# Introduction to 60 GHz Millimeter Wave Multi-Gigabit Wireless Networks


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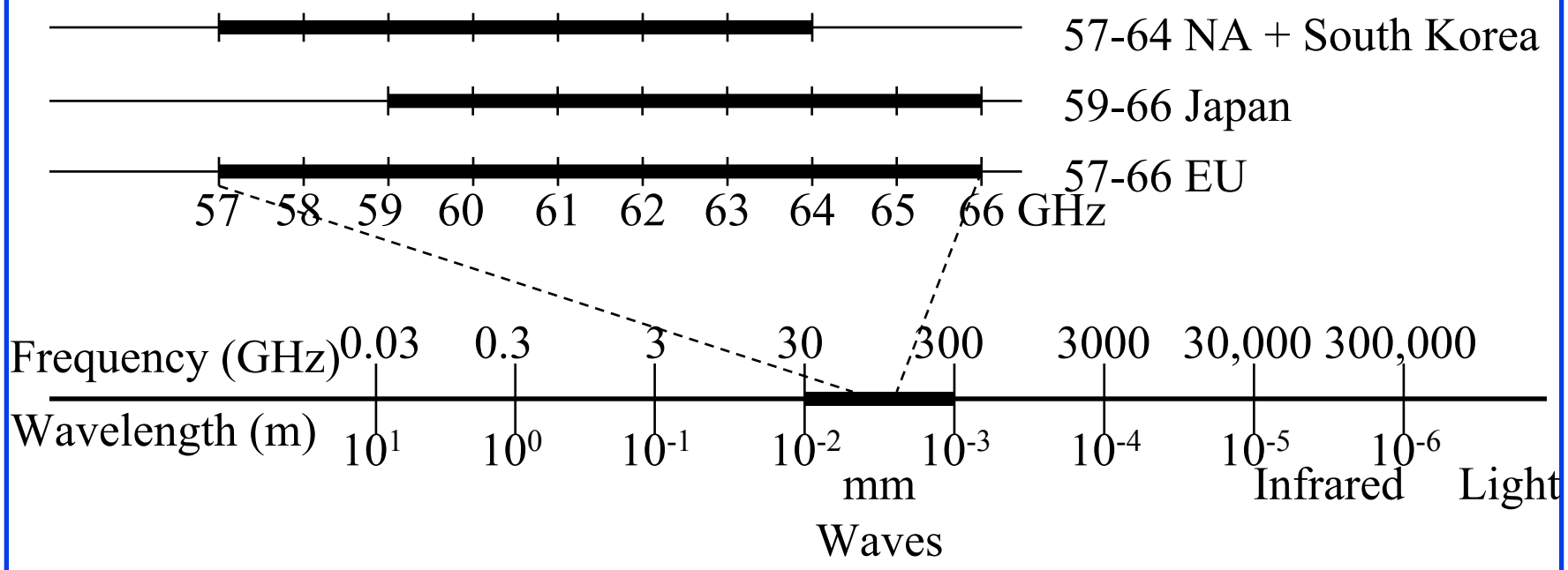
Audio/Video recordings of this class lecture are available at:

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

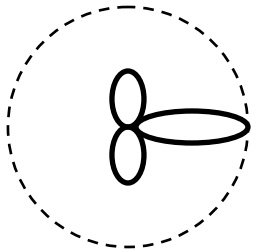
- 7-9 GHz in 57-66 GHz (**millimeter** waves 30GHz-300GHz)
- 4 Channels of ≈ 2 GHz
- Significant activity after FCC made 57-64 GHz license-exempt




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

# 60 GHz Power Limits

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

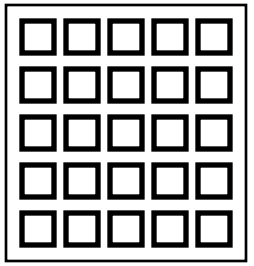


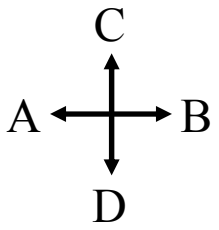
| Region | GHz | Transmit dBm | EIRP dBm | Antenna Gain dBi |
|---|---|---|---|---|
| US/Canada | 7 | 27 | 43 | 33 if 10dBm Transmit |
| Japan | 7 | 10 | 58 | 47 |
| Korea | 7 | 10 | 27 | 17 |
| Australia | 3.5 | 10 | 51.7 | 41.8 |
| Europe | 9 | 13 | 57 | 30 |

