IEEE802.11ad

- **IEEE802.11ad**
  - **PHY Layer**
  - **MAC Layer**

Review

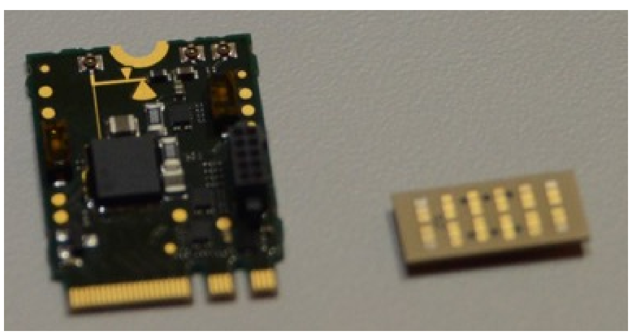
- **IEEE802.11ac**
  - **Wider channel bandwidths:**
  - **Support for up to 8 spatial streams (vs. 4 as in 11n)**
  - **Multi-user MIMO (MU-MIMO)**
  - **256-QAM Modulation**

802.11ad Overview

- **802.11ad (WiGig)**

  - **mmWave “WiFi”, with up to 7 Gbps rate**
  - **Arguably the most mature mobile mmWave standard, with many commercial products since 2013**

Qualcomm/Intel 802.11ac/ad tri-band adapter



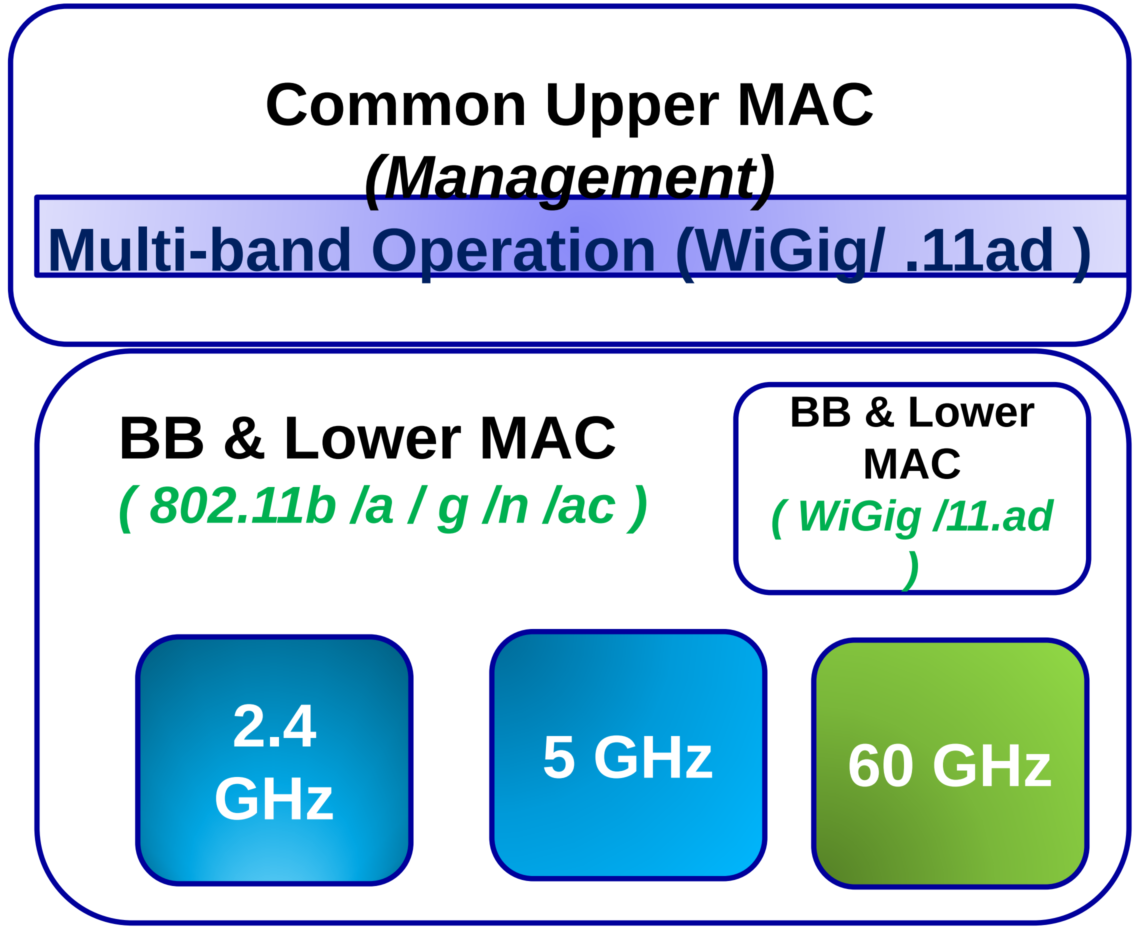
TP-Link 802.11ac/ad tri-band access point

