Millimeter-Wave Wireless Networking and Sensing

Xinyu Zhang

Associate Professor

Department of Electrical and Computer Engineering

University of California San Diego

mmWave communication and networking standards

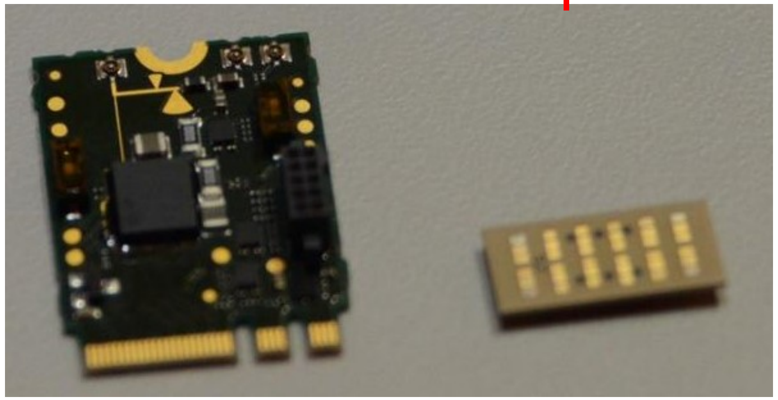
A Roadmap of mmWave standards

	Wireless PAN	Wireless LAN	Cellular
Standards (year ratified)	802.15.3c (2006)	802.11ad (2012), 802.11ay (?)	5G NR (?)
Use cases	Cable replacement	Gbps Internet access, cordless computing, mesh networking, wireless data center	Gbps wireless broadband, mobile edge computing, V2X
Spectrum	60 GHz band (57-64 GHz)	60 GHz band (57-64 GHz)	28 GHz band (24.25-29.5 GHz)
Channel bandwidth	2.16 GHz	2.16 GHz	?
Range	Below 10m	10s of meters	100s of meters
Rate	5 Gbps	7 Gbps	Gbps