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

# 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 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



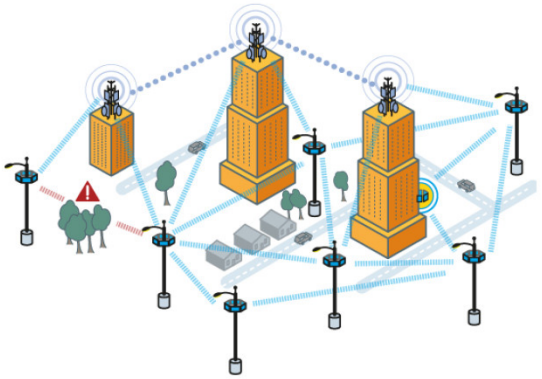


# Disadvantages of 60 GHz Band

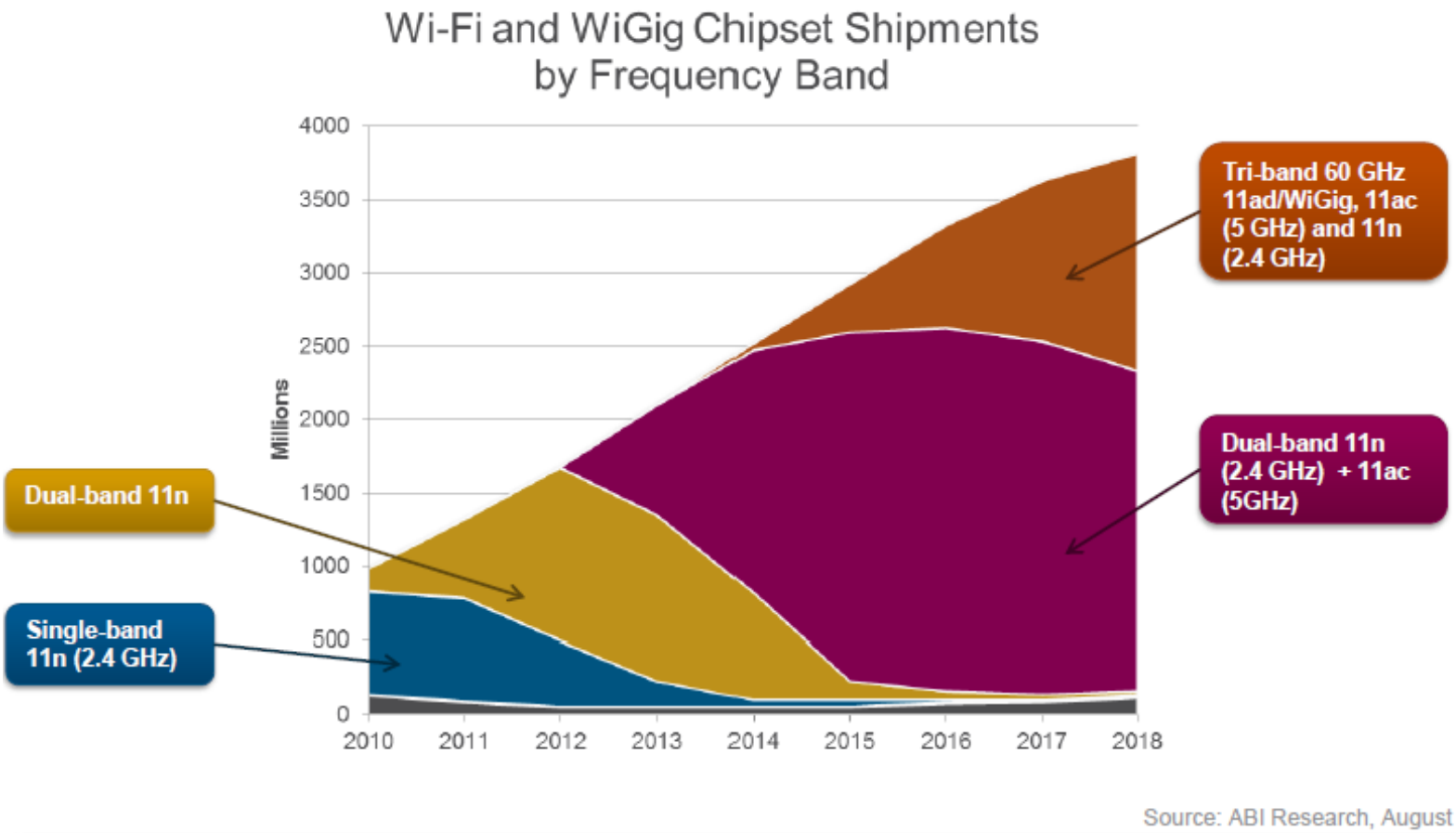
1. **Large Attenuation**: Attenuation $\propto$ frequency$^2$
   - Strong absorption by Oxygen
   - Need larger transmit power: 10W allowed in 60GHz
   - Need high antenna gain $\Rightarrow$ directional antennas
   - Short Distance $\approx$ 10m
2. **Directional Deafness**: Can't hear unless aligned
   - 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)

# Tri-band Wireless Forecast




Source: ABI Research, August 2013

- 60 GHz devices are already in the market

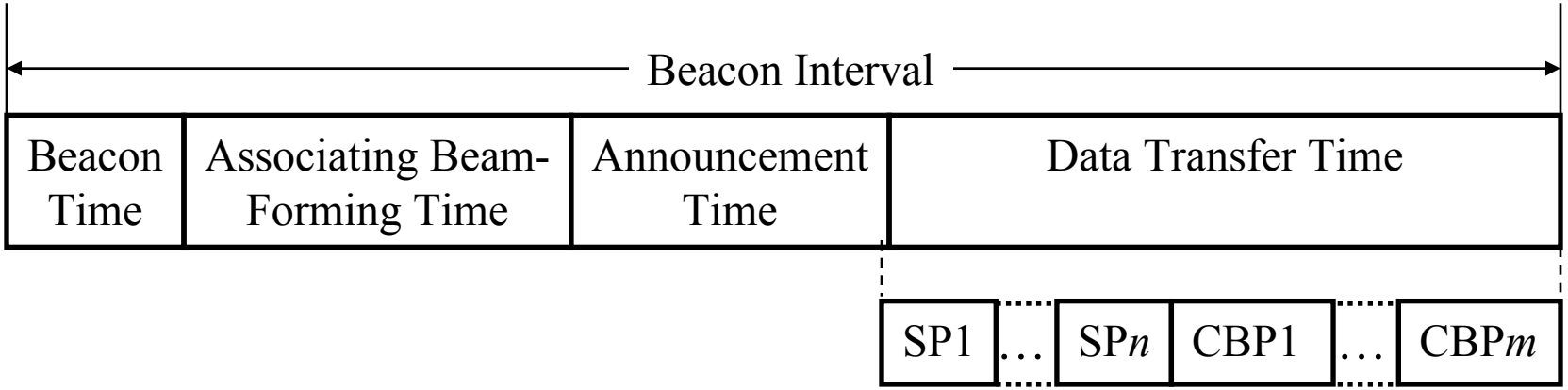
Ref: ABI Research, "802.11ac Products Making Their Way into the Market," August 2013, available for purchase.

