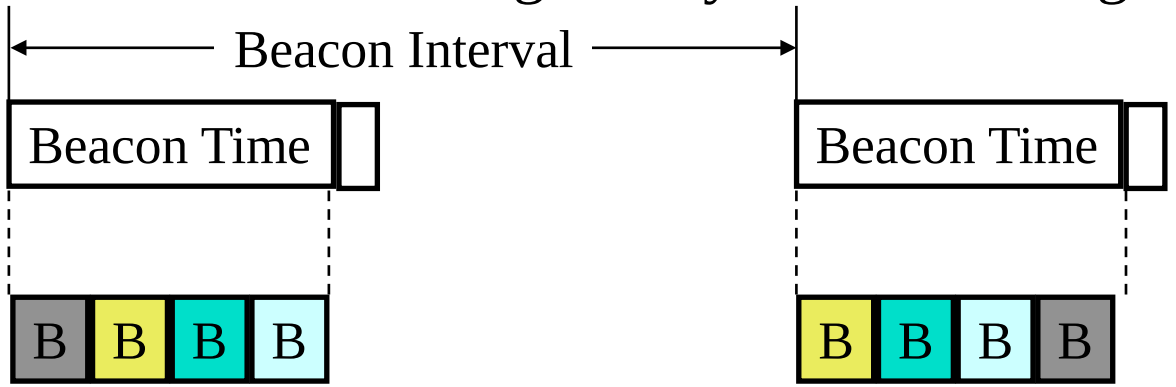
Some slots in DTT are pre-assigned and announced in the beacon if requested in PCP. Others are available by contention.

- Why is DCF parallel to HCF instead of CAP (Controlled Access Phase)?

CAP is a period, and HCF is the method. CBP is the period, and DCF is the method.

IEEE 802.11ad Beacon

- Beacon transmissions are omni-directional ⇒ One beacon is transmitted through every antenna configuration



Beacons in Different Antenna Configurations

Student Questions

- How many antenna configurations are there likely to be? How does the number scale with the number of antennae?

Configuration = Sectors in the space. The number of sectors can be much less than the number of antennae.

- Is there always an antenna array being used in 802.11ad?

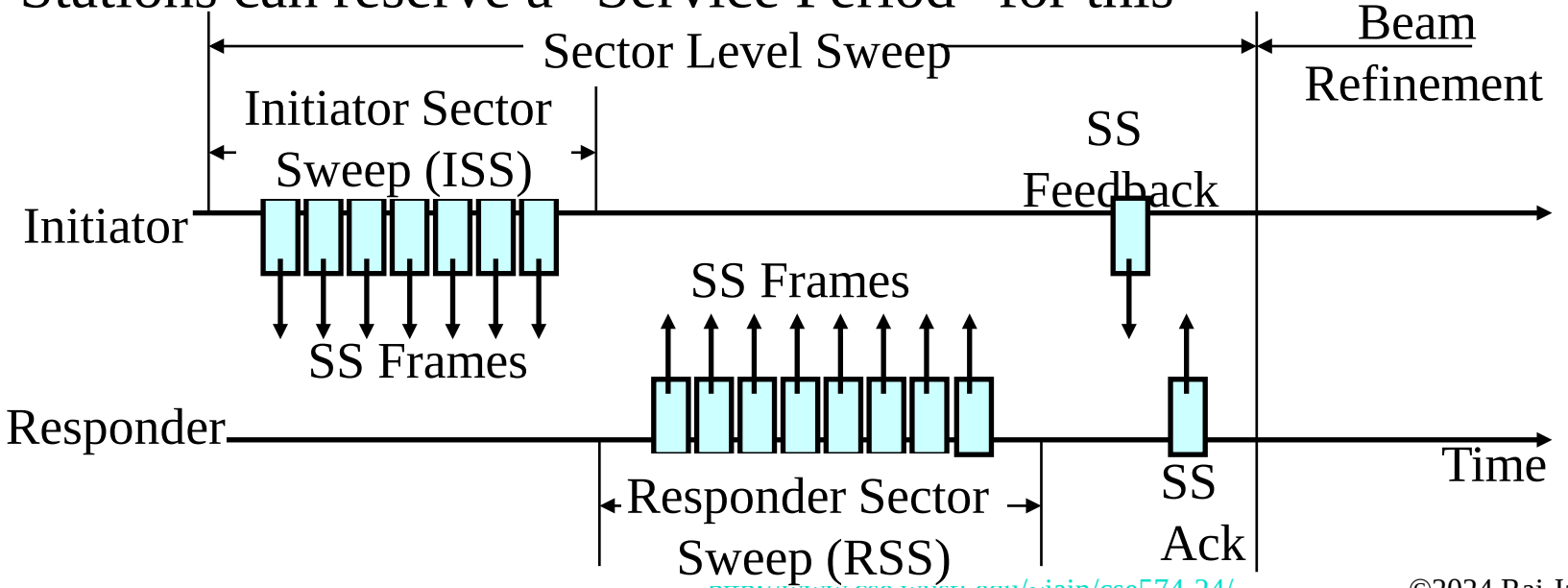
Yes.

- How do different antenna configurations impact the transmission of beacons in the IEEE 802.11ad standard?

Beacon is transmitted through all antenna as shown. Antenna configurations are explained in Slides 7.16-7.17.

IEEE 802.11ad Antenna Training

- Each station finds the optimal antenna configuration with its recipient using a two-stage search
- **Sector Level Sweep (SLS):** First, it sends in all sectors and finds the optimal sector
- **Beam Refinement Procedure (BRP):** It searches through the optimal sector to find the optimal parameters in that sector
- Stations can reserve a "Service Period" for this



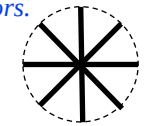
Student Questions

- What is sector? Is it physical location?

See next slide

- What is a sector?

Space is divided into sectors.



You can have 2, 3, 4, … sectors.

- How long does it take for antenna training? Is it inefficient?

