Introduction to 60 GHz Millimeter Wave Multi-Gigabit Wireless Networks

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Audio/Video recordings of this class lecture are available at:
http://www.cse.wustl.edu/~jain/cse574-14/
1. 60GHz Band: Advantages and Disadvantages
2. IEEE 802.11ad
3. ECMA-387 Standard
4. IEEE 802.15.3c-2009
5. WirelessHD
60GHz Frequency Allocations

- 7-9 GHz in 57-66 GHz (millimeter waves 30GHz-300GHz)
- 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. \( \lambda/4 = 1.25 \text{ mm} \)

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 $\propto$ frequency$^2$
   - Strong absorption by Oxygen
   - Need larger transmit power: 10W allowed in 60GHz
   - Need high antenna gain $\Rightarrow$ directional antennas
   - Short Distance $\approx$ 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 devices are already in the market

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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.
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)

---

<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></td>
<td></td>
<td></td>
<td>SP1 ... SPn CBP1 ... CBPm</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 performance 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 ⇒ One beacon is transmitted through every antenna configuration

Beacon Interval

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

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
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
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.

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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 fine tuning.

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.
ECMA-387 Standard

- **Two types of devices:**
  - High-End **Type A**: LoS (line of sight) and non-LoS, 10m, may have adaptive antenna arrays
  - Economic **Type B**: LoS, 3m (low power handheld) (**Type C** was defined in 1st edition but removed in 2nd edition)
- **Two types of Channels:**
  - **Discovery Channel**: to find each-other and for antenna training. Can also be used as data channel
  - **Data Channels**: Exchange data and control frames
- Fully distributed MAC. **No** coordinator.


ECMA-387 Discovery

- Time of discovery channel consists of "Discovery intervals (DI)"
- Each device performs a "discovery block set (DBS)" during a DI.

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ECMA-387 Discovery (Cont)

- **Type-A DBS**: consists of sending a Type-A discovery frame, Type-B discovery frame, scanning for type-B discovery responses and type-A discovery responses, followed by Type-B discovery frame and discovery scanning all other sectors. The first sector is incremented in successive scans.

- Type-A device scans the channel and responds to DBS frames from other stations at the time indicated in the frames.

- Type-A stations may perform antenna training or start data transmissions.

- **Type B DBS**: send a Type-B discovery frame and scan for Type-B discovery responses. Also, respond to Type-B discovery frames of Type-A and Type-B stations.

- Discovery channel can be used for data transmission but discovery and antenna training have priority.
Antenna Training and Tracking

- During discovery, each station knows which neighbors are in each sector
- A station sends a RTS on discovery channel (waits if busy) to one of its neighbors in a sector
- After receiving a CTS, the two stations exchange a series of tracking frames to determine the optimal antenna configuration
- Later the stations may perform “antenna tracking” to confirm optimal operation by reserving some time during data transmissions on data channel
ECMA-387 Data Channel

- Super-frame consists of **Beacon Period (BP)** and **Data Transfer Period (DTP)**
- Each station sends a beacon during BP. Each station has a fixed slot in BP
- To find its slot, stations listen during one superframe and find an empty slot for itself. Find another if collision.

![Diagram of superframe with beacon periods and data transfer periods]

**Source’s Beacons** → **Destination’s Beacons** → **Cooperative Transmission**
ECMA-387 Data Channel (Cont)

- Type-B stations can not receive Type-A beacons but they can send a Type-A beacon. They send both Type-A and Type-B beacons. Note: Type B range is only 3 m and may not receive all Type-A beacons (10m)

- Beacon consists of source announcements of required time duration, antenna, and destination(s)

- Destination(s) check their schedule and send confirmations in their beacons

- Everyone listens to everyone else’s requests and check if there will be interference.

- Relays: Type-A devices that amplify and forward. If direct transmission is blocked, relays can be reserved by a source-destination pair via request and antenna training.
## 802.11ad vs. ECMA-387

<table>
<thead>
<tr>
<th>802.11ad</th>
<th>ECMA-387</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centralized Control</td>
<td>Distributed Control</td>
</tr>
<tr>
<td>PCP is a single point of failure</td>
<td>No single point of failure</td>
</tr>
<tr>
<td>PCP may shut down or sleep</td>
<td></td>
</tr>
<tr>
<td>One beacon per sector</td>
<td>One omni-directional beacon per device</td>
</tr>
<tr>
<td>PCP Antenna training with all devices</td>
<td>Only communicating pairs train antennas</td>
</tr>
<tr>
<td>No dedicated control channel</td>
<td>Dedicated discovery channel</td>
</tr>
<tr>
<td>Point to multipoint easy</td>
<td>All active corresponds return to discovery channel periodically for antenna training $\Rightarrow$ multicast difficult</td>
</tr>
<tr>
<td>Ideal for data and multicast applications</td>
<td>Ideal for point-to-point video links</td>
</tr>
</tbody>
</table>
IEEE 802.15.3c-2009 60 GHz