# 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)

# 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 in to: Beacon Time (**BT**), Associating Beamforming Training (**A-BFT**), Announcement Time (**AT**), and Data Transfer Time (**DTT**)

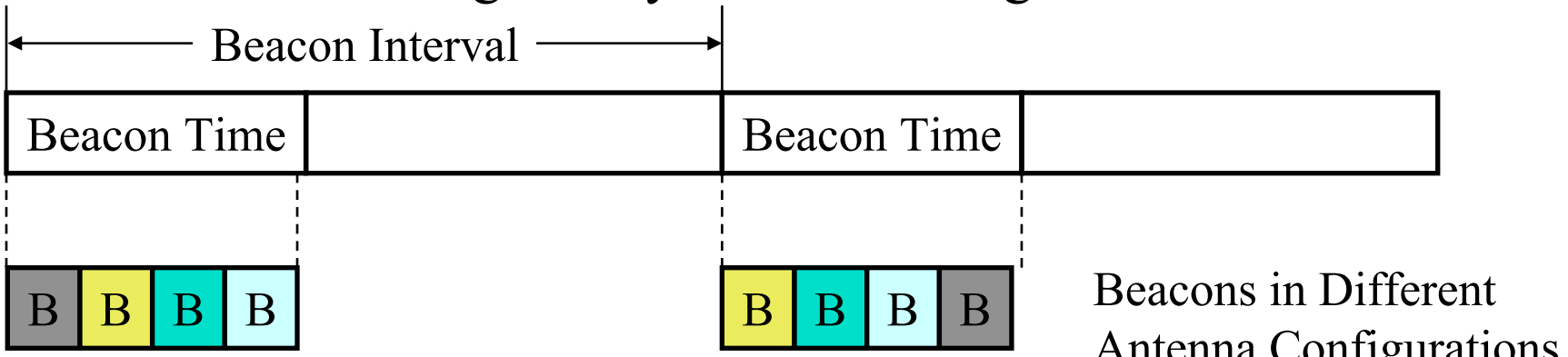


# IEEE 802.11ad (Cont)

- 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)

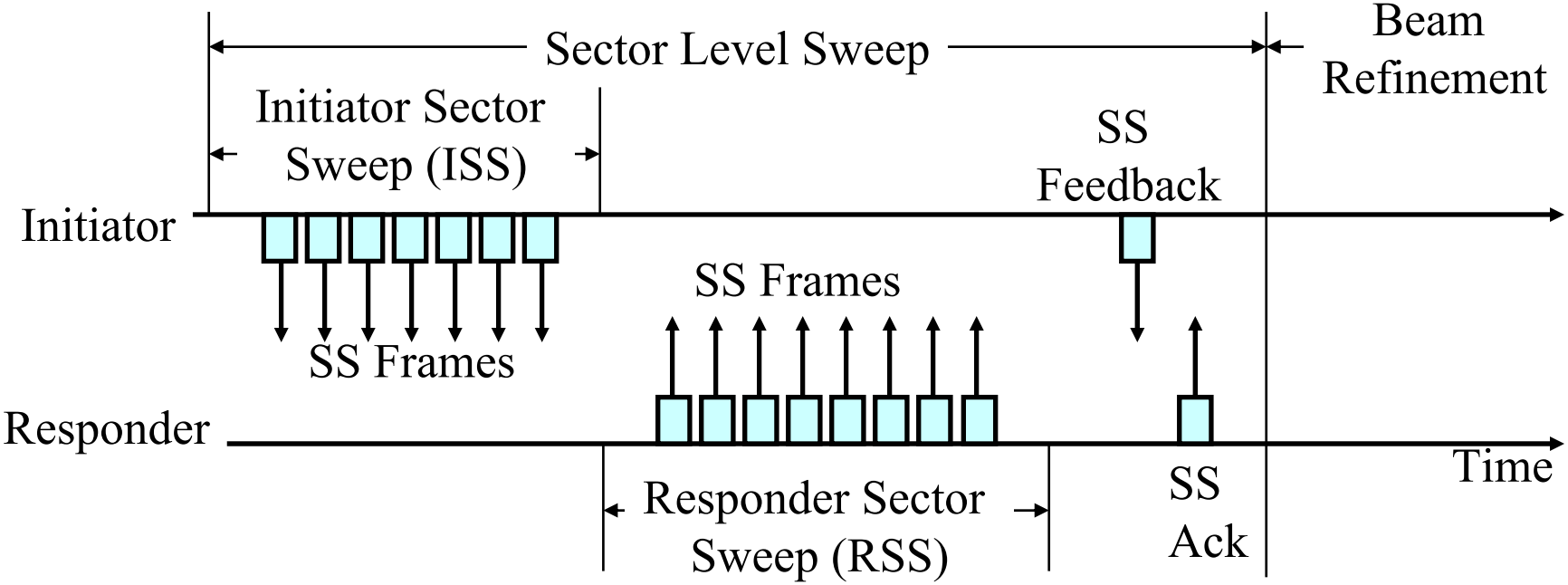
# IEEE 802.11ad Beacon

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



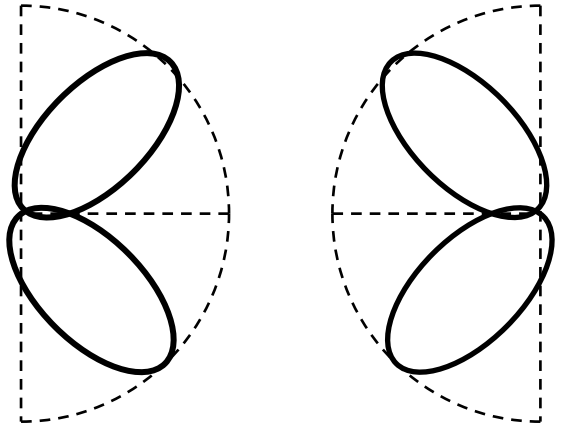
# IEEE 802.11ad Antenna Training

- 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

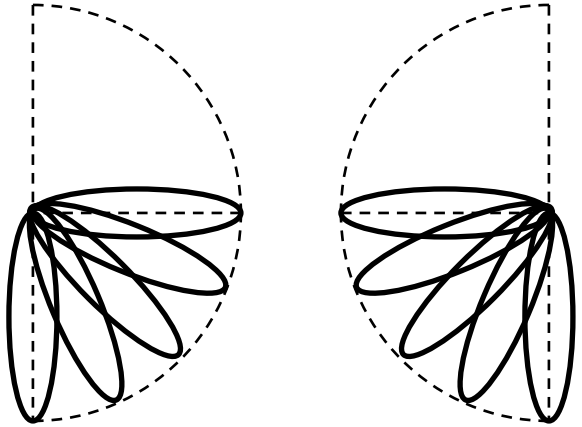


# Antenna Alignment

- **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.