In the order of milliseconds. It is imperceptible to humans. It is efficient if a large amount of data is transmitted after alignment.

IEEE 802.11ad Antenna Training

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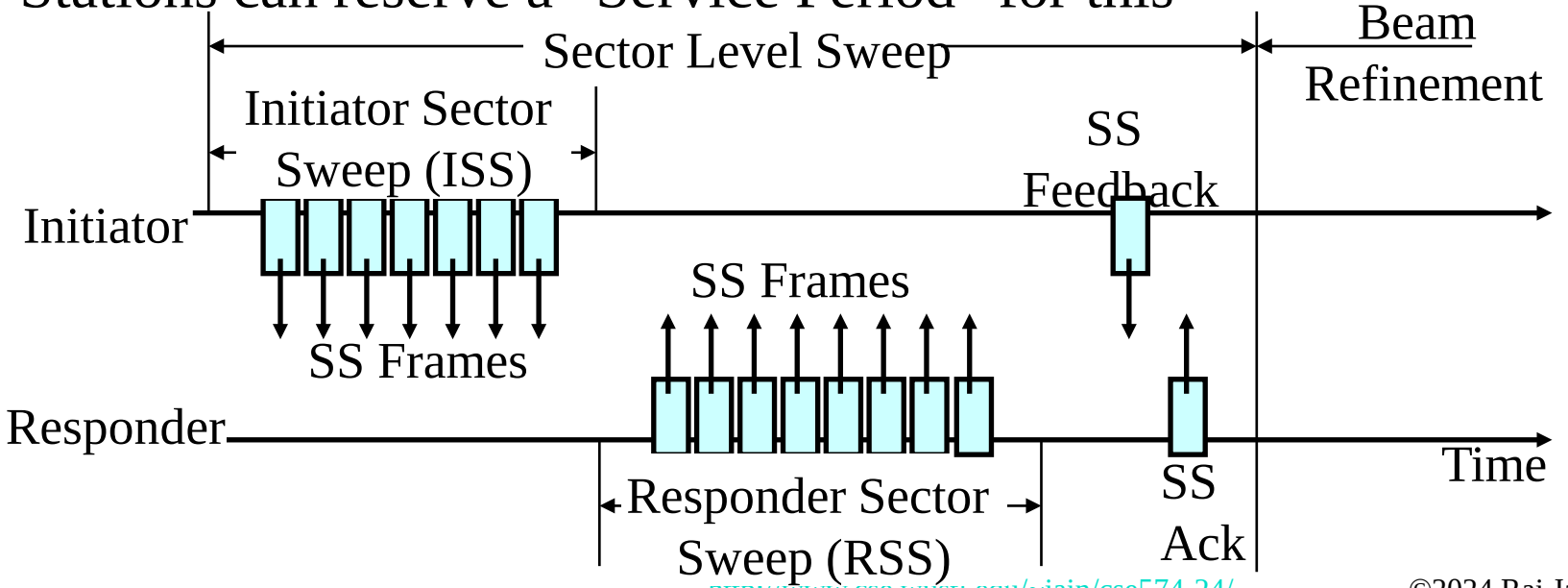

Student Questions

- Why can stations reserve a SP (Service Period) for antenna training which is supposed to happen in A-BFT (associated beamforming training)?

SP is used between two stations. A-BFT is used between a station and the PCP.

- Why does the responder send 8 SS frames? Does that mean that the responder has eight sectors?

8 frames inside a sector will make the alignment correct to 1/8th of a sector.

IEEE 802.11ad Antenna Training

- Each station finds the optimal antenna configuration with its recipient using a two-stage search
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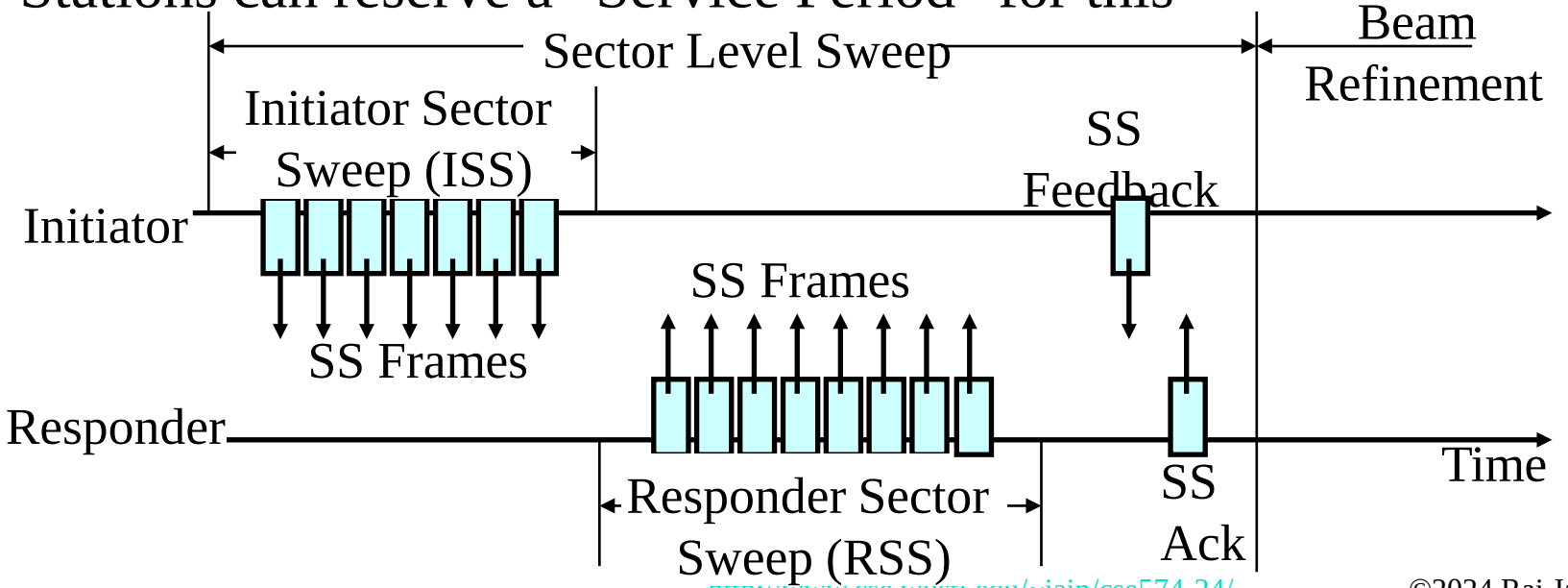
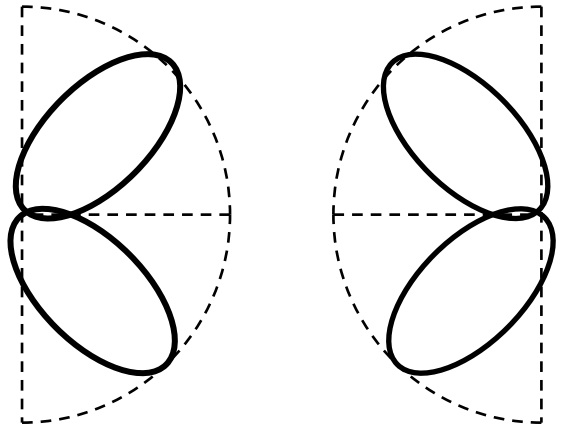