Dell 802.11ad laptop & docking station

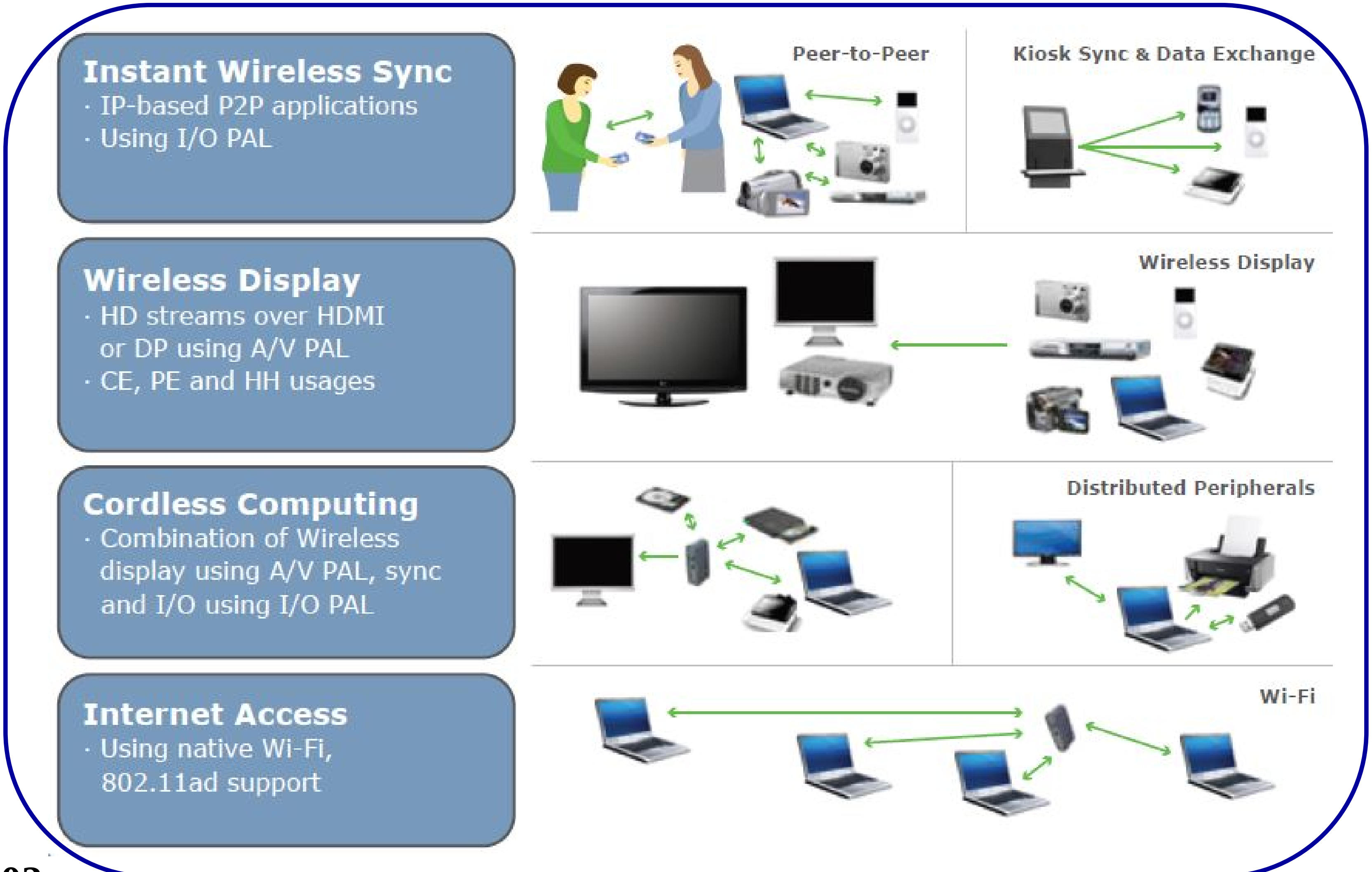
3

802.11ad Protocol Stack

- Extending 802.11

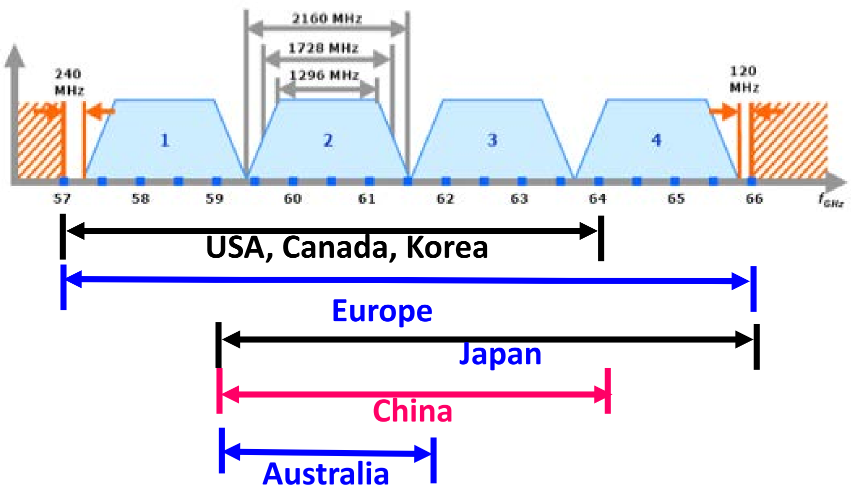


802.11ad Usage Models (From standard group)



802.11ad PHY Layer

- Channelization: up to 4 channels (depending on regulation), each 2.16 GHz



Unlicensed 60 GHz spectrum bands
(Note: FCC further released 64-71 GHz band in 2016).

- Support phased-array antenna beamforming (but not MIMO)

802.11ad PHY Layer: MCS Levels

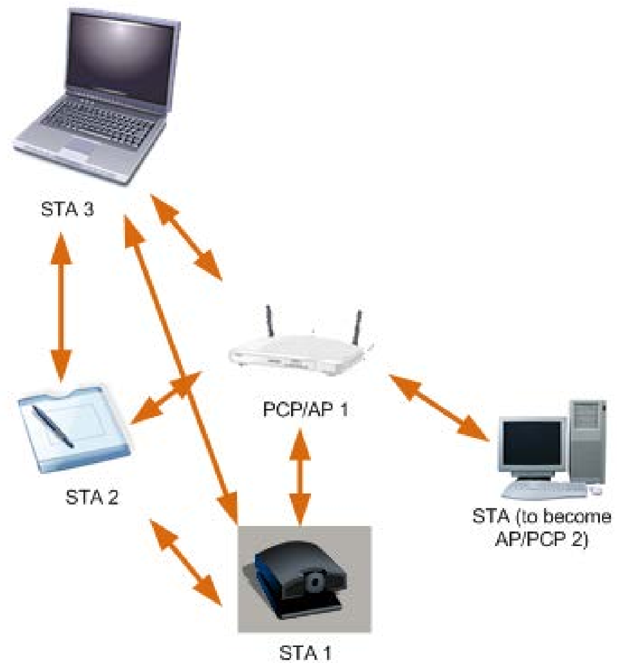
- Control PHY: Robust, low-rate (27.5 Mbps); for signaling, management and control frames
- Data PHY: High-rate
  - OFDM: Support longer distances (larger delay spread), up to 7 Gbps
  - Single-carrier (SC): Simpler hardware, more power-efficient, suitable for mobile devices, up to 4.6 Gbps