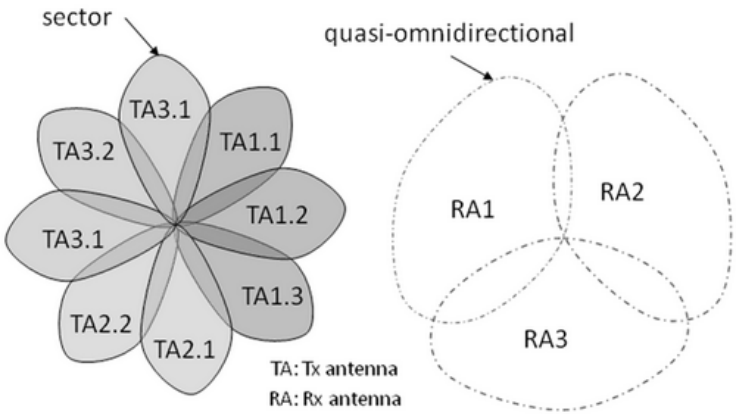
Sector-Level Sweep



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.




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

# 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 received 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.

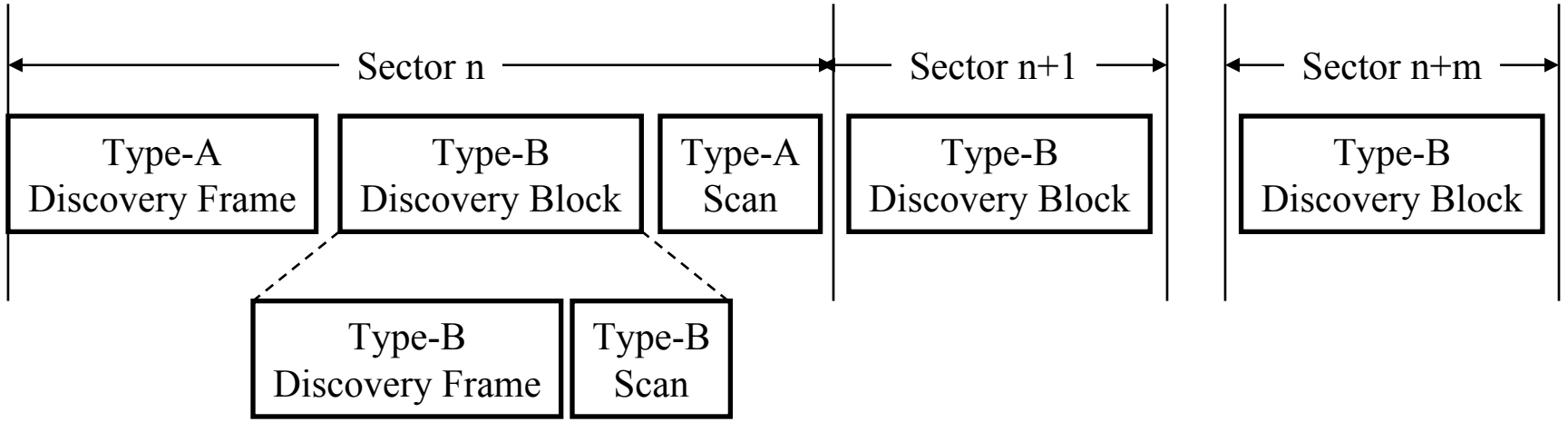
# ECMA-387 Standard

- 1st Edition completed December 2008. 2nd Edition Dec 2010.
- **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.

Ref: 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

# ECMA-387 Discovery

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




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

# ECMA-387 Discovery (Cont)

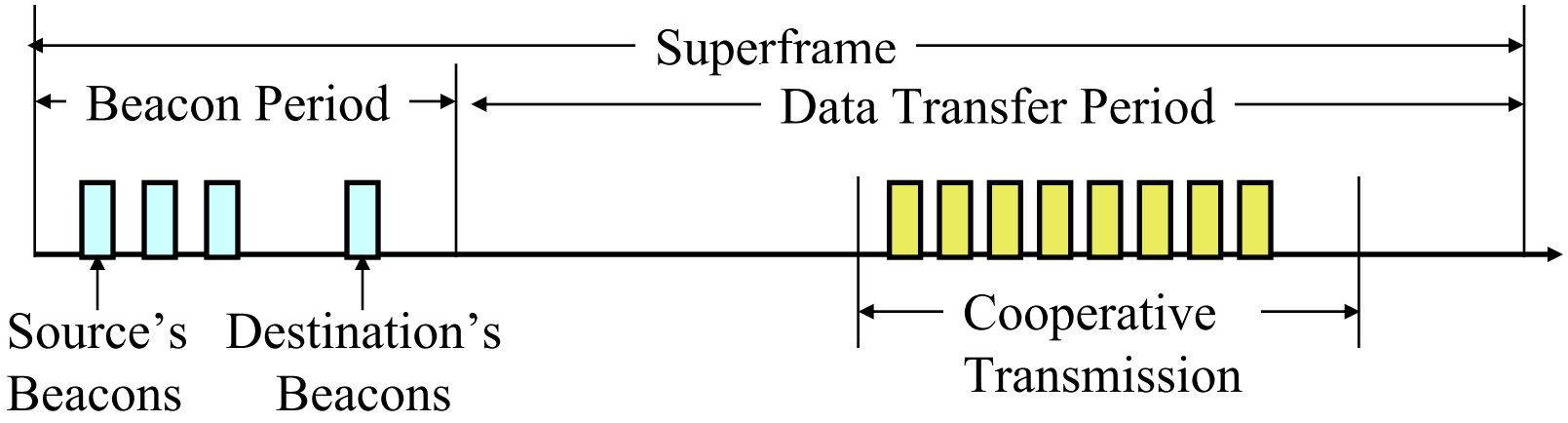
- **Type-A DBS**: consists of sending a Type-A discovery frame, Type-B discovery frame, scanning for type-B discovery responses and type-A discovery responses, followed by Type-B discovery frame and discovery scanning all other sectors. The first sector is incremented in successive scans.
- Type-A device 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 stations sends a RTS on discovery channel (waits if busy) to one of its neighbor 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 stations 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.



