Introduction to 60 GHz Millimeter Wave Multi-Gigabit Wireless Networks

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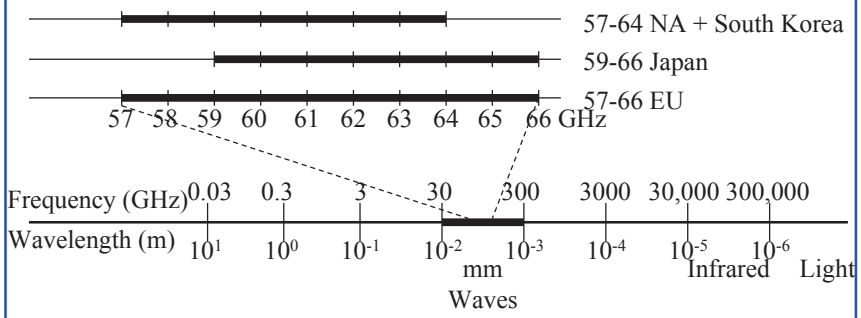
Audio/Video recordings of this class lecture are available at:
http://www.cse.wustl.edu/~jain/cse574-16/

Overview

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

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

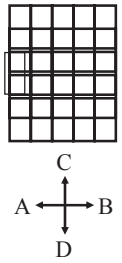
- **Equivalent Isotropically Radiated Power (EIRP):** Power that an isotropic antenna would have to emit to match the directional reception

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. ,/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

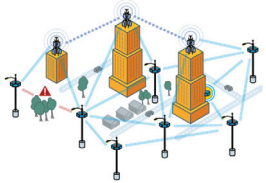


Disadvantages of 60 GHz Band

1. **Large Attenuation**: Attenuation / frequency^2
   - Strong absorption by Oxygen
   - Need larger transmit power: 10W allowed in 60GHz
   - Need high antenna gain ⇒ directional antennas
   - 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

Multi-Gigabit Wireless Applications

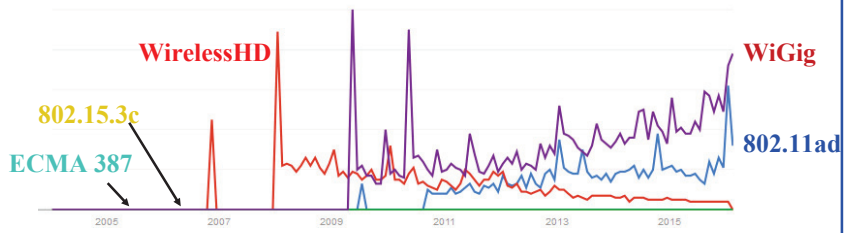
- **Cable Replacement**: High-Definition Uncompressed streaming video
- Interactive **gaming**
- High-speed file transfer
- Wireless Mesh **Backhaul** (200-400m)



60 GHz Wireless Standards

1. **IEEE 802.11ad-2014**
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)

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
- Google Search:
  - 2-3 products on WiHD on Amazon
  - 10-15 products on WiGig on Amazon

Sample 60 GHz Products

Dell Latitude WiGig Capable

11n+WiGig Card for Latitude

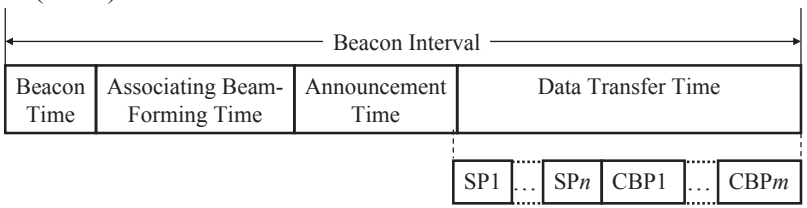
Dell WiGig Docking Station

HP WiGig Docking Station

DVDO WirelessHD HDMI Cable Replacement Kit

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**)

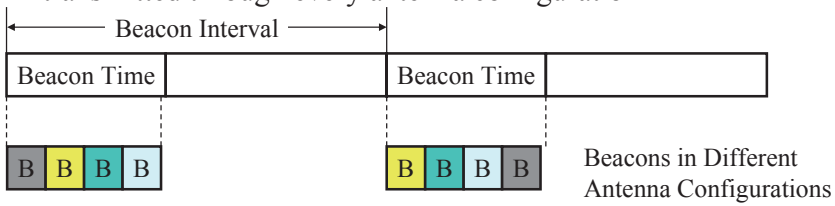


IEEE 802.11ad (Cont)

- Only PCP can send a beacon during beacon time
- In A-BFT, PCP 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)