Control (CPHY)			
MCS	Coding	Modulation	Raw Bit Rate
0	1/2 LDPC, 32x Spreading	π/2-DBPSK	27.5 Mbps
Single Carrier (SCPHY)			
MCS	Coding	Modulation	Raw Bit Rate
1-12	1/2 LDPC, 2x repetition 1/2 LDPC, 5/8 LDPC 3/4 LDPC 13/16 LDPC	π/2-BPSK, π/2-QPSK, π/2-16QAM	385 Mbps to 4620 Mbps
Orthogonal Frequency Division Multiplex (OFDMPHY)			
MCS	Coding	Modulation	Raw Bit Rate
13-24	1/2 LDPC, 5/8 LDPC 3/4 LDPC 13/16 LDPC	OFDM-SQPSK OFDM-QPSK OFDM-16QAM OFDM-64QAM	693 Mbps to 6756.75 Mbps
Low-Power Single Carrier (LPSCPHY)			
MCS	Coding	Modulation	Raw Bit Rate
25-31	RS(224,208) + Block Code(16/12/9/8,8)	π/2-BPSK, π/2-QPSK	625.6 Mbps to 2503 Mbps

MCS: Modulation and Coding Scheme

802.11ad: Network Architecture

- PCP/AP: Central coordinator in a 802.11ad network
  - Enhanced 802.11 AP to support directional networking
- STA: 802.11ad client (can be mobile)
- Topology: Simultaneously support infrastructure and P2P connections



PCP: Priority Code Point

8

802.11ad MAC: Overview

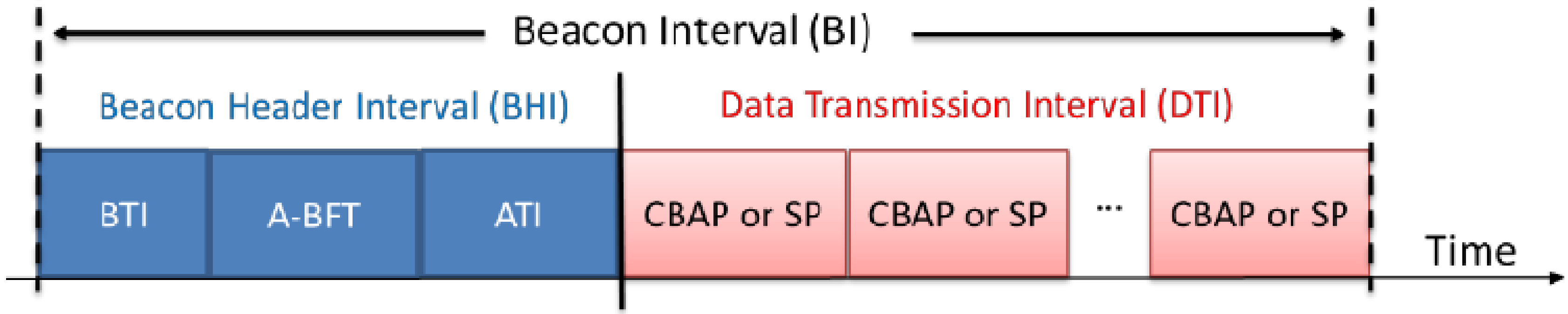
- Key functionalities
  - Association, scheduling, beamforming training, interference management, etc.
- Isn’t it the same as the directional MAC 10+ years ago? No!
  - Large phased-array with hundreds of antennas, instead of a horn
  - Much narrower beams (down to a few degrees)
  - Electronically steerable beams
  - Stronger attenuation at mmWave frequency (vulnerable to blockage)
- Need new system design for scalability and robustness!

802.11ad MAC: Framing

➢ **Beacon interval**

- **Following existing 802.11, all nodes are synchronized in beacon intervals**
- **Beacon interval (BI) = BHI + DTI**
  BHI(Beacon Header Interval): training, signaling; **DTI**: Data Transmission Interval

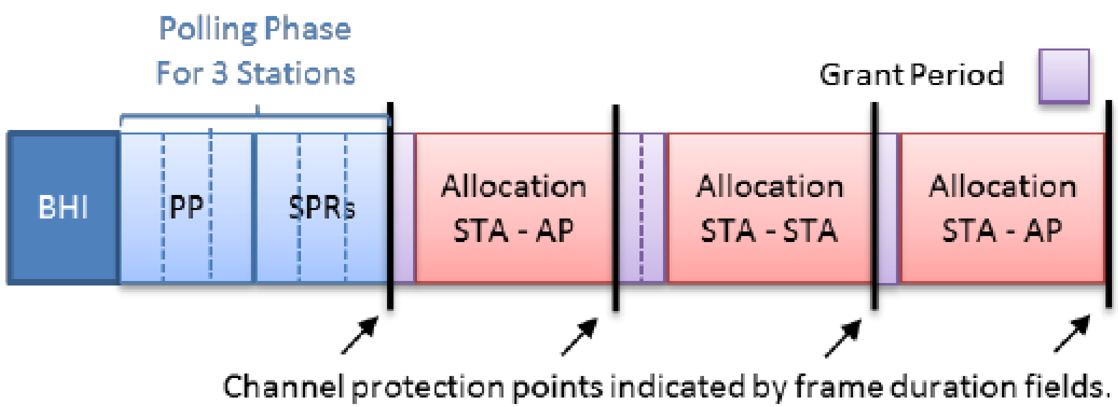
BTI: beacon transmission interval; A-BFT:association beamforming training;
ATI: announcement time interval.