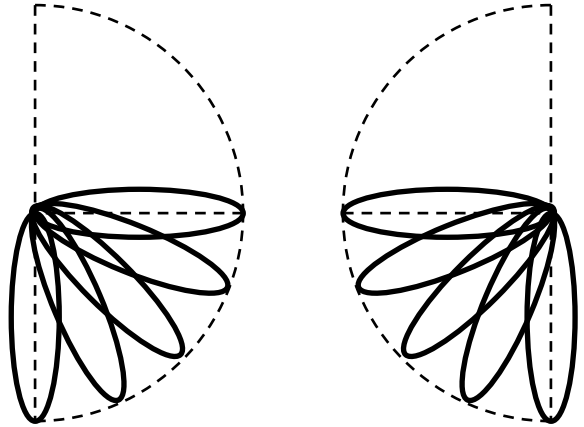
Student Questions

Antenna Alignment

- **Beam Search**: Binary search through sectors using beam steering
- **Beam Tracking**: Some bits are appended to each frame to ensure that the beams are still aligned.



Sector-Level Sweep



Beam Refinement

Student Questions

- Does this relate to the signal waves being in phase? Is directional deafness caused from out of phase signals?

Directional deafness is when the receiver is not in the transmit lobe. For example, receivers on the left of the antenna in the left-most picture here.

- Can you explain how the extra bits are appended to a framework for beam tracking?

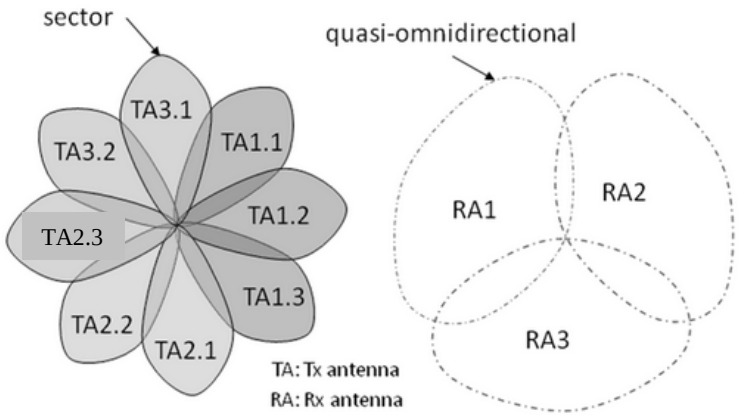
Extra bits are used for measuring the error rate in a well-known bit sequence.

- Are these Beam Search and Beam tracking related to SLS and BRP? How? They have different names.

Beam search is done using SLS and BRP. Beam tracking is done by adding bits to each frame.

Antenna Training Example

- Initiator (left) has three antennae with 3, 3, and 2 sectors. Responder (right) has three antennae with one sector each
- Initiator performs three sweeps with eight frames, each using a different sector. The responder sends feedback.
- They find the best receive antenna and the best transmit antenna.



Ref: A. Suarez Sarmiento and E. M. Lopez, "Multimedia Services and Streaming for Mobile Devices," IGI Global, Sep 2011, ISBN:1613501447

Student Questions

- What is the relation between the number of antennae and the number of sectors?

No strict relationship. More sectors per antenna require more beam forming.

- Does the initiator send 3*8*8 sweep frames?

Eight sweep frames total.

- Are these eight data frames or dummy frames used for antenna training?

Training frames. Not data frames.

- In Slide 14 of the Q&A session, you said the number of sectors could be much less than the number of antennas. What I see here is that it is at least equal or more. Could you please explain?

The antenna can be steerable. One antenna can change direction electronically.

- In the slide, you said the responder sends feedback. How many? Three? Or one frame per received frame?

One feedback for all 8 SS frames. Indicates the best direction.

- Can you explain the order that the initiator performs the eight sweep frames?

Any order. Sequential is OK.

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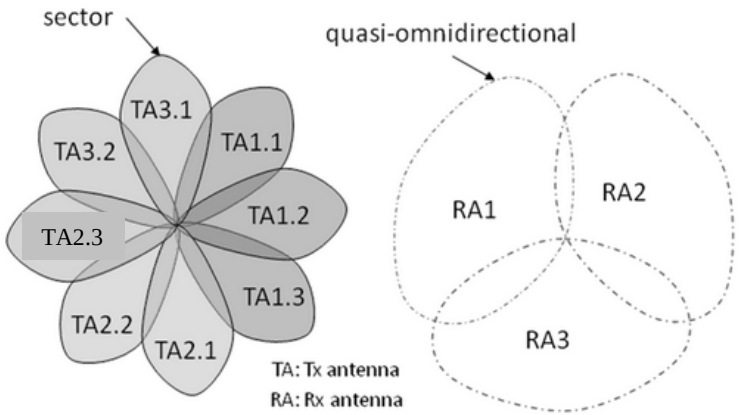

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Student Questions

- Can we use fewer, omnidirectional receive antennas because there are lower power requirements for Rx vs Tx?