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

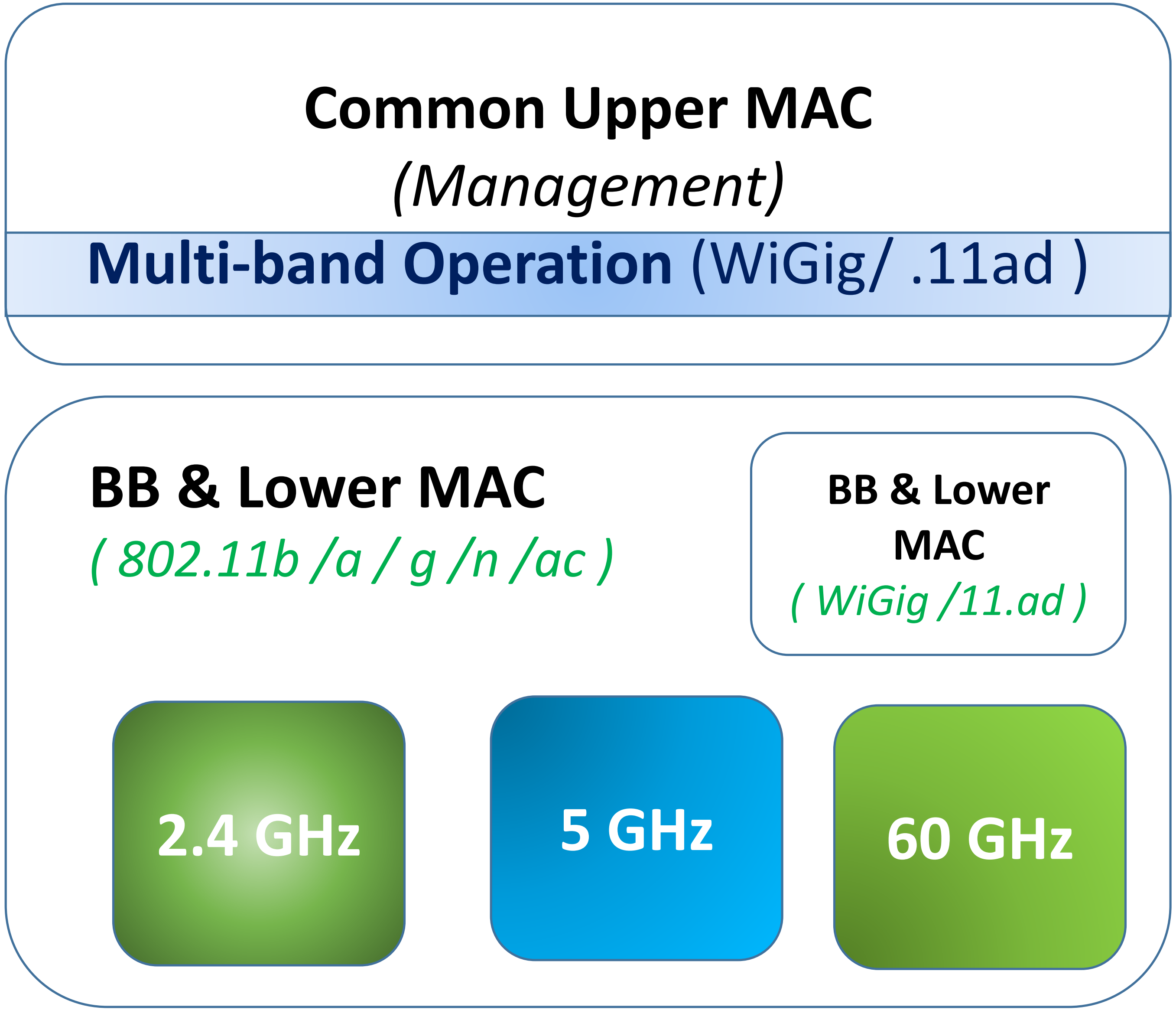


TP-Link 802.11ac/ad tri-band access point

Dell 802.11ad laptop & docking station

802.11ad Protocol Stack

- Extending 802.11



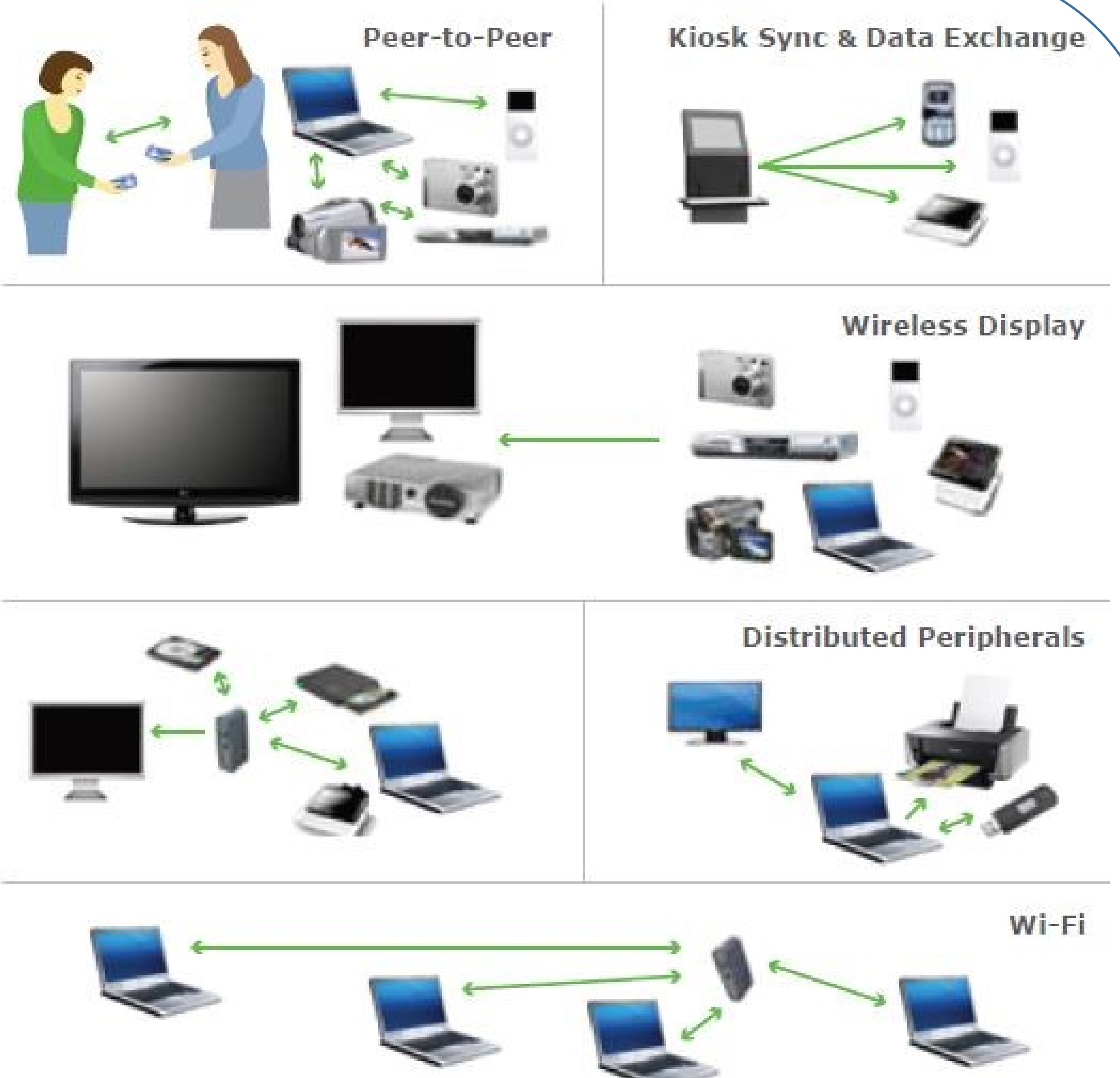
802.11ad Usage Models (From standard group)