- **Two modes of data transmission**
  CBAP: contention-based access periods;
  SP: Service periods (TDMA)

802.11ad MAC: SP Medium Access

- SP: TDMA for directional networking
  - Can be scheduled between AP and STA, or between two STAs (P2P mode)
  - Need to be coordinated by the AP
  - Can be dynamically allocated based on polling mechanism:



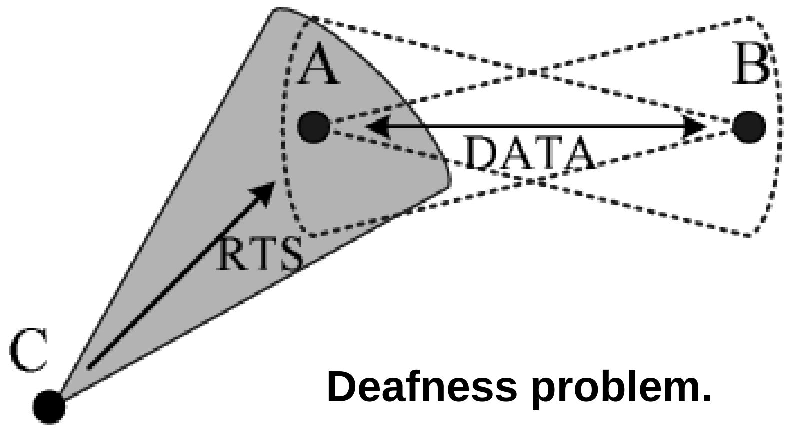
802.11ad MAC: CBAP Medium Access

- **CBAP: hybrid TDMA+CSMA/CA for directional networking**
  - **Physical carrier sensing: energy or preamble detection**
  - **Virtual carrier sensing: directional channel reservation**
- **Virtual carrier sensing**
  - **Before transmission, send a directional RTS**
  - **Nodes who overhear the directional RTS update the NAV (indicating busy time period)**
  - **Imperfect! Deafness and hidden terminal problem.**
- **Other operations, e.g., ACK, backoff, packet aggregation, are similar to 802.11ac**

12

802.11ad MAC: CSMA Interference management

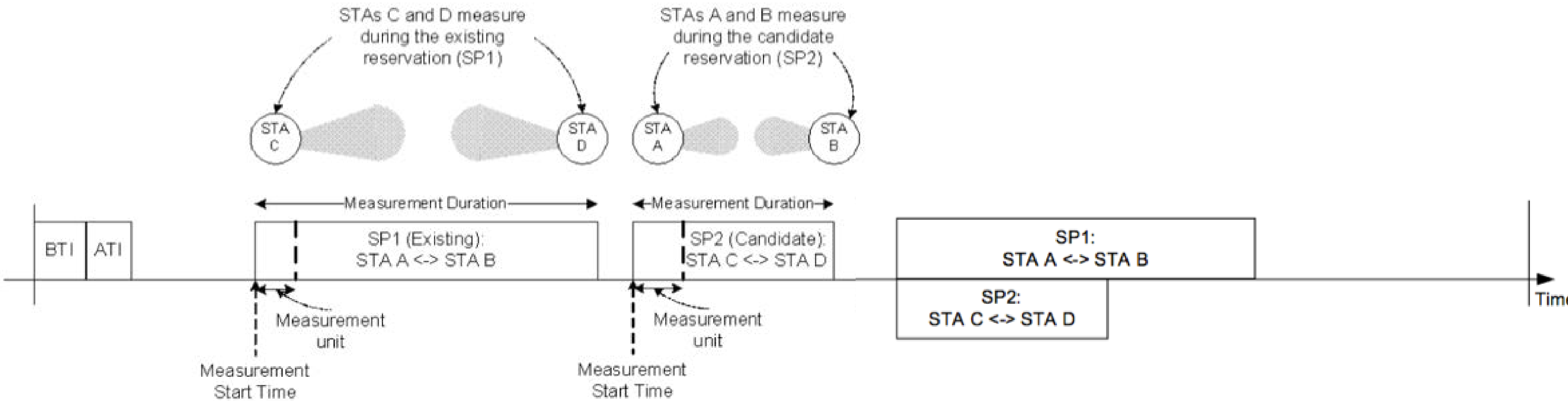
- **CSMA based**
  - **Directional carrier sensing**
  - **Open problems: hidden terminals & deafness**
  - **Studied in ad-hoc directional MAC protocols (~2005), but more challenging due to higher directionality, more beams, and imperfect beam patterns**



Deafness problem.