- Min 2 Gbps over a few meters
- **Three PHYs:**
  - **Single Carrier (SC):** Low cost low power mobile
  - **High Speed Interface (HSI) with OFDM:** Data
  - **Audio Video (AV) OFDM PHY:** Video
- **Common mode signaling (CMS):** SC-based $\pi/2$ BPSK used by the piconet coordinator in synch frames to avoid interference between 3 PHYs
- Beamforming (in all 3 PHYs). Two-stage antenna alignment
- **Unequal error protection (UEP)** for video transmission. Most significant bits (msbs) are protected more than Least significant bits (lsbs). MAC also has msb and lsb subframes.
π/2-Shifted BPSK

- **BPSK (Binary Phase Shift Keying):**

  - \( \text{a: (+1 -1)} \)
  - \( \text{b: (+j -j)} \)

- **π/2 BPSK:** Above two choices are used alternatively.

  - **Table:**
    | Bits | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 0 | 1 |
    |------|---|---|---|---|---|---|---|---|---|---|---|---|
    | Code | +1 | -j | +1 | +j | +1 | -j | -1 | +j | -1 | +j | +1 | -j | +1 |
    | Scheme | a | b | a | b | a | b | a | b | a | b | a | b | a |

- Increases the error detection capability by a factor of 2

# 802.15.3c PHY Modes

<table>
<thead>
<tr>
<th>Feature</th>
<th>SC</th>
<th>HSI</th>
<th>AV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulation</td>
<td>BPSK- 16QAM</td>
<td>QPSK- 64QAM</td>
<td>QPSK-16QAM</td>
</tr>
<tr>
<td>Data Rate</td>
<td>25.3Mbps-5.1Gbps</td>
<td>31.5 Mbps-5.67Gbps</td>
<td>0.95-3.8Gbps</td>
</tr>
<tr>
<td>Unequal Error Prot.</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Beamforming</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Channel</td>
<td>1.782GHz</td>
<td>1.782GHz</td>
<td>1.76GHz (HRP)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>92MHz (LRP)</td>
</tr>
</tbody>
</table>
802.15.3c MAC

- **Centralized MAC** with a **Piconet Coordinator (PNC)**
- PNC transmits beacons with schedules
- Super-frame = a **beacon period**, a **Contention Access Period (CAP)**, and **Channel Time Allocation (CTA)** period
- Stations need antenna alignment using a 2-stage sector tuning and fine tuning process.

<table>
<thead>
<tr>
<th>Beacon Period</th>
<th>Contention Access Period (CAP)</th>
<th>Channel Time Allocation (CTA) Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 [\ldots] n</td>
<td>Association S-CAP</td>
<td>Regular S-CAP</td>
</tr>
</tbody>
</table>

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802.15.3c MAC (Cont)

- **A-MSDU**: Multiple MSDU aggregated in one MAC frame. Each MSDU has its own subframe header and CRC.
- Each MSDU is acked and retransmitted.
- Block Ack
- PHY header indicates type of MSDU aggregation:
  - Standard Aggregation: Large data
  - Low Latency Aggregation: Small latency-sensitive data
  - AV Aggregation: Video
802.15.3c Standard Aggregation

- **Used for** large data. Fragmentation allowed.
- **8 Subframes**: Each contains an MSDU or a fragment. Each has a CRC.
- Subframe length in MAC subheader.
  - Length=0 ⇒ No subframe
- MAC header and MAC subheader protected by CRCs.
- Acks piggybacked.
802.15.3c Low-Latency Aggregation

<table>
<thead>
<tr>
<th>PHY Header</th>
<th>MAC Header</th>
<th>HCS</th>
<th>UEP MCS</th>
<th>RX Buffer Size</th>
<th>MSDU Req #</th>
<th>MSDU Res #</th>
<th>Block-Ack Bitmap</th>
<th>HCS Subframe Len</th>
<th>Subframe HCS</th>
<th>MSDU #</th>
<th>FCS</th>
</tr>
</thead>
</table>

**MAC Subheader**

- **Used for bidirectional latency sensitive** data, e.g., USB, PCIE.
- **Up to 256 small** subframes. No fragmentation. Length field included in the subframe header.
- **Req #**: Last ack received, **Res #**: First Ack bit in this frame.
- **Source and destination divide the transmission time for the two directions during a pre-allocated CTA.**
- **In EEP mode, MCS in indicated in PHY.**
- **In UEP mode, UEP MCS is indicated in MAC subheader.**
802.15.3c Audio/Video Aggregation