Instant Wireless Sync
- IP-based P2P applications
- Using I/O PAL

Wireless Display
- HD streams over HDMI or DP using A/V PAL
- CE, PE and HH usages

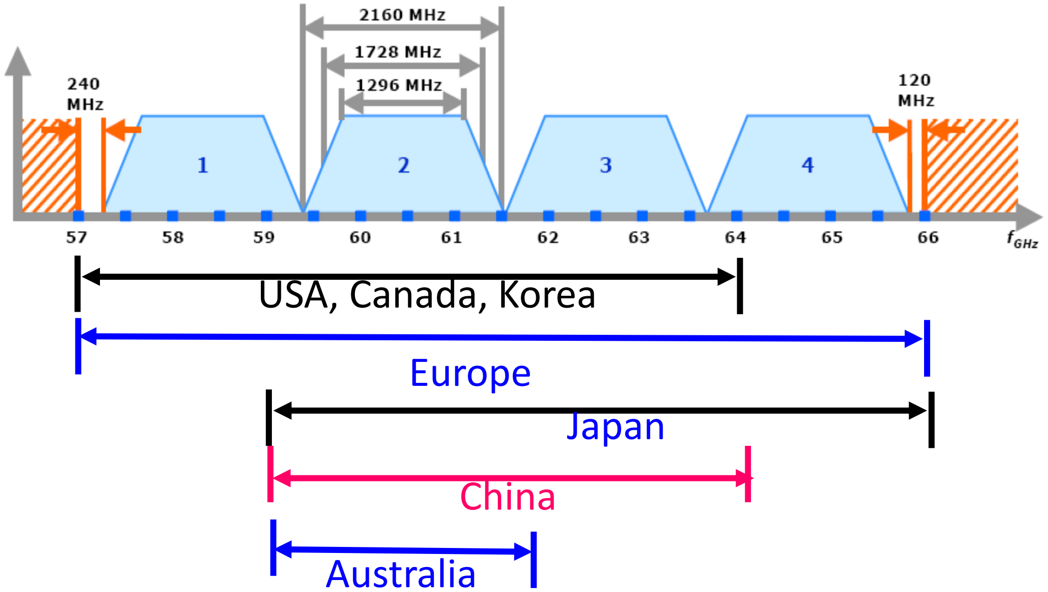
Cordless Computing
- Combination of Wireless display using A/V PAL, sync and I/O using I/O PAL