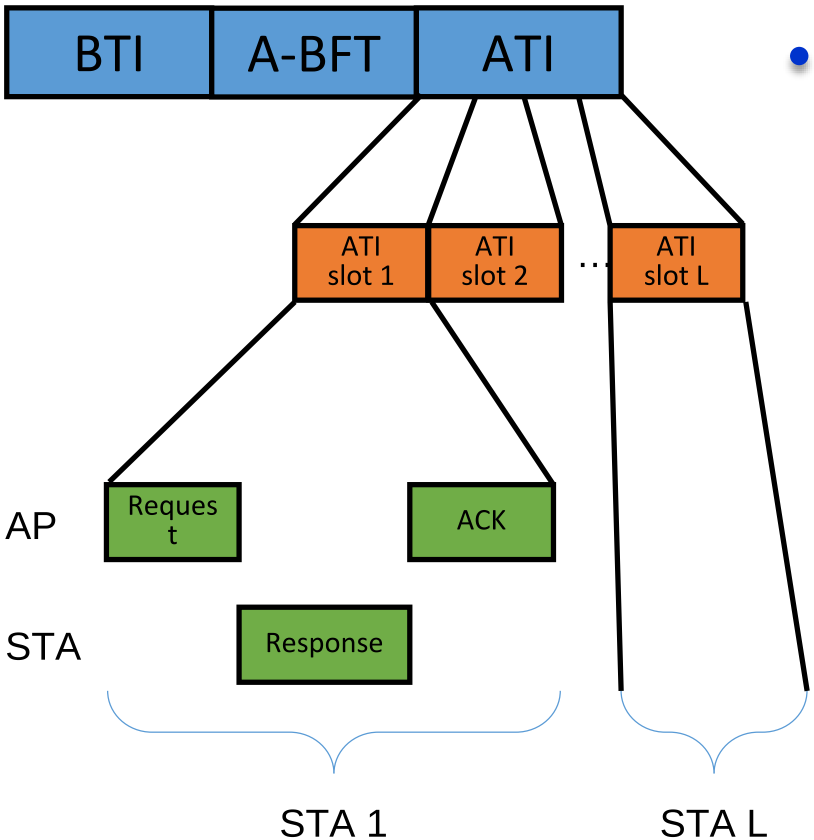
802.11ad MAC: TDMA interference management

- **TDMA based**
  - **Each STA periodically builds interference map**
  - **Sending interference map to AP**
  - **AP coordinates multiple links to avoid interference**
  - **Open problem: huge overhead in interference mapping, esp. during mobility**



802.11ad MAC: TDMA interference management

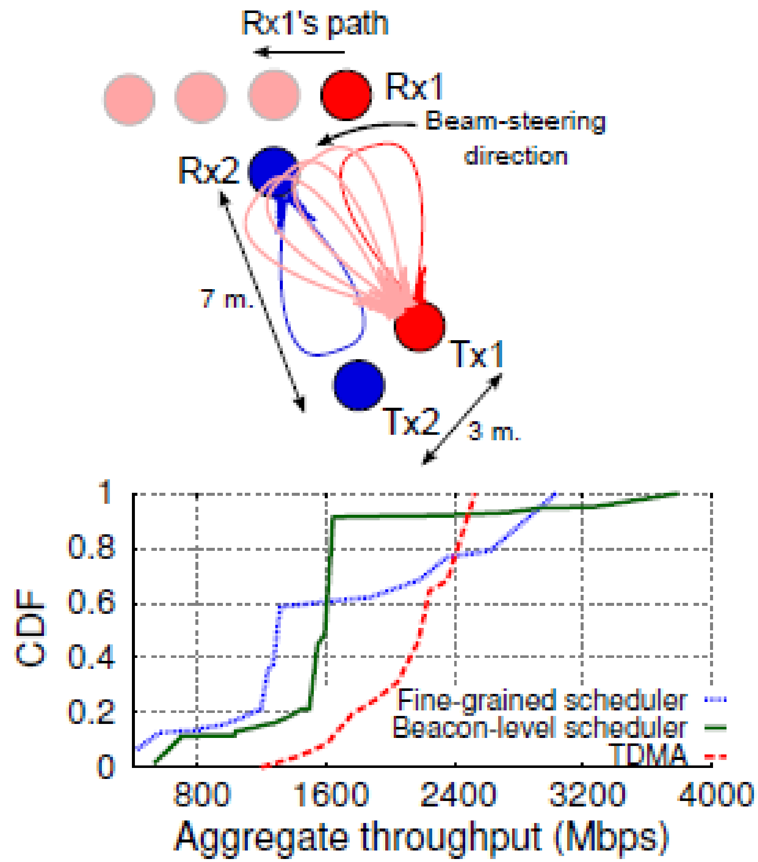
➢ **Scheduling TDMA slots: decision made in beacon header**



- **ATI: exchange resource information**
  - L slots
  - Use a request-response protocol to exchange the resource request and allocation information, e.g., which STA should transmit at which SP

802.11ad MAC: TDMA interference management

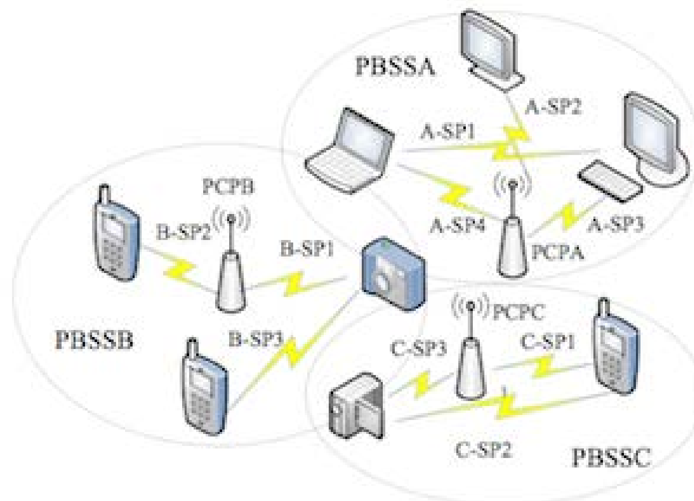
- **TDMA based**
  - **An experiment involving 2 links**
  - **Update interference map at either beacon intervals or packet level (fine-grained), or not at all (fixed TDMA)**
  - **Interference mapping may be even worse due to huge overhead**
  - **A tradeoff between responsiveness and overhead**