# 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 amply 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

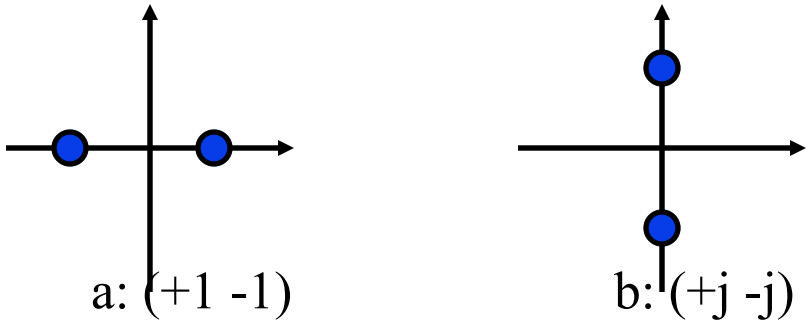
| 802.11ad | ECMA-387 |
|---|---|
| Centralized Control | Distributed Control |
| PCP is a single point of failure<br>PCP may shut down or sleep | No single point of failure |
| One beacon per sector | One omni-directional beacon per device |
| PCP Antenna training with all devices | Only communicating pairs train antennas |
| No dedicated control channel | Dedicated discovery channel |
| Point to multipoint easy | All active corresponds return to discovery channel periodically for antenna training ⇒ multicast difficult |
| Ideal for data and multicast applications | Ideal for point-to-point video links |

# 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 π/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):**




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

| **Bits** | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 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

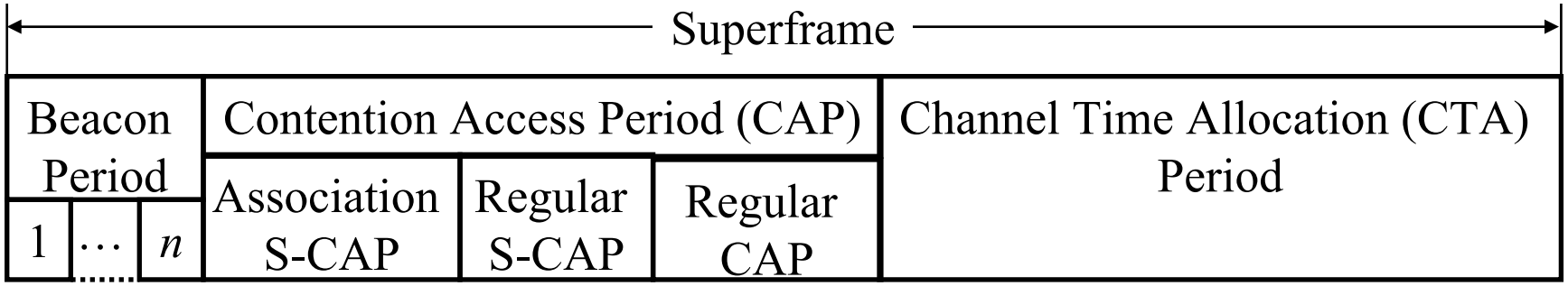
Ref: M. Riediger, P. Ho, J. Kim, "A Receiver for Differential Space-Time p/2 Shifted BPSK Modulation Based on Scalar-MSDD and the EM Algorithms," EURASIP Journal on Wireless Communications and Networking, 2005, No. 2, pp. 83-91, http://jwcn.eurasipjournals.com/content/pdf/1687-1499-2005-135356.pdf

# 802.15.3c PHY Modes

| Feature | SC | HSI | AV |
|---|---|---|---|
| Modulation | BPSK- 16QAM | QPSK- 64QAM | QPSK-16QAM |
| Data Rate | 25.3Mbps-5.1Gbps | 31.5 Mbps-5.67Gbps | 0.95-3.8Gbps |
| Unequal Error Prot. | Yes | Yes | Yes |
| Beamforming | Yes | Yes | Yes |
| Channel | 1.782GHz | 1.782GHz | 1.76GHz (HRP)<br>92MHz (LRP) |

# 802.15.3c MAC

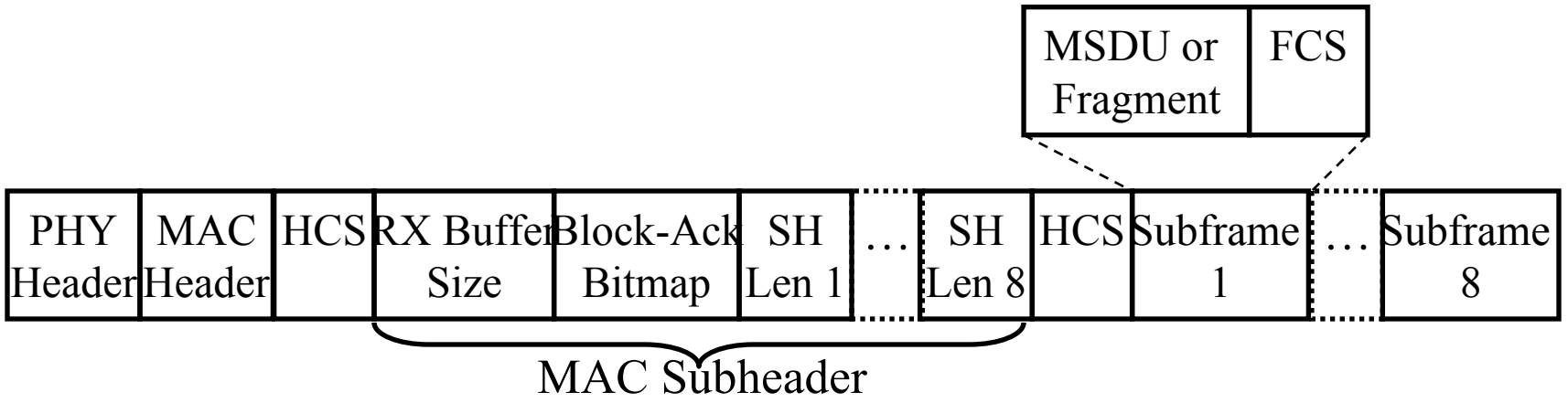
- **Centralized MAC** with a **Piconet Coordinator (PNC)**
- PNC transmits beacons with schedules
- Super-frame = a **beacon period**, a **Contention Access Period (CAP)**, and **Channel Time Allocation (CTA)** period
- Stations need antenna alignment using a 2-stage sector tuning and fine tuning process.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