Each antenna is transmit/receive.

- Would it be possible to transmit to two separate receivers simultaneously? Or could that lead to interference?

Yes. Sectoring allow space multiplexing.

- ❖. Is there BRP during Antenna training? If not, why?

Yes. The first step is to find the best antenna pair along with sector direction. Then BRP is done.

IEEE 802.11ad PCP Cluster

- Overlapping PBSS avoids interference by electing a "**Synchronization PCP**" (**S-PCP**) for the PCP cluster
- All PCPs select the beacon interval to be an integral multiple of that selected by S-PCP
  ⇒ Non-overlapping beacon transmit intervals
- All PCP allocate Service Periods in their schedule for BT of all other PCPs
  ⇒ All PCPs hear all allocations
  ⇒ Avoid overlapping scheduling

Student Questions

- Please explain 3rd point again.

BT=Beacon Time. In a cluster, beacon time for each PCP is reserved by all other PCPs.

- (Point one) Is that "Overlapping PCP" or "Overlapping PBSS"? I think for a PBSS, we have a PCP. And if these PCPs detect any interference in their clusters, they select an S-PCP.

PBSS is the area. PCP is a point. If a PCP detects interference or another beacon, it forms a cluster.

- (Last point): In which section do these PCPs allocate some time to hear the BT of other PCPs? in their Beacon time interval or service time interval?

Each PCP reserves some SPs in their beacon time interval as agreed with the other PCP.

Spatial Frequency Sharing (SFS)

- Multiple transmissions may be scheduled on the same frequency at the same time if they don't interfere
- PCP asks stations to send "Directional Channel Quality" results during an overlapping SP. The stations measure the channel quality and send it to PCP.
  PCP then knows which station pairs can share the same slot.

Student Questions

- Are there design standards we should be aware of re: implementation of SFS? I.e.: how can we increase throughput without maximizing interference?

Measure interference as discussed in the 2nd point.

IEEE 802.11ad Relays

- **Link Switch Relays**: MAC relays like a switch. Receive complete frames from the source and send them to the destination.
- **Link Cooperation Relays**: Phy relays like a hub. Amplify and forward (AF) or decode and forward (DF)
  ⇒ Destination may receive direct signal and relayed signal.
  ⇒ Spatial diversity

Student Questions

- Can other clients be used as relay stations?

Yes, only if the client implements the relay function.

- What are amplify and forward and decode and forward, and when are they used?

These are two types of relays. DF is suitable for noisy environments. AF is suitable for long distances.

- Is the DF a physical layer relay?

Yes. They can transmit bit-by-bit.

- What are MAC and PHY relays, and what are the differences?

MAC devices understand MAC frame format and can check CRC. PHY devices operate on bits and do not understand MAC frame format.

IEEE 802.11ad Relays

- **Link Switch Relays**: MAC relays like a switch. Receive complete frames from the source and send them to the destination.
- **Link Cooperation Relays**: Phy relays like a hub. Amplify and forward (AF) or decode and forward (DF)
  ⇒ Destination may receive direct signal and relayed signal.
  ⇒ Spatial diversity

Student Questions

- How does the spatial diversity provided by Link Cooperation Relays in IEEE 802.11ad enhance communication reliability compared to using Link Switch Relays?

Switch = MAC layer = Frames
Hub = Phy Layer = bits

802.11ad Summary

1. **Centralized** scheduling. Only **PCP** can send beacons. It sends beacons in all sectors.
2. Superframe (**Beacon Interval**) consists of Beacon Time, Associating Beamforming Training, Announcement Time, and Data Transfer Time
3. Announcement time is used for collecting requests
4. Data transfer can be pre-allocated or by contention
5. **Antenna training** is a 2-phase process. Sector selection and beam refinement.
6. Multiple transmissions can simultaneously occur on the same frequency (**Spatial Frequency Sharing**).
7. **Relays** can be used if LoS blocked.

Student Questions

- Can you re-explain the superframe components briefly?

See Slide 7-12

WirelessHD

- 60 GHz wireless standard to connect television displays to laptops, Blu-ray players, DVRs, …
- Designed for high-quality, uncompressed video
  e.g., 2560×1440p, 60Hz, 36b color = 8.0 Gbps
- Lossless, 3D, 48b color, 240 Hz refresh, 4K (4096p) resolution video streaming from smartphones and tablets
- **Wireless Video Area Network (WVAN):** 10m - 30m
- 4 Channels of 1.76 GHz each
- Very-high data rates (28 Gbps+) using spatial multiplexing (4 concurrent streams)
- Non-line of sight operation

Ref: WirelessHD.org, "WirelessHD Specification Overview,"
http://www.wirelesshd.org/pdfs/WirelessHD-Specification-Overview-v1.1May2010.pdf

Student Questions

- How is non-LoS possible?

Using reflections.
Ref: WirelessHD Specification Version 1.1 Overview, May 2010.

- Possible correction in slide content: 4k resolution is represented by 2160p not 4048p.

4K=4096. 4k=4000. It relates to the horizontal resolution of the video. Vertical varies.
UHD 4k = 3840×2160
DCI 4K = 4096×2160

- Is it 4k or 4K?

Both are possible. However, marketing people use these interchangeably.

- Can it support high fps streaming (120hz) or 8k video? Or will those be worked on in a future 802.11 revision?

WirelessHD is not 802.11. However, since it can handle 240Hz 4k, it can handle 120Hz 8k. Same bit rate.