Internet Access
- Using native Wi-Fi, 802.11ad support



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

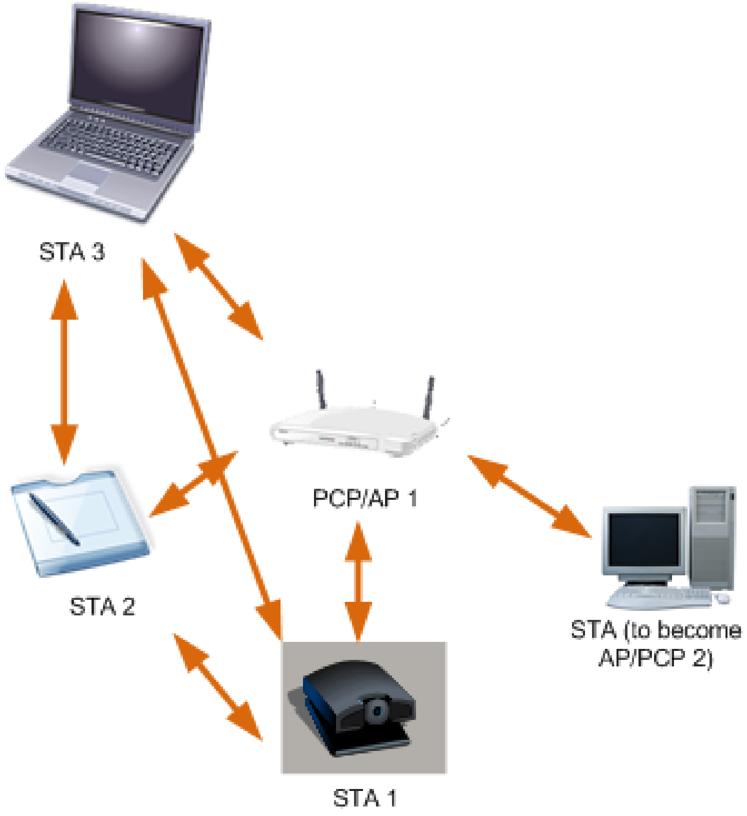
- Control PHY: Robust, low-rate (27.5 Mbps); for signaling, management and control frames