# 802.15.3c MAC (Cont)

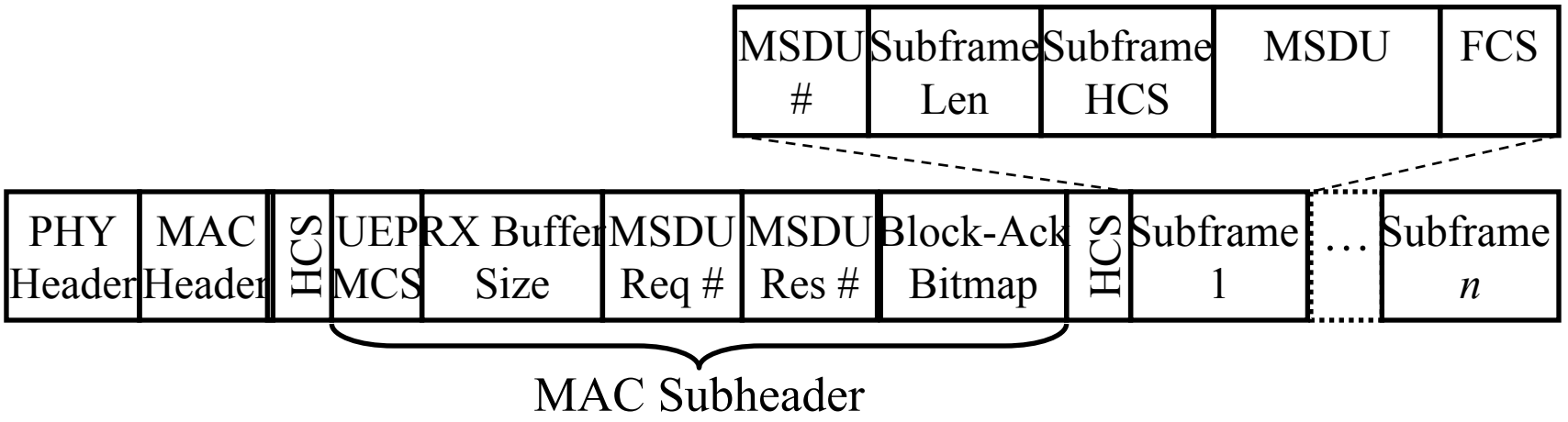
- **A-MSDU**: Multiple MSDU aggregated in one MAC frame. Each MSDU has its own subframe header and CRC.
- Each MSDU is acked and retransmitted.
- Block Ack
- PHY header indicates type of MSDU aggregation:
  - Standard Aggregation: Large data
  - Low Latency Aggregation: Small latency-sensitive data
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

# 802.15.3c Standard Aggregation



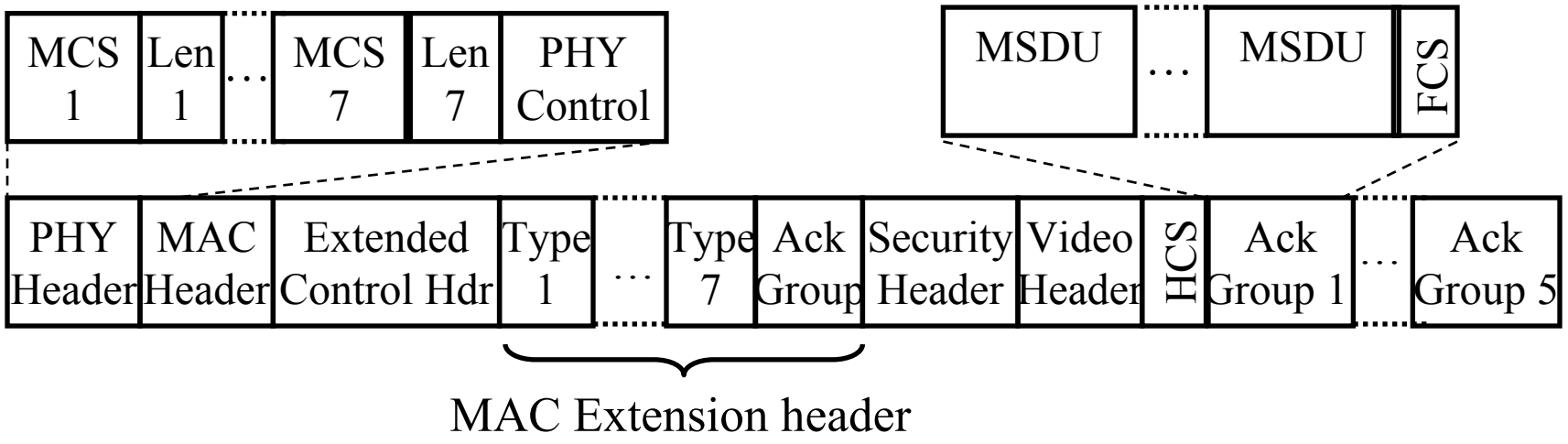

- **Used for** large data. Fragmentation allowed.
- **8 Subframes**: Each contains an MSDU or a fragment. Each has a CRC.
- Subframe length in MAC subheader.
  Length=0 ⇒ No subframe
- MAC header and MAC subheader protected by CRCs.
- Acks piggybacked.