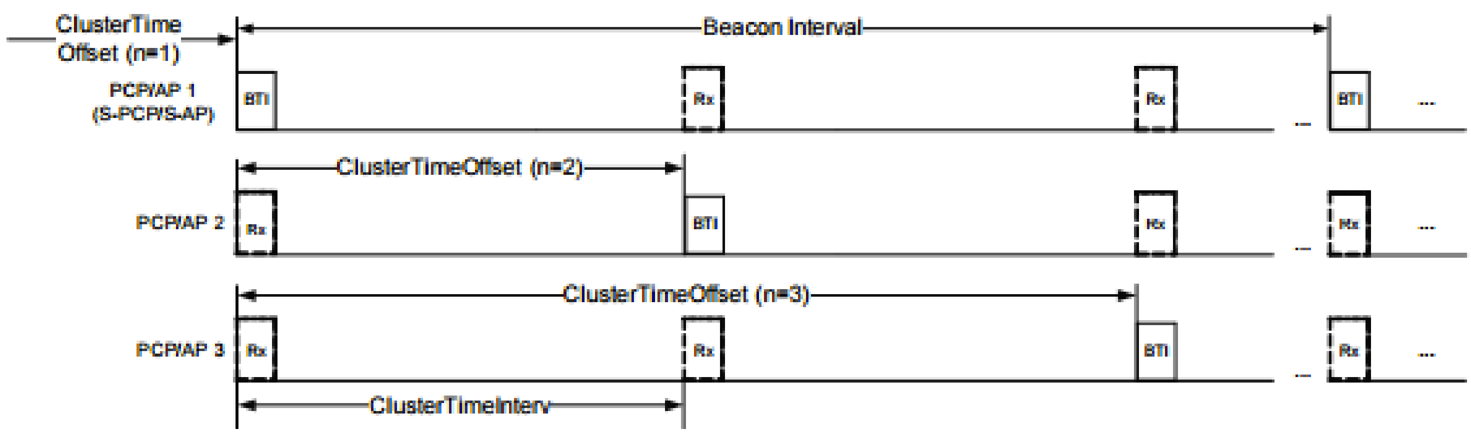
* **S. Sur et al., ACM SIGMETRICS'15**

802.11ad MAC: multiple AP/PCP networks coexist

- PCP/AP clustering
  - One of the APs serves as the synchronization AP



- BI timing
  - Example with 3 APs

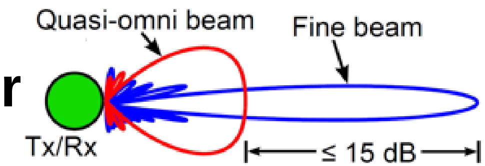


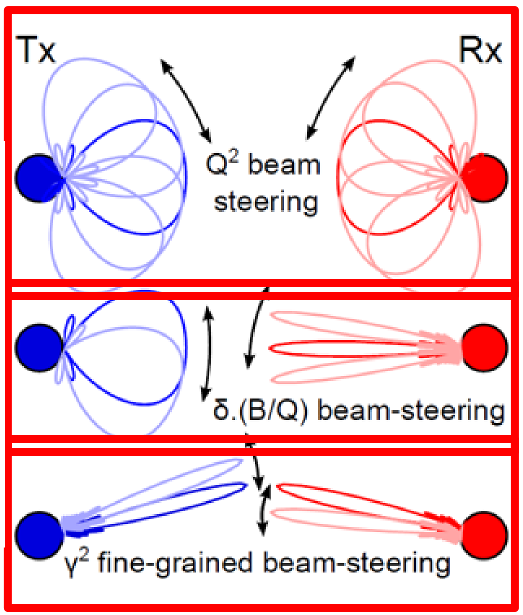
802.11ad MAC: Beamforming protocol

- **Challenge:**
  - A phased-array may have hundreds of beam directions to steer to
  - The TX&RX must decide on the beam direction of each, to maximize “alignment”, thus maximizing link SNR
- **802.11ad beamforming**
  - Decision making in BHI (can be updated dynamically during DTI)
  - Essentially a beam training (selection) process

802.11ad MAC: Beamforming training

- **Basic beamforming training procedur**



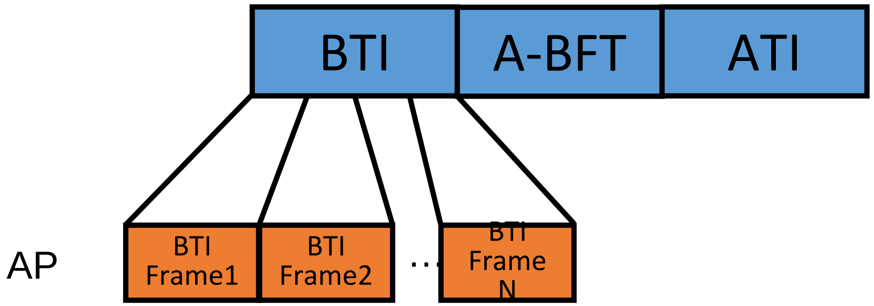


Sector level sweeping (SLS): quasi-omni beams

Multiple sector ID detection (MID): TX quasi-omni, RX directional, or vice versa

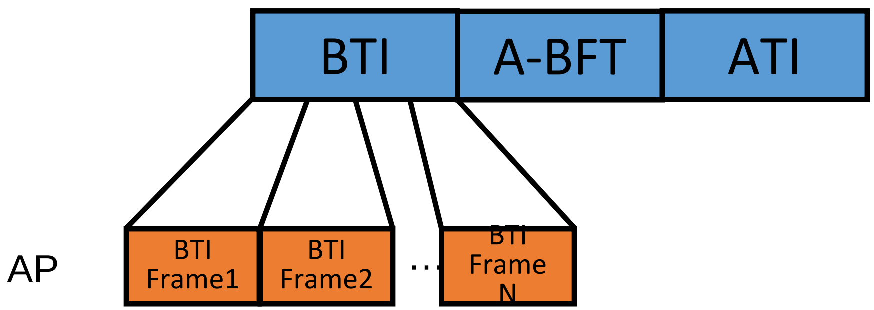
Beam Combining (BC): both TX and RX are directional