- For data/Audio/Video frames. No Fragmentation.
- 7 MSDUs aggregated in to 5 ack groups.
  - Video MSDUs are not aggregated or fragmented
- **Video header** indicates position of first pixel of videos for 4 Video MSDUs. Not present in Low-Rate (LRP) PHY.
  - ⇒ Application specific MAC
Audio/Video Aggregation (Cont)

- Extended Control header indicates whether the frame is a Beacon, Ack, or AV aggregated frame, and whether video header, security header, and extension headers are valid.
- MAC extension header indicates the type of MSDU (Command, Data, Audio, Video)
- PHY header indicates MCS and length for each MSDU. PHY control field indicates UEP
- Security header indicates if security is applied to a MSDU
- Ack groups field indicates if a MSDU is in the same ack group as previous one. 8th bit is not used. No more than 5 bits can be 0 (max 5 ack groups), e.g., 0101100

| MSDU1 | MSDU2 | MSDU3 | MSDU4 | MSDU5 | MSDU6 | MSDU7 |
# 802.15.3c Aggregation Schemes: Summary

<table>
<thead>
<tr>
<th>Feature</th>
<th>Standard</th>
<th>Low Latency</th>
<th>Audio Video</th>
</tr>
</thead>
<tbody>
<tr>
<td>Different MCS for each subframe</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
</tr>
<tr>
<td>Max Subframes</td>
<td>8</td>
<td>256</td>
<td>7</td>
</tr>
<tr>
<td>Bi-directional low latency data</td>
<td>N</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Best for audio/video</td>
<td>N</td>
<td>N</td>
<td>Y</td>
</tr>
<tr>
<td>Fragmentation of video</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Video header protected</td>
<td>N</td>
<td>N</td>
<td>Y</td>
</tr>
</tbody>
</table>
IEEE 802.15.3c Summary

1. Three Phys: Single Carrier (SC), OFDM for Data (HSI), OFDM for Video (AV)
2. All PHYs use single-carrier base p/2 BPSK to avoid interference
3. Unequal error protection for video
4. Piconet Coordinator (PNC) sends beacons and schedules transmissions
5. Three aggregation modes:
   - Standard aggregation with 8 Data subframes with Fragmentation
   - Low Latency aggregation with 256 subframes without fragmentation
   - AV aggregation with 7 subframes (5 ack groups) and 4 video streams
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+
  - 4 Channels of 1.76 GHz each
  - Very-high data rates (28 Gbps+) using spatial multiplexing (4 concurrent streams)
  - Non-line of sight operation

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Sample WirelessHD Products

Dell Alienware Laptops

Epson Powerlite home Cinema Projector

DVDO-Air (Cable Replacement)

ZyXel AeroBeam WirelessHD A/V Kit

Sony Personal 3D Viewer

Ref: http://www.wirelesshd.org/consumers/product-listing/
Washington University in St. Louis http://www.cse.wustl.edu/~jain/cse574-14/
**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 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 HRP 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>Reference Sample Rate</td>
<td>2.538 Gsamples/s</td>
<td>$f_s$</td>
</tr>
<tr>
<td>Number of subcarriers</td>
<td>512</td>
<td>$N_{sc}$</td>
</tr>
<tr>
<td>FFT Period</td>
<td>$N_{sc}/f_s = 201.73$ ns</td>
<td>$T_{FFT}$</td>
</tr>
<tr>
<td>Subcarrier Spacing</td>
<td>$1/T_{FFT} = 4.957$ MHz</td>
<td>$\Delta f_{sc}$</td>
</tr>
<tr>
<td>Guard Interval</td>
<td>$64/f_s = 25.22$ 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>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>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>
<td></td>
</tr>
</tbody>
</table>

- Similar tables for MRP and LRP
Similar masks exist for LRP and MRP

\[ \text{dBr} = \text{Deci-Bel Relative} \]


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WirelessHD MAC

- The superframe consists of a number of “Random Access Time Blocks (RATBs)” and “Channel Time Blocks (CTBs)”.
- RATBs are used for unallocated communications
  CTBs are used for pre-allocated communication (generally at high-speed)
- The coordinator announces the number, length, and position of CTBs and RATBs in the beacons
- Before starting a new WVAN, stations scan a set of channels. It will select the least busy HMRP channel and select a LRP channel within that and becomes the coordinator.
- If a more suitable coordinator comes on, the coordinator may handover responsibilities (state information) to new coordinator. E.g., DTV is higher priority than STB.
WirelessHD MAC (Cont)

- **Centralized Access**: Coordinator controls the access. All stations make a request to the coordinator. Coordinator allocates the time. Stations transmit in specified time.