WirelessHD PHYs

- Three Phys:
  1. **High-Rate PHY (HRP):** 1-7 Gbps for high-quality video
  2. **Medium-Rate PHY (MRP):** 0.5-2 Gbps for lower power mobile applications
  3. **Low-Rate PHY (LRP):** 2.5-40 Mbps for Omni-directional control and discovery, multicast, acks for HRP/MRP, antenna beam forming, capability exchange
- HRP/MRP (**HMRP**) and LRP use the same band: Use TDMA
- Peer-to-Peer ⇒ No access point (but need one coordinator)
- A device may have coordinator capability. | Generally, displays and storage devices have this capability.

Student Questions

WirelessHD HRP OFDM Parameters

- Similar tables for LRP and MRP

Parameter	Value	Symbol	
Occupied Bandwidth	1.76 GHz	B	
Subcarrier Spacing	4.957 MHz	Δf_{sc}	
Number of subcarriers	355 = 1.76/4.957	$B/\Delta f_{sc}$	
FFT Size	512	F=Round up to a power of 2	Frequency Domain
Number of Data Subcarriers	336	N_{dsc}	Frequency Domain
Number of DC Subcarriers	3 (355)	N_{dc}	Frequency Domain
Number of Pilots	16	N_p	Frequency Domain
Number of Null subcarriers	157	$F-N_{dsc}-N_{dc}-N_p$	
FFT Period	$1/\Delta f_{sc}$ = 201.73 ns	T_{FFT}	Time Domain
Guard Interval	$T_{FFT}/8$ = 25.22 ns	T_{GI}	Time Domain
Symbol Duration	$T_{FFT}+T_{GI}$ = 226.95 ns	T_S ⇒ Symbols/s	Time Domain
Modulation	QPSK, 16-QAM, 64-QAM	⇒ bits/Symbol	
Outer block code	RS(224, 216) ⇒ 224–216=8 check bits		Coding
Inner Code	1/3, 1/2, 2/3, 5/6 (EEP) 2/5, 1/2, 4/7, 2/3, 4/5 (UEP)	x/y ⇒ x info bits in y total bits	Coding

Student Questions

- I'm confused by the numbers for EEP/UEP

x/y ⇒ for every y bits, only x are data bits. y-x are check bits.
The numbers are in the standard.

- I don't understand how the numbers of data subcarriers, DC subcarriers, and pilots are chosen/calculated.

All formulas have been added on the left. ***Please practice****.*
Example: *PHY bit rate with 64-QAM, 2/5 UEP*
=(1/(226.95×10^-9))×6 ×(216/224)×(2/5)
=10.2 Mbps per data subcarrier
*=10.2*336=3.4272 Gbps*
Exam Question*: What would the data rate with 5/6 EEP and 16-QAM?*

- Could you explain the exam question asked by former students?

You need to calculate the results if we change these parameters.

WirelessHD HRP OFDM Parameters

- Similar tables for LRP and MRP

Parameter	Value	Symbol
Occupied Bandwidth	1.76 GHz	B
Subcarrier Spacing	4.957 MHz	Δf_{sc}
Number of subcarriers	355 = 1.76/4.957	$B/\Delta f_{sc}$
FFT Size	512	F=Round up to a power of 2
Number of Data Subcarriers	336	N_{dsc}
Number of DC Subcarriers	3 (355)	N_{dc}
Number of Pilots	16	N_p
Number of Null subcarriers	157	$F-N_{dsc}-N_{dc}-N_p$
FFT Period	$1/\Delta f_{sc}$ = 201.73 ns	T_{FFT}
Guard Interval	$T_{FFT}/8$ = 25.22 ns	T_{GI}
Symbol Duration	$T_{FFT}+T_{GI}$ = 226.95 ns	T_S ⇒ Symbols/s
Modulation	QPSK, 16-QAM, 64-QAM	⇒ bits/Symbol
Outer block code	RS(224, 216) ⇒ 224–216=8 check bits	
Inner Code	1/3, 1/2, 2/3, 5/6 (EEP) 2/5, 1/2, 4/7, 2/3, 4/5 (UEP)	x/y ⇒ x info bits in y total bits

Frequency Domain

Time Domain

Coding

Student Questions

- What does 8 in Guard Interval mean?

Guard Interval is 1/8th of the FFT period.

- The calculation you mentioned under "Exam question": The first term (1/226*10^-9) gives us the number of symbols per second. The second term is for 64 QAM, and it says we send 6 bits per symbol (but in the question, it is 16 QAM). The third term is for the R-S code, and the last term is for 2/5 UEP and not for the 5/6 EEP.

You are supposed to change the calculations accordingly.

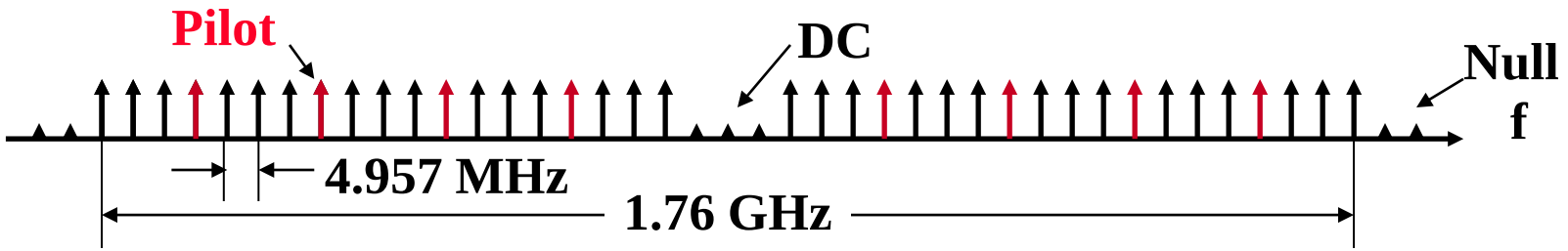
- Are DC subcarriers only used in WirelessHD?