Scheduling beamforming training

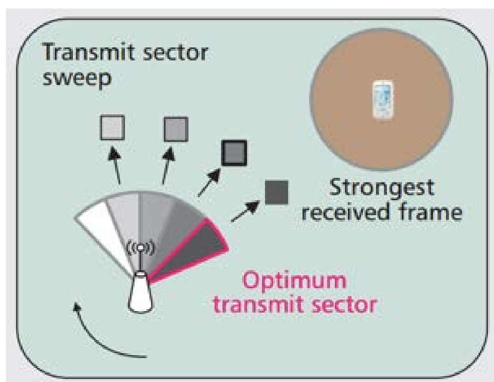


- **Training during Beacon Transmission Interval**
  - N frames
  - PCP/AP broadcasts beacon information in each frame
  - PCP/AP uses different beam patterns in different frames
  - The beam index in used is encoded in the beacon information
  - If a STA can decode a certain frame, record the beam index and the received SNR

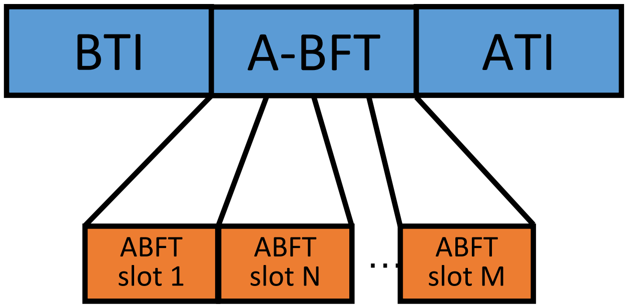
Scheduling beamforming training



- **BTI: Complete SLS-Tx beam training from AP to STA**

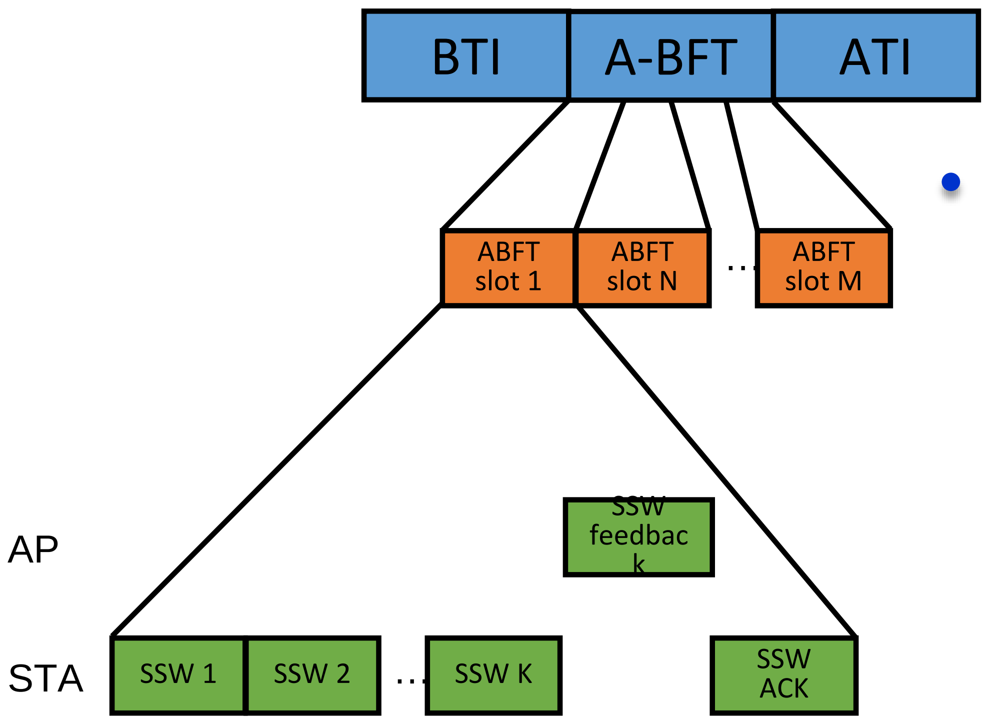


Scheduling beamforming training



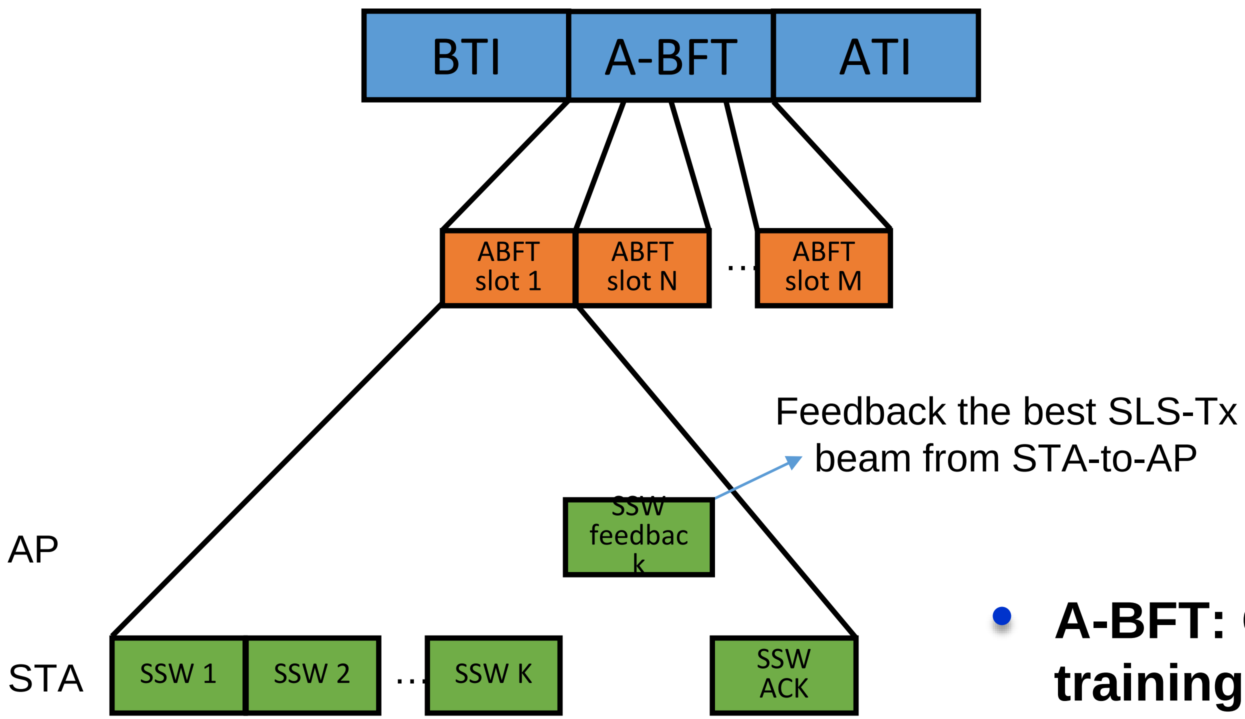
- **Beamforming training during A-BFT**
  - M slots
  - STA randomly picks one slot
  - If 2 STAs choose the same slot, they will collide
  - Collision is resolved by retry

Scheduling beamforming training



- **Beamforming training in A-BFT**
  - Sector SWeep (SSW) frame, SSW-feedback frame, and SSW-ACK frame
  - STA transmits each SSW using a different beam pattern
  - The index of beam pattern is encoded into the SSW
  - AP records the beam index and SNR of decodable SSW

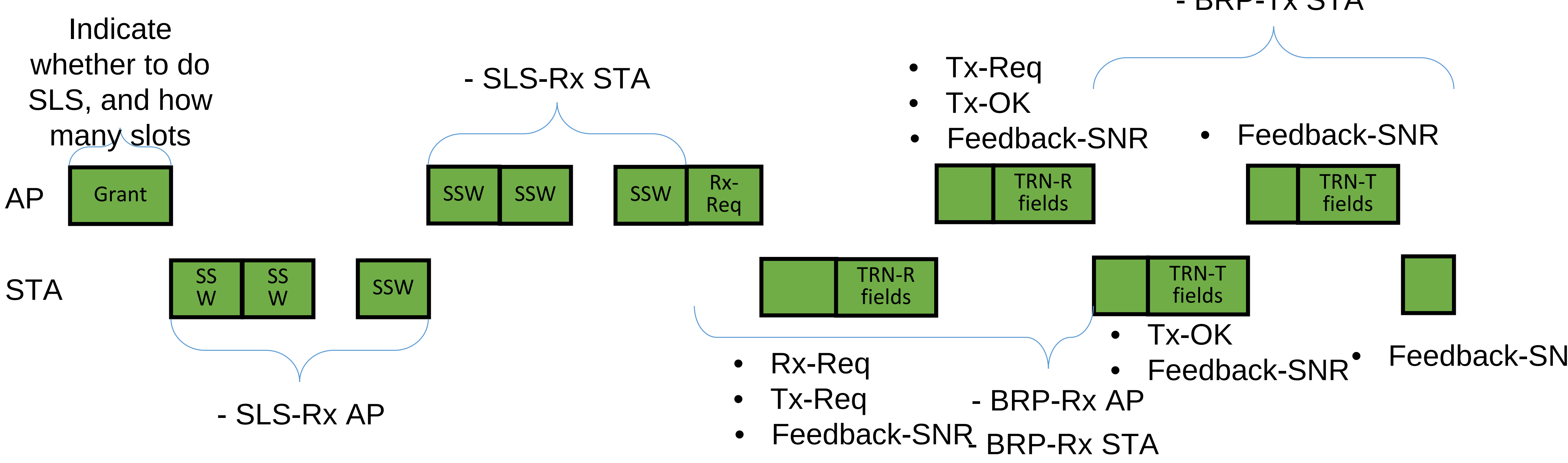
Scheduling beamforming training