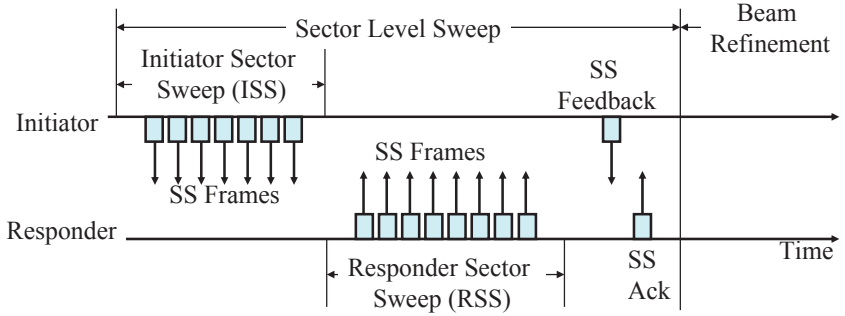
IEEE 802.11ad Beacon

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



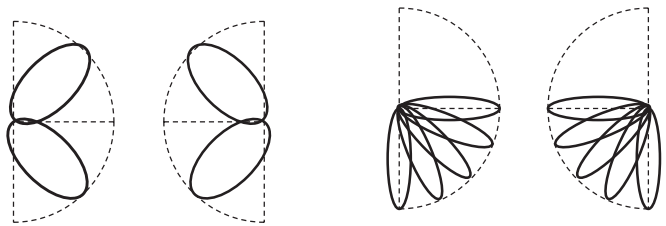
IEEE 802.11ad Antenna Training

- 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

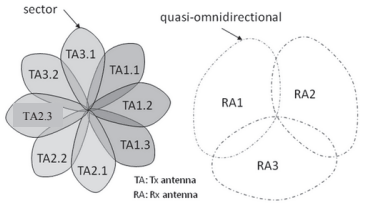
- **Beam Search**: Binary search through sectors using beam steering
- **Beam Tracking**: Some bits are appended to each frame to ensure that the beams are still aligned.



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

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+
- 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

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

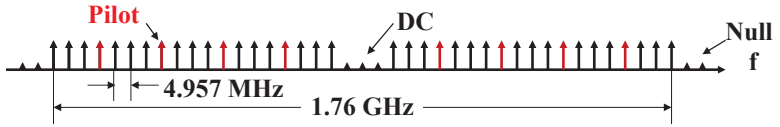
- Two MAC capabilities:
  1. **Coordinator**: Controls timing and keeps track of members of WVAN
  2. Other stations
- Everyone can transmit and receive LRP
- Some may be able to receive HMRP
  but may/may not be able to transmit HMRP
- Shutdown and sleep modes
- Channel estimation
- Higher Layer: Video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

WirelessHD HRP OFDM Parameters

Parameter	Value	Symbol	
Occupied Bandwidth	1.76 GHz		Frequency Domain
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		
FFT Period	$1/Df_{sc}$ = 201.73 ns	T_{FFT}	Time Domain
Guard Interval	$T_{FFT}/8$ = 25.22 ns	T_{GI}	
Symbol Duration	$T_{FFT}+T_{GI}$ = 226.95 ns	T_S	
Modulation	QPSK, 16-QAM, 64-QAM		Coding
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)		

- Similar tables for LRP and MRP

HRP OFDM Frequency Parameters



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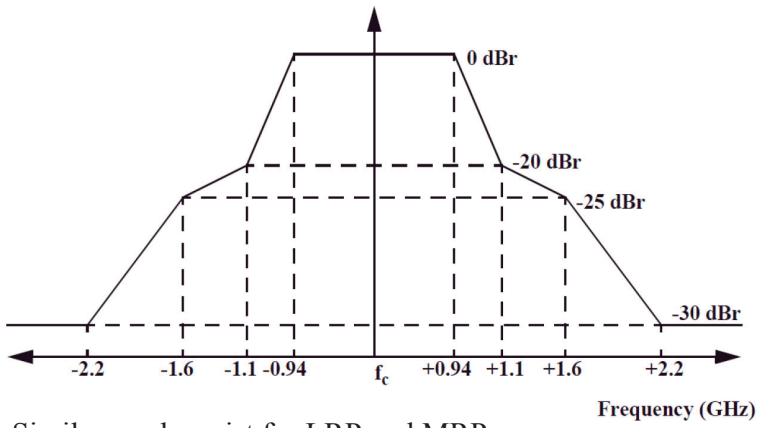
- Similar tables for MRP and LRP

HRP Transmit Mask

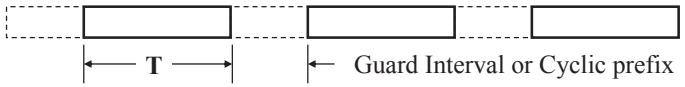


- Similar masks exist for LRP and MRP
- dBr = deci-Bel relative

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

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

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

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)	

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 1/4th 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.

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

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/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

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

References (Cont)

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

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 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

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

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Introduction to Vehicular Wireless Networks,
http://www.cse.wustl.edu/~jain/cse574-16/j_08vwn.htm

Internet of Things,
http://www.cse.wustl.edu/~jain/cse574-16/j_10iot.htm

Audio/Video Recordings and Podcasts of Professor Raj Jain's Lectures,
https://www.youtube.com/channel/UCN4-5wzNP9-ruOzQMs-8NUw