No, many other standards use DC subcarriers.

- Could you elaborate on how modulation scheme affects error rate in WirelessHD HRP OFDM?

See text in blue.

HRP OFDM Frequency Parameters



Parameter	Value	Symbol
Occupied Bandwidth	1.76 GHz	
Subcarrier Spacing	4.957 MHz	Df_{sc}
Number of subcarriers	355	
FFT Size	512	
Number of Data Subcarriers	336	N_{dsc}
Number of DC Subcarriers	3	
Number of Pilots	16	
Number of Null subcarriers	157	

- Similar tables for MRP and LRP

Student Questions

- Are DC subcarriers always in the middle?

Yes, as much as I have seen.

- What is the difference between DC and null?

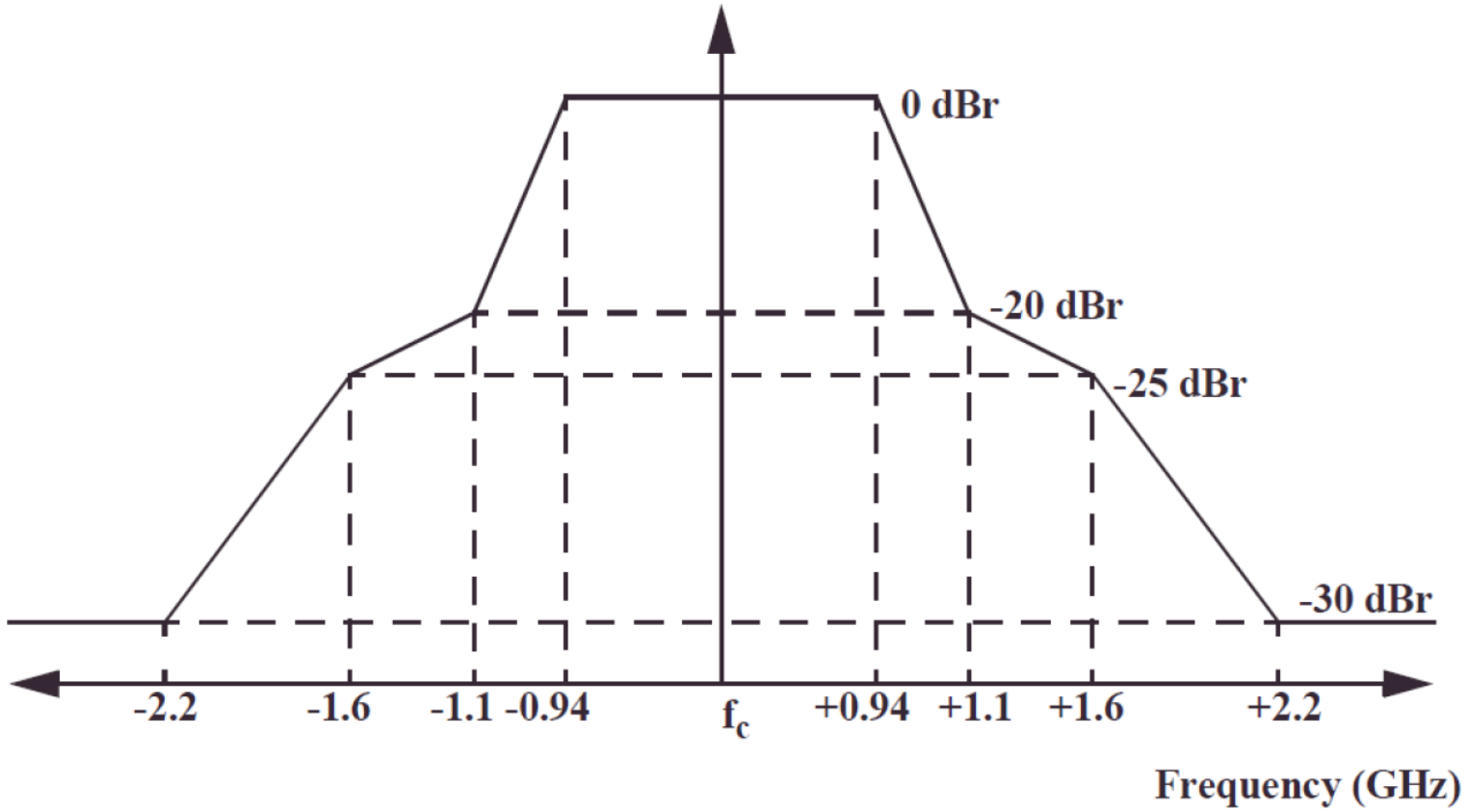
DC subcarriers are used as reference frequencies. Nulls are used as guards at the edge.

- Can you explain more about how DC subcarriers are used?

DC subcarriers indicate the key locations in frequency domain as shown in the figure.

HRP Transmit Mask

- Similar masks exist for LRP and MRP
- dBr = deci-Bel relative



Ref: WirelessHD.org, "WirelessHD Specification Overview,"
http://www.wirelesshd.org/pdfs/WirelessHD-Specification-Overview-v1.1May2010.pdf

Student Questions

- Please explain what the equation for dBr is.

This example is relative to a reference point on the mask, e.g., peak.

- What is dBr relative to?

Relative to the peak as indicated.

- What is the unit of this -30dBr? Does this mean we have to send 30 dBm less than what we sent in the reference frequency?

Yes.

- Can you go over one example of how we calculate the HRP transmit mask?

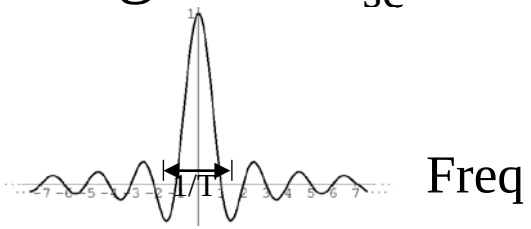
You will not have to calculate the mask. It is specified in the standards.

