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/cse574-18/
1. 60 GHz Frequency Allocations and characteristics
2. 60 GHz Wireless Standards
3. IEEE 802.11ad
4. WirelessHD
5. WirelessHD HRP OFDM Parameters
60 GHz Frequency Allocations

- 7-9 GHz in 57-66 GHz (millimeter waves 30 GHz-300 GHz)
- 4 Channels of ~ 2 GHz
- Significant activity after FCC made 57-64 GHz license-exempt


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60 GHz Power Limits

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

<table>
<thead>
<tr>
<th>Region</th>
<th>GHz</th>
<th>Transmit dBm</th>
<th>EIRP dBm</th>
<th>Antenna Gain dBi</th>
</tr>
</thead>
<tbody>
<tr>
<td>US/Canada</td>
<td>7</td>
<td>27</td>
<td>43</td>
<td>33 if 10dBm Transmit</td>
</tr>
<tr>
<td>Japan</td>
<td>7</td>
<td>10</td>
<td>58</td>
<td>47</td>
</tr>
<tr>
<td>Korea</td>
<td>7</td>
<td>10</td>
<td>27</td>
<td>17</td>
</tr>
<tr>
<td>Australia</td>
<td>3.5</td>
<td>10</td>
<td>51.7</td>
<td>41.8</td>
</tr>
<tr>
<td>Europe</td>
<td>9</td>
<td>13</td>
<td>57</td>
<td>30</td>
</tr>
</tbody>
</table>

Advantages of 60 GHz Band

1. **Large spectrum**: 7 GHz
   - 7 Gbps requires only 1 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 Antennas**: 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
Disadvantages of 60 GHz Band

1. **Large Attenuation**: Attenuation $\alpha$ frequency$^2$
   - Strong absorption by Oxygen
   - Need larger transmit power: 10W allowed in 60GHz
   - Need high antenna gain $\Rightarrow$ directional antennas
   - Short Distance $\sim$ 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
Multi-Gigabit Wireless Applications

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

1. IEEE 802.11ad-2014
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.
Google Trends

- Google trends shows number of searches over time
  - No one is interested in ECMA 387 or 802.15.3c
  - WirelessHD was hot in 2008-2009 but now being taken over by 802.11ad

- Amazon Search:
  - 4 pages of products on WirelessHD on Amazon
  - 9 pages of products on WiGig on Amazon

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![Google Trends Chart](chart.png)
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.
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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.
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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),
  - Data Transfer Time (DTT)

```
[          ] Beacon Interval

<table>
<thead>
<tr>
<th>Beacon Time</th>
<th>Associating Beam-Forming Time</th>
<th>Announcement Time</th>
<th>Data Transfer Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP1</td>
<td>...</td>
<td>SPn</td>
<td>CBP1</td>
</tr>
<tr>
<td>CBPn</td>
<td>...</td>
<td>CBPm</td>
<td></td>
</tr>
</tbody>
</table>
```

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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 contention-based period (CBP)
- During DTT, stations use either Distributed Coordination Function (DCF) or Hybrid Coordination Function (HCF)
IEEE 802.11ad Beacon

- Beacon transmissions are omni-directional $\Rightarrow$ One beacon is transmitted through every antenna configuration

Beacon Interval

Beacon Time | Beacon Time
---|---
B B B B B | B B B B B

Beacons in Different Antenna Configurations
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

```
Initiator Sector Sweep (ISS)  Sector Level Sweep  SS Frames  Beam Refinement
Initiator

Responder Sector Sweep (RSS)  SS Feedback
Responder
```

SS Ack
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.
Antenna Training Example

- Initiator (left) has 3 antennas with 3, 3, 2 sectors. Responder (right) has 3 antennas with 1 sector each.
- Initiator performs 3 sweeps with 8 frames each using a different sector. Responder sends feedbacks.
- They find the best receive antenna and the best transmit antenna.

IEEE 802.11ad PCP Cluster

- Overlapping PBSS avoid interference by electing a “Synchronization PCP” (S-PCP) for the PCP cluster
- All PCP’s 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 PCP’s
  ⇒ All PCP’s hear all allocations
  ⇒ Avoid overlapping scheduling
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 results of “Directional Channel Quality” during an overlapping SP. The stations measure the channel quality and send to PCP. PCP then knows which station pairs can share the same slot.
IEEE 802.11ad Relays

- **Link Switch Relays**: MAC relays like a switch. Receive complete frames from the source and send to 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
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 transmission can take place on the same frequency at the same time (Spatial Frequency Sharing).
7. **Relays** can be used if LoS blocked.
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 (4048p) resolution video streaming from smart phones 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

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
### WirelessHD HRP OFDM Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occupied Bandwidth</td>
<td>1.76 GHz</td>
<td></td>
</tr>
<tr>
<td>Subcarrier Spacing</td>
<td>4.957 MHz</td>
<td>$D_{f_{sc}}$</td>
</tr>
<tr>
<td>Number of subcarriers</td>
<td>355</td>
<td></td>
</tr>
<tr>
<td>FFT Size</td>
<td>512</td>
<td></td>
</tr>
<tr>
<td>Number of Data Subcarriers</td>
<td>336</td>
<td>$N_{dsc}$</td>
</tr>
<tr>
<td>Number of DC Subcarriers</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Number of Pilots</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>Number of Null subcarriers</td>
<td>157</td>
<td></td>
</tr>
<tr>
<td>FFT Period</td>
<td>$1/D_{f_{sc}} = 201.73$ ns</td>
<td>$T_{FFT}$</td>
</tr>
<tr>
<td>Guard Interval</td>
<td>$T_{FFT}/8 = 25.22$ ns</td>
<td>$T_{GI}$</td>
</tr>
<tr>
<td>Symbol Duration</td>
<td>$T_{FFT} + T_{GI} = 226.95$ ns</td>
<td>$T_{S}$</td>
</tr>
<tr>
<td>Modulation</td>
<td>QPSK, 16-QAM, 64-QAM</td>
<td></td>
</tr>
<tr>
<td>Outer block code</td>
<td>RS(224, 216)</td>
<td></td>
</tr>
<tr>
<td>Inner Code</td>
<td>1/3, 1/2, 2/3, 5/6 (EEP)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2/5, 1/2, 4/7, 2/3, 4/5 (UEP)</td>
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## HRP OFDM Frequency Parameters

![HRP OFDM Frequency Parameters Diagram](image)

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</table>

- Similar tables for MRP and LRP

Similar masks exist for LRP and MRP.

HRP OFDM Time Parameters

- Symbol time = 1/subcarrier spacing = \( \frac{1}{\Delta f_{sc}} \)

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<tr>
<td>Symbol Duration</td>
<td>( T_{FFT} + T_{GI} = 226.95 ) ns</td>
<td>( T_{S} )</td>
</tr>
</tbody>
</table>
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 in subgroups. Each subgroup has a different protection level

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<td></td>
</tr>
<tr>
<td>Inner Code</td>
<td>1/3, 1/2, 2/3, 5/6 (EEP) 2/5, 1/2, 4/7, 2/3, 4/5 (UEP)</td>
<td></td>
</tr>
</tbody>
</table>
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, …
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. 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
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 large 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 is required.
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 1/4\textsuperscript{th} cyclic prefix
   - Data bit rate using QPSK with RS(224, 216) coding with 3/4 rate inner code. Assume 7/8\textsuperscript{th} of the subcarriers are used for data transmission.
Reading List

Wikipedia Links

References


References (Cont)

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
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
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
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
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
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
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