- 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

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

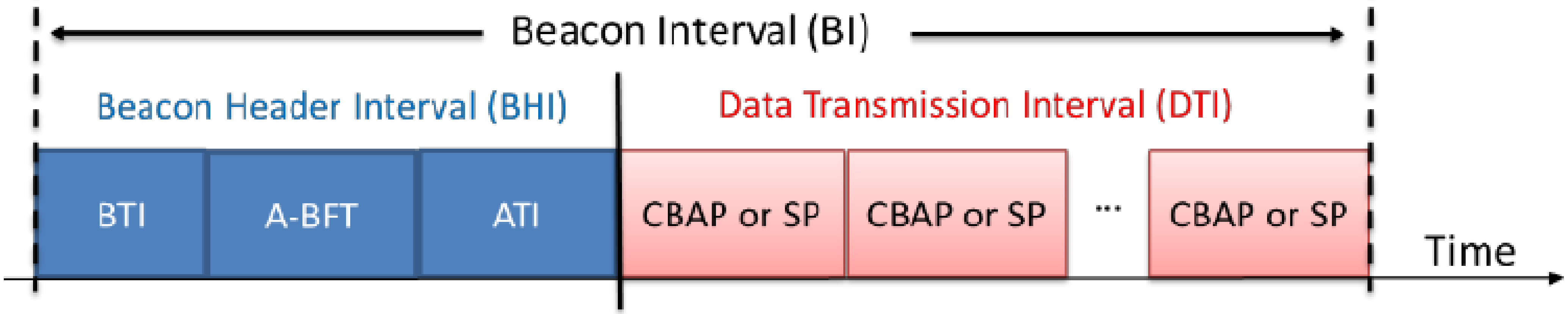


802.11ad MAC: Overview

- 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

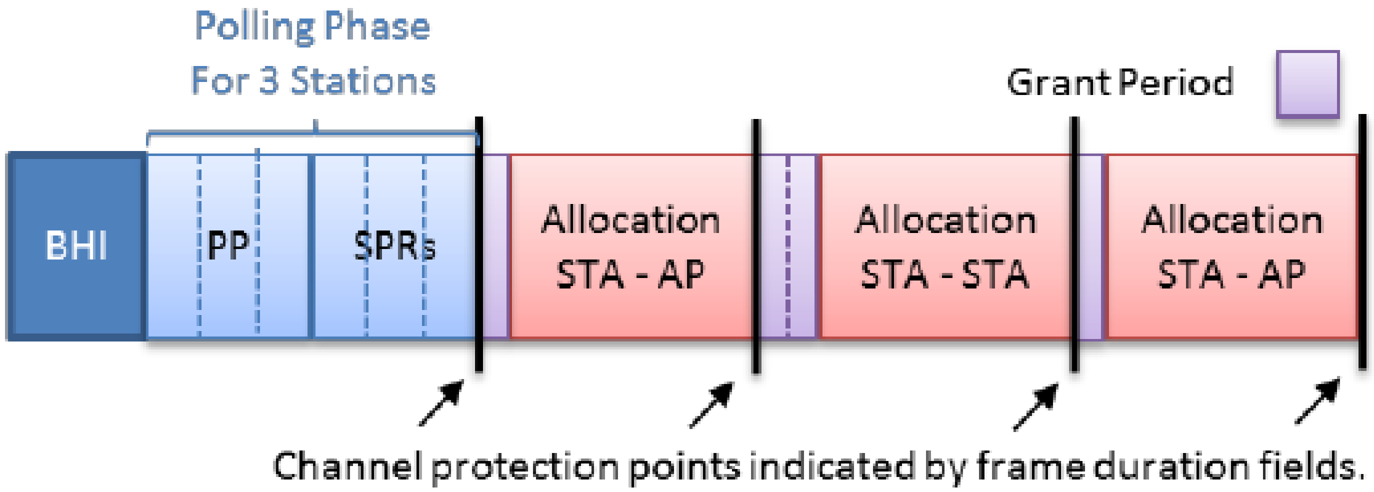
- Beacon interval
  - Following existing 802.11, all nodes are synchronized in beacon intervals
  - Beacon interval (BI) = BHI + DTI
    BHI: training, signaling; DTI: data transmission



  - 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:

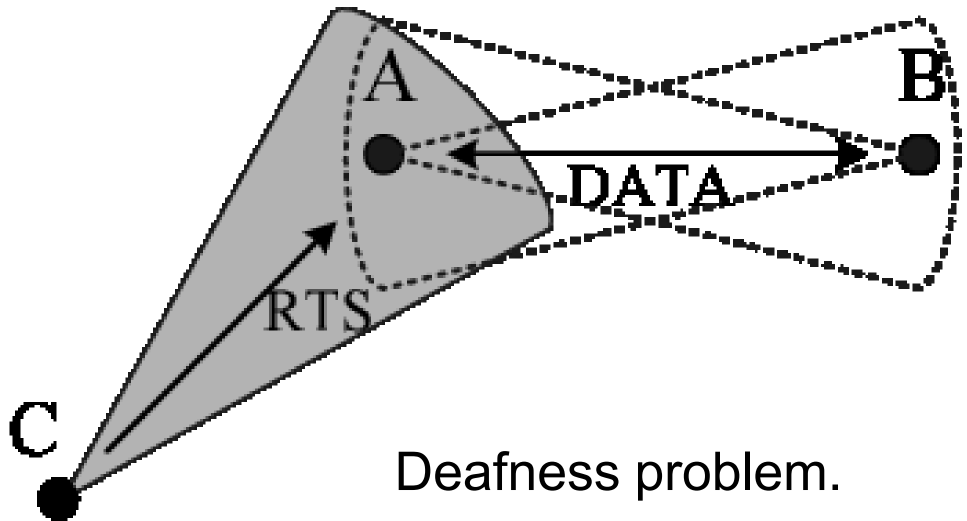


802.11ad MAC: CBAP Medium Access

- 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

802.11ad MAC: CSMA Interference management

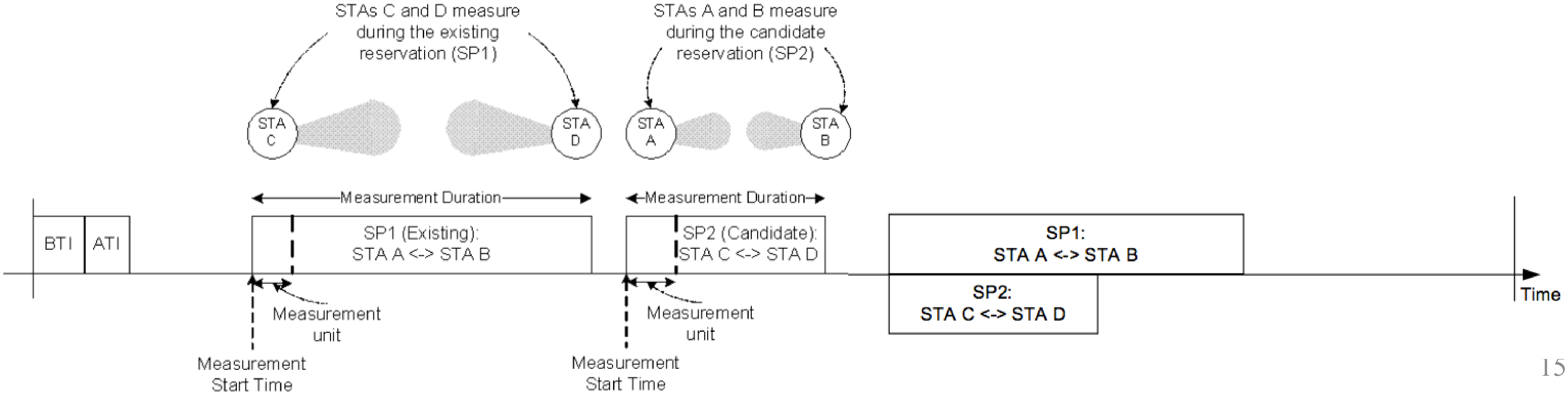
- CSMA based
  - Directional carrier sensing
  - Open problems: hidden terminals & deafness
  - Studied in ad-hoc directional MAC protocols (~2005), but more challenging due to higher directionality, more beams, and imperfect beam patterns



Deafness problem.

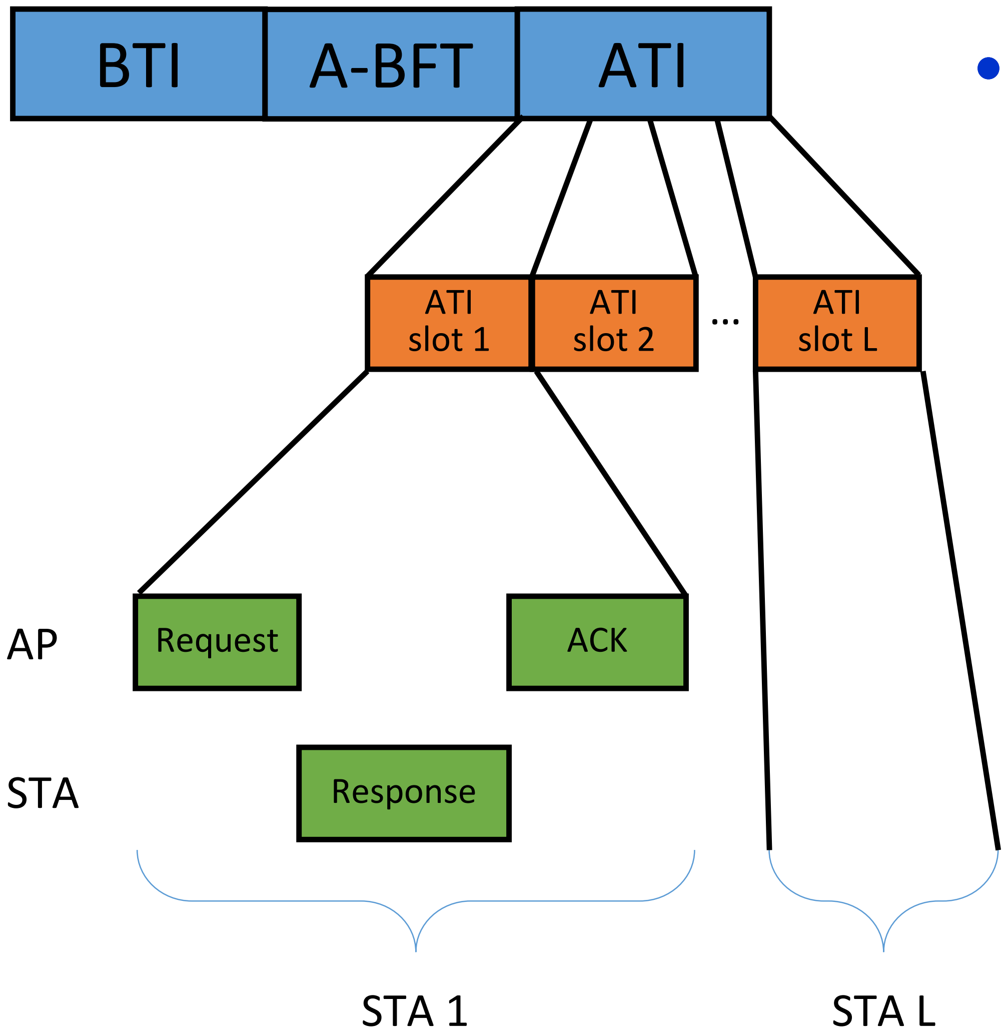
802.11ad MAC: TDMA interference management