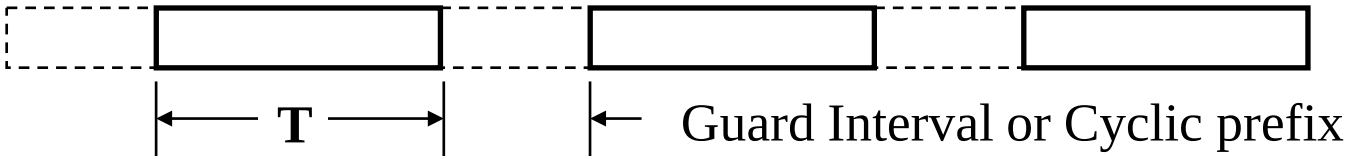
- In the video, you mentioned that 0 dBr is equivalent to 1. Does the "1" refer to 1 watt?

No relative to the max power (the power at central frequency).

HRP OFDM Time Parameters

- Symbol time = 1/subcarrier spacing = $1/\Delta f_{sc}$





Parameter	Value	Symbol
FFT Period	$1/\Delta f_{sc}$ = 201.73 ns	T_{FFT}
Guard Interval	$T_{FFT}/8$ = 25.22 ns	T_{GI}
Symbol Duration	$T_{FFT}+T_{GI}$ = 226.95 ns	T_S

Student Questions

- On this picture, what does the 1/T refer to strictly?

T is the pulse width in the time domain. 1/T is the inter-carrier spacing in the frequency domain, e.g., 1 ms and 1 kHz.

HRP OFDM Coding Parameters

- Reed-Solomon Coding: RS(n,k) ⇒ Send n bits for k bits
- Equal Error Protection (EEP): All data bits and ECC bits are equally protected
- Unequal Error Protection (UEP): Bits are divided into subgroups. Each subgroup has a different protection level

Parameter	Value	Symbol
Modulation	QPSK, 16-QAM, 64-QAM	
Outer block code	RS(224, 216)	
Inner Code	1/3, 1/2, 2/3, 5/6 (EEP) 2/5, 1/2, 4/7, 2/3, 4/5 (UEP)	

Student Questions

WirelessHD MAC

- Two MAC capabilities:
  1. **Coordinator**: Controls timing and keeps track of members of WVAN
  2. Other stations
- Everyone can transmit and receive LRP
- Some may be able to receive HMRP but may/may not be able to transmit HMRP
- Shutdown and sleep modes
- Channel estimation
- Higher Layer: Video format selection, video coding/encoding, service discovery, …

Student Questions

WirelessHD Summary

1. Designed for uncompressed video. Video Cable replacement.
2. **Three PHYs**: High-Rate (1-7 Gbps), Medium-Rate (0.5-2 Gbps), and Low-Rate(2.5-40 Mbps)
3. LRP is used for discovery, multicast
4. Centralized Access. The coordinator issues beacons and allocates reserved transmission slots
5. No access points. But some devices need **coordinator capabilities**.
6. Random Access Time Blocks (**RATBs**) are used for unallocated transfers
7. Channel Time Blocks (**CTBs**) are used for pre-allocated transfers
8. Power save mode and device control commands in MAC

Student Questions

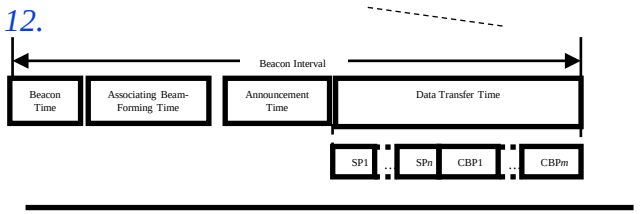
- Can WirelessHD do other IEEE features we learned about, such as MIMO?

Multiple antennae can be used for both beamforming and MIMO. There is a slight difference between MIMO and beamforming.

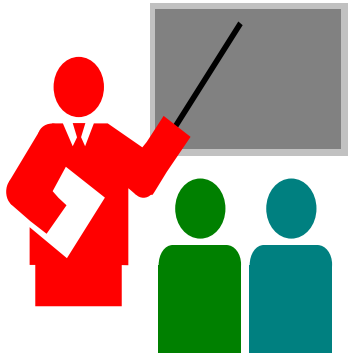
Beamforming *MIMO*

- Could you explain RATBs and CTBs again?

These are similar to CBPs and SPs in Slide 7-12.



Summary



1. 60 GHz, a.k.a. mm-wave, has large bandwidth, small antenna separation allows easy beamforming and gigabit speeds but short distance due to significant attenuation
2. Tri-band Wireless LAN devices with 2.4 GHz, 5.8GHz, and 60GHz are coming
3. 802.11ad LAN uses a PBSS central control point (PCP)
4. WirelessHD was designed for HD video.
5. In all cases, antenna alignment and tracking are required.

Student Questions

Homework 7

- A. What is the EIRP of a system that transmits 1 Watt using a 10 dBi antenna?
- B. An OFDM system has to be designed using 1GHz band with 5 MHz spacing. What is the number of:
  - Used Subcarriers
  - Size of FFT
  - FFT duration
  - Symbol duration assuming 1/4th cyclic prefix
  - Data bit rate using QPSK with RS(224, 216) coding with ¾ rate inner code. Assume 7/8th of the subcarriers are used for data transmission.

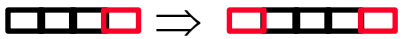
Student Questions

- FTT duration and period are the same, right?
- Can we get the answers to the homework we have done before the exam?

Sure. At the end of this class.

- Is cyclic prefix the same as guard interval? Is it 1/4 rather than 1/8 here, just as an example?

Guard interval is idle time. The cyclic prefix consists of a repeat of the part of the frame.