- **A-BFT: Complete SLS-Tx beam training from STA to AP**

Scheduling beamforming training in DTI

- **SLS (optional)**
  - SLS-Rx AP
  - SLS-Rx STA
- **BRP (optional)**
  - BRP-Tx AP
  - BRP-Rx AP
  - BRP-Tx STA
  - BRP-Rx STA



802.11ad MAC: Fast Session Transfer (FST)

- Seamless switching between 60 GHz 802.11ad and 2.4/5 GHz 802.11n/ac
- These three bands share the same MAC address, so channel switching is transparent to higher layers
- A request/response protocol is needed between the FST initiator and responder (w/ overhead!)

Beyond 802.11ad: 802.11ay

- **Next-generation mmWave network standard; expected to be approved in 2020**
- **Core techniques**
  - **Bandwidth aggregation: up to 4x channel bandwidth over 802.11ad**
  - **mmWave MIMO and MU-MIMO: up to 4 streams**
- **Performance**
  - **Bit-rate: up to 44 Gbps with bandwidth aggregation, and 176 Gbps with MIMO**

27

Beyond 802.11ad: 802.11ay

- **Targeting demanding use cases**
  - **Wireless VR**
  - **Inter-rack connectivity for wireless data centers**
  - **Video/mass-data distribution in: trains, airplanes, classrooms…**

28

Class Quiz

- What is the drive for IEEE802.11ad?
- What are the data rates in IEEE802.11ad?
- What are the new technologies in IEEE802.11ad?