# 802.15.3c Low-Latency Aggregation




- 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

# 802.15.3c Aggregation Schemes: Summary

| Feature | Standard | Low Latency | Audio Video |
|---|---|---|---|
| Different MCS for each subframe | Y | N | Y |
| Max Subframes | 8 | 256 | 7 |
| Bi-directional low latency data | N | Y | N |
| Best for audio/video | N | N | Y |
| Fragmentation of video | Y | Y | N |
| Video header protected | N | N | Y |

# 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

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

# 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/

# 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

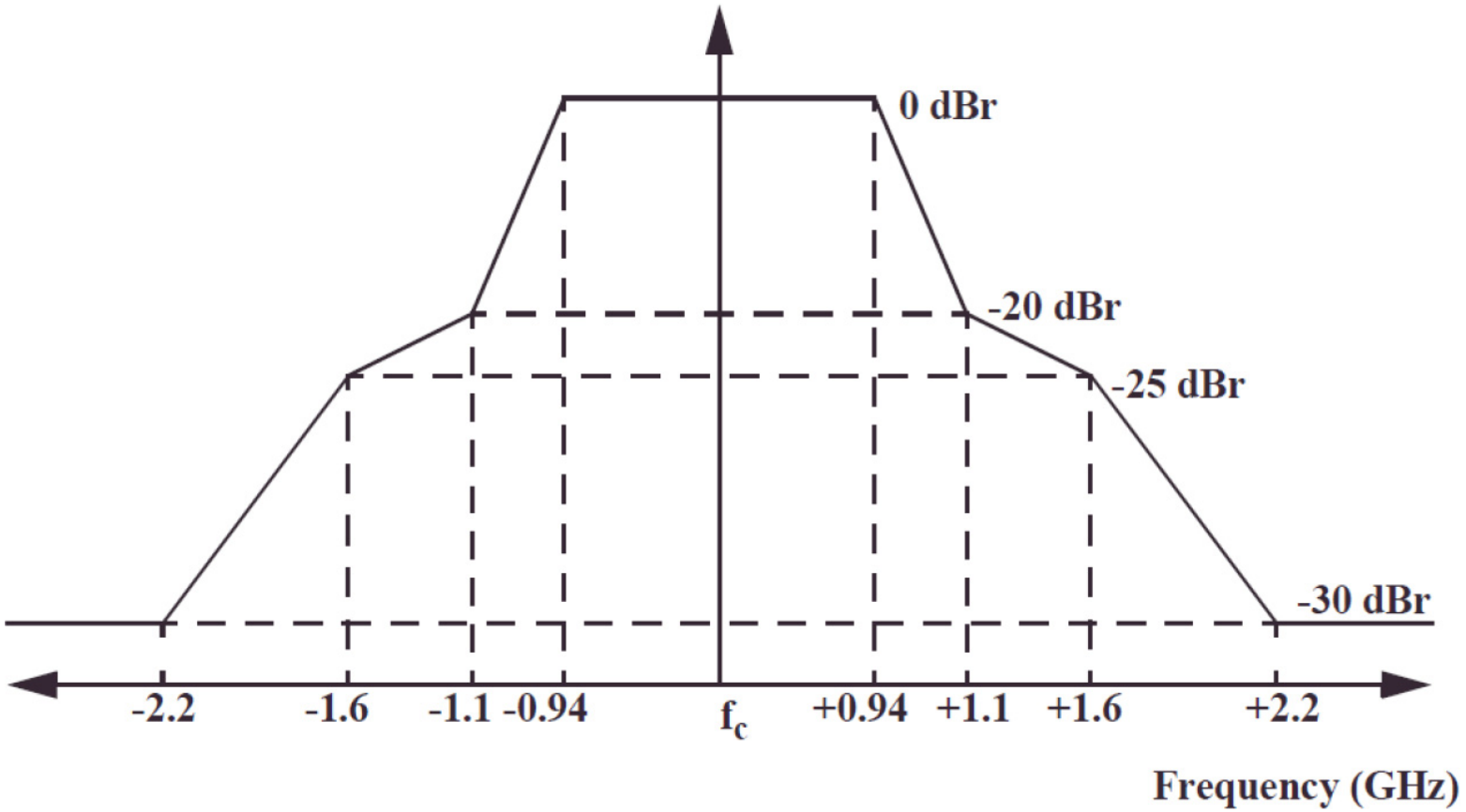
- Two MAC capabilities:
  1. **Coordinator**: Controls timing and keeps track of members of WVAN
  2. Other stations
- Everyone can transmit and receive LRP
- Some may be able to receive HMRP but may/may not be able to transmit HMRP
- Shutdown and sleep modes
- Channel estimation
- Higher Layer: Video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

# WirelessHD HRP Parameters

| Parameter | Value | Symbol |
|---|---|---|
| Occupied Bandwidth | 1.76 GHz | |
| Reference Sample Rate | 2.538 Gsamples/s | $f_s$ |
| Number of subcarriers | 512 | $N_{sc}$ |
| FFT Period | $N_{sc}/f_s$ = 201.73 ns | $T_{FFT}$ |
| Subcarrier Spacing | $1/T_{FFT}$ = 4.957 MHz | $\Delta f_{sc}$ |
| Guard Interval | $64/f_s$ = 25.22 ns | $T_{GI}$ |
| Symbol Duration | $T_{FFT}+T_{GI}$ = 226.95 ns | $T_S$ |
| Number of Data Subcarriers | 336 | $N_{dsc}$ |
| Number of DC Subcarriers | 3 | |
| Number of Pilots | 16 | |
| Number of Null subcarriers | 157 | |
| Modulation | QPSK, 16-QAM, 64-QAM | |
| Outer block code | RS(224, 216) | |
| Inner Code | 1/3, 1/2, 2/3, 5/6 (EEP)<br>2/5, 1/2, 4/7, 2/3, 4/5 (UEP) | |