Reading List

- S. Yong, P. Xia, A. Valdes-Garcia, “60 GHz Technology for Gbps WLAN and WPAN: From Theory to Practice,” Wiley, Aug. 2011, 296 pp., ISBN:0470747706, Safari Book
- WirelessHD.org, "WirelessHD Specification Overview," http://www.wirelesshd.org/pdfs/WirelessHD-Specification-Overview-v1.1May2010.pdf

Student Questions

Wikipedia Links

- http://en.wikipedia.org/wiki/Wireless_Gigabit_Alliance
- http://en.wikipedia.org/wiki/WirelessHD
- https://en.wikipedia.org/wiki/Effective_radiated_power
- http://en.wikipedia.org/wiki/Extremely_high_frequency
- http://en.wikipedia.org/wiki/Frame_aggregation
- http://en.wikipedia.org/wiki/Beamforming
- http://en.wikipedia.org/wiki/Phased_array
- http://en.wikipedia.org/wiki/Antenna_array_(electromagnetic)
- http://en.wikipedia.org/wiki/Wireless_USB
- http://en.wikipedia.org/wiki/MAC_service_data_unit
- http://en.wikipedia.org/wiki/Protocol_data_unit
- http://en.wikipedia.org/wiki/Block_acknowledgement

Student Questions

References

- IEEE 802.11ad-2012, "IEEE Standard for Information Technology – Telecommunications and Information Exchange Between Systems – Local and Metropolitan Area Networks – Specific Requirements – Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specification, Amendment 3: Enhancements for Very High Throughput in the 60 GHz Band," 28 December 2012, 628 pp.
- FCC, "Part 15 Rules for Unlicensed Operation in the 57-64 GHz Band," FCC13-112, August 2013, http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-13-112A1.pdf
- IEEE 802.15.3c-2009, "IEEE Standard for Information Technology – Telecommunications and Information Exchange Between Systems – Local and Metropolitan Area Networks – Specific Requirements, Part 15.3: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for High Rate Wireless Personal Area Networks (WPANs), Amendment 2: Millimeter-Wave-Based Alternative Physical Layer Extension," 12 October 2009, 203 pp.
- ECMA, "High Rate 60 GHz PHY, MAC and PALs," 2nd Edition, December 2010, 302pp. http://www.ecma-international.org/publications/files/ECMA-ST/ECMA-387.pdf

Student Questions

References (Cont)

- A. Suarez Sarmiento and E. M. Lopez, "Multimedia Services and Streaming for Mobile Devices," IGI Global, Sep 2011, ISBN:1613501447.

Student Questions

Acronyms

- A-BFT Associating Beamforming Time
- AF Amplify and forward
- ARIB Association of Radio Industries and Business
- AT Announcement Time
- AV Audio Video
- BFT Beamforming Time
- BP Beacon Period
- BPSK Binary Phase Shift Keying
- BRP Beam Refinement Procedure
- BT Beacon Time
- CAP Contention Access Period
- CBP Contention-based period
- CMS Common mode signaling
- CRC Cyclic Redundancy Check
- CTA Channel Time Allocation

Student Questions

Acronyms (Cont)

CTS	Clear to Send
dBi	Deci-Bel Isotropic
dBm	Deci-Bel milliwatt
DBS	Discovery Block Set
DCF	Distributed Coordination Function
DF	Decode and forward
DI	Discovery Interval
DTP	Data Transfer Period
DTT	Data Transfer Time
DTV	Digital Television
DVDO	Name of a company
DVR	Digital Video Recorder
ECMA	European Computer Manufacturers Association
EEP	Equal Error Protection
EIRP	Equivalent Isotropically Radiated Power
EM	Expectation Maximization

Student Questions

Acronyms (Cont)

EU	Europe
EURASIP	Name of a Publisher
FCC	Federal Communications Commission
FFT	Fast Fourier Transform
GHz	Giga Hertz
HCF	Hybrid Coordination Function
HCS	Header Check Sequence
HD	High Definition
HMRP	HRP/MRP
HRP	High Rate Protocol
HSI	High Speed Interface
IEEE	Institution of Electrical and Electronics Engineers
LAN	Local Area Network
LoS	Line of Sight
LRP	Low Rate Protocol
MAC	Media Access Control

Student Questions

Acronyms (Cont)

- MCS Modulation and Coding Scheme
- MHz Mega Hertz
- MRP Medium Rate Protocol
- MSDU MAC Service Data Unit
- NA North America
- OFDM Orthogonal Frequency Division Multiplexing
- OSD On-Screen Display
- PAL Protocol Adaptation Layer
- PAN Personal Area Network
- PBSS Personal Basic Service Set
- PCI Peripheral Component Interconnect
- PCIE PCI Express
- PCP PBSS Control Point
- PHY Physical Layer
- PNC Piconet Coordinator

Student Questions

Acronyms (Cont)

- QAM Quadrature Amplitude Modulation
- QPSK Quadrature Phase Shift Keying
- RATB Random Access Time Block
- RTS Ready to Send
- S-CAP Sub-Contention Access Period
- SC Single Carrier
- SFS Spatial Frequency Sharing
- SH Subframe Header
- SLS Sector Level Sweep
- SP Service Period
- SS Sector Sweep
- STB Set-Top Box
- STD Standard
- TA Transmit Antenna
- TDMA Time Division Multiple Access

Student Questions

Acronyms (Cont)

- UEP Unequal Error Protection
- USB Universal Serial Bus
- WiGig Wireless Gigabit Alliance
- WiMAX Worldwide Interoperability for Microwave Access
- WLAN Wireless Local Area Network
- WPAN Wireless Personal Area Network
- WVAN Wireless Video Area Network

Student Questions

Scan This to Download These Slides

Raj Jain
http://rajjain.com

http://www.cse.wustl.edu/~jain/cse574-24/j_07sgh.htm

Student Questions

- Practice Exam Q4: "short wavelength" is confusing. One lecture said that f<10GHz is better for mobile applications due to the potential doppler shift. Thus, I thought a relatively larger wavelength is better.

Q4: Short wavelengths are better for mobile applications. False.
Canvas has been updated to award points for both answers.

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

Student Questions