- **Isochronous**: Need time in every super-frame
- **Asynchronous**: Total time needed once. Allocated in multiple frames.

- Allocations announced in the nth Beacon are used in n+1st super-frame

- If too many stations, child WVAN (called **Drone WVAN**) are started on another channel. Stations first join the main WVAN and then migrate to D-WVAN if too much traffic.
WirelessHD Power Save Mode

- Active stations wake up simply to listen to beacon can deactivate electronics for the rest of the super-frame
- Stations can tell the coordinator and go to sleep
  ⇒ Do not wake up for every beacon
- When a station wants to transmit to sleeping station, it tells the coordinator. Coordinator announces it in subsequent beacons. When a station wakes up, it tells the coordinator and it allocates slot for the other station to contact
WirelessHD Device Control

Remote control of devices:

- **One-Touch Play**: Start playing
- **Device Power Control**: On/Off
- **One Touch Record**: Display is recorded on selected device
- **Timer Programming**: DVR/STB timer programming
- **Deck Control**: play/fast forward/reverse/…
- **Tuner Control**: Change channels
- **Remote Control Pass Thru**: Commands to another device
- **Audio Amplifier Control**: Control audio configuration
- **OSD Display**: Use on-screen display to show text
- **Vendor-Specific Commands**
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. No access points. But some devices need **coordinator capabilities**.
5. Random Access Time Blocks (RATBs) are used for unallocated transfers
6. Channel Time Blocks (CTBs) are used for pre-allocated transfers
7. 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. ECMA-387 is fully distributed
5. 802.15.3c PAN also uses centralized coordinator
6. WirelessHD is designed for HD video.
7. In all cases antenna alignment and tracking is required.
Google Trends

- Google trends shows number of searches over time
  - No one is interested in ECMA 387
  - 802.15.3c was hot in 2008 but the interest is gone
  - WirelessHD was hot for the last 5 years but now being taken over by 802.11ad

- Google Search:
  - “ECMA 387” +site:.com 2400 results mostly from book publishers
  - WirelessHD +site:.com 1.1 million results from ebay, amazon, …
  - 802.15.3c +site:.com 18k results mostly from publishers and chip makers
  - 802.11ad +site:.com 80k results mostly from publishers and chip makers
Reading List

Wikipedia Links

- [http://en.wikipedia.org/wiki/IEEE_802.15#Task_Group_3:_High_Rate_WP_AN](http://en.wikipedia.org/wiki/IEEE_802.15#Task_Group_3:_High_Rate_WP_AN)
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
- **CTB**: Channel Time Blocks
Acronyms (Cont)

- CTS: Clear to Send
- dBi: Deci-Bel Isotropic
- dBm: Dec-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
Acronyms (Cont)

- **EM**: Expectation Maximization
- **EU**: Europe
- **EURASIP**: Name of a Publisher
- **FCC**: Federal Communications Commission
- **FCS**: Frame Check Sequence
- **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
- **MSDD**: Multiple-Symbol Differential Detection
- **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
<table>
<thead>
<tr>
<th>Acronyms</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>QAM</td>
<td>Quadrature Amplitude Modulation</td>
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<tr>
<td>QPSK</td>
<td>Quadrature Phase Shift Keying</td>
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<tr>
<td>RATB</td>
<td>Random Access Time Block</td>
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<tr>
<td>RTS</td>
<td>Ready to Send</td>
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<tr>
<td>RX</td>
<td>Receiver</td>
</tr>
<tr>
<td>S-CAP</td>
<td>Sub-Contention Access Period</td>
</tr>
<tr>
<td>SC</td>
<td>Single Carrier</td>
</tr>
<tr>
<td>SFS</td>
<td>Spatial Frequency Sharing</td>
</tr>
<tr>
<td>SH</td>
<td>Subframe Header</td>
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<tr>
<td>SLS</td>
<td>Sector Level Sweep</td>
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<tr>
<td>SP</td>
<td>Service Period</td>
</tr>
<tr>
<td>STB</td>
<td>Set-Top Box</td>
</tr>
<tr>
<td>STD</td>
<td>Standard</td>
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<td>TDMA</td>
<td>Time Division Multiple Access</td>
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<td>UEP</td>
<td>Unequal Error Protection</td>
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</tbody>
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Acronyms (Cont)

- **USB** Universal Serial Bus
- **WLAN** Wireless Local Area Network
- **WPAN** Wireless Personal Area Network
- **WVAN** Wireless Video Area Network