- Similar tables for MRP and LRP

# HRP Transmit Mask




- Similar masks exist for LRP and MRP
- dBr = Deci-Bel Relative

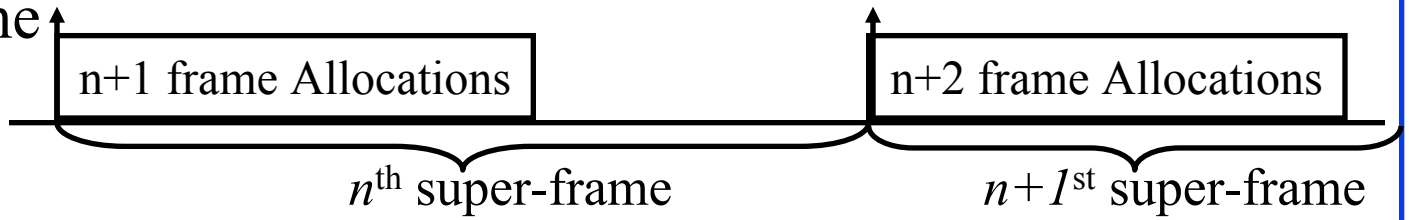
Ref: WirelessHD.org, "WirelessHD Specification Overview,"
http://www.wirelesshd.org/pdfs/WirelessHD-Specification-Overview-v1.1May2010.pdf

# 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
  $\Rightarrow$ 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

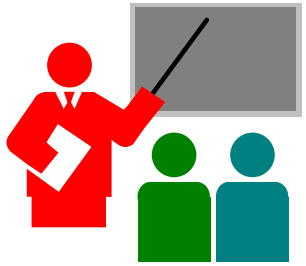
**Remote control of devices**:

- **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

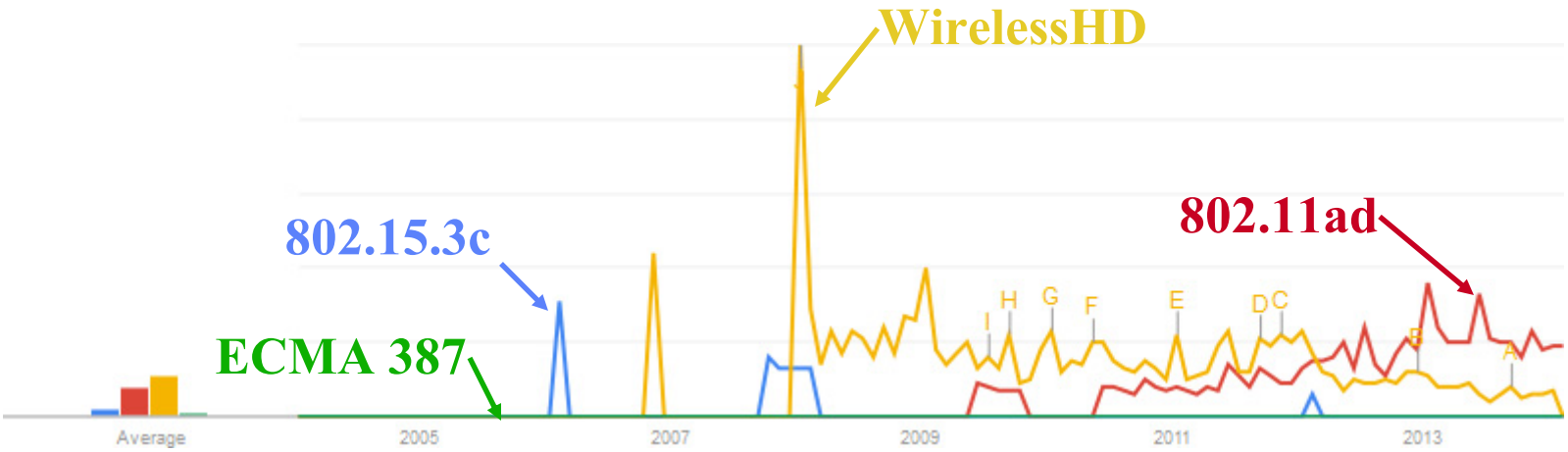
1. Designed for uncompressed video. Video Cable replacement.
2. **Three PHYs**: High-Rate (1-7 Gbps), Medium-Rate (0.5-2 Gbps), and Low-Rate(2.5-40 Mbps)
3. LRP is used for discovery, multicast
4. No access points. But some devices need **coordinator capabilities**.
5. Random Access Time Blocks (**RATBs**)are 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


- 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
- A. Suarez Sarmiento and E. M. Lopez, "Multimedia Services and Streaming for Mobile Devices," IGI Global, Sep 2011, ISBN:1613501447, Safari book
- WirelessHD.org, "WirelessHD Specification Overview," http://www.wirelesshd.org/pdfs/WirelessHD-Specification-Overview-v1.1May2010.pdf

# Wikipedia Links

- http://en.wikipedia.org/wiki/Wireless_Gigabit_Alliance
- http://en.wikipedia.org/wiki/WirelessHD
- http://en.wikipedia.org/wiki/Equivalent_isotropically_radiated_power
- http://en.wikipedia.org/wiki/IEEE_802.15#Task_Group_3:_High_Rate_WPAN
- 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
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# 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.
- 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
- 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

# References (Cont)


- M. Riediger, P. Ho, J. Kim, "A Receiver for Differential Space-Time p/2 Shifted BPSK Modulation Based on Scalar-MSDD and the EM Algorithms," EURASIP Journal on Wireless Communications and Networking, 2005, No. 2, pp. 83-91, http://jwcn.eurasipjournals.com/content/pdf/1687-1499-2005-135356.pdf
- ABI Research, "802.11ac Products Making Their Way into the Market," August 2013, available for purchase.
- http://www.wirelesshd.org/consumers/product-listing/

# 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

# Acronyms (Cont)

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

# Acronyms (Cont)

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