- 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

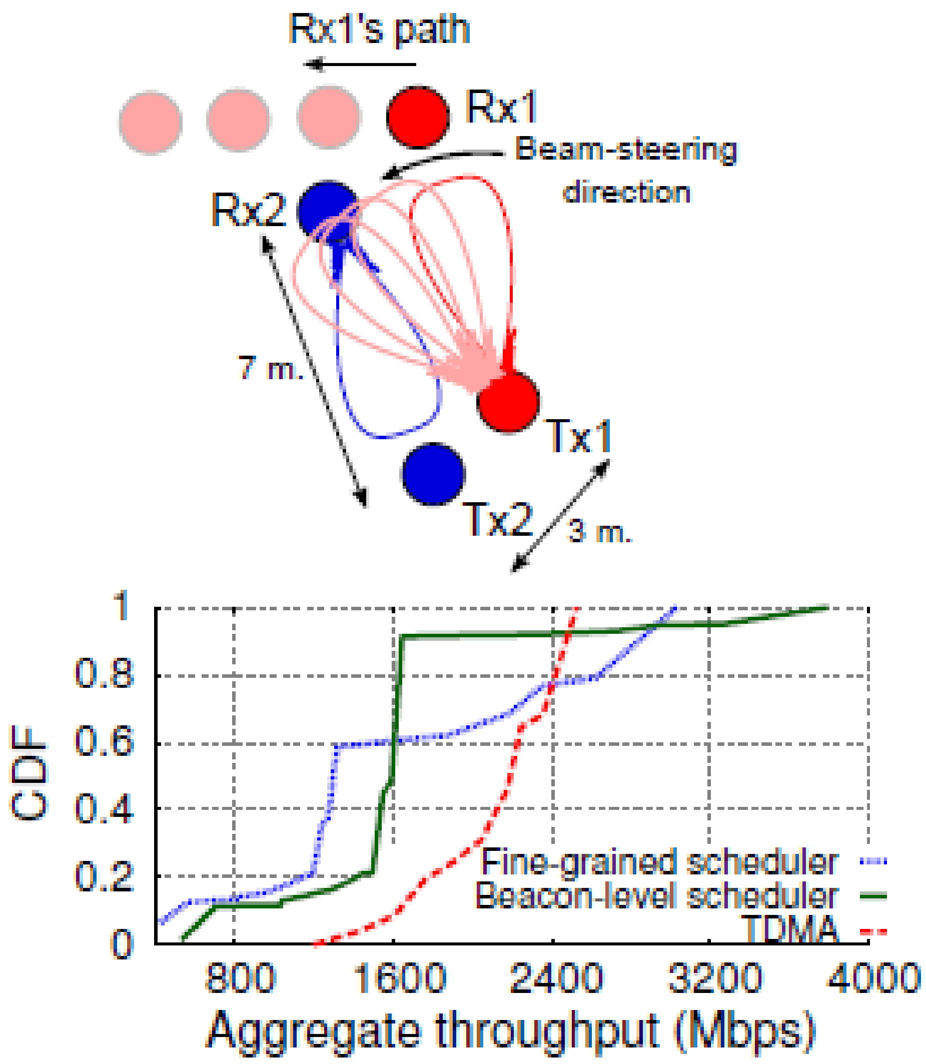
- Scheduling TDMA slots: decision made in beacon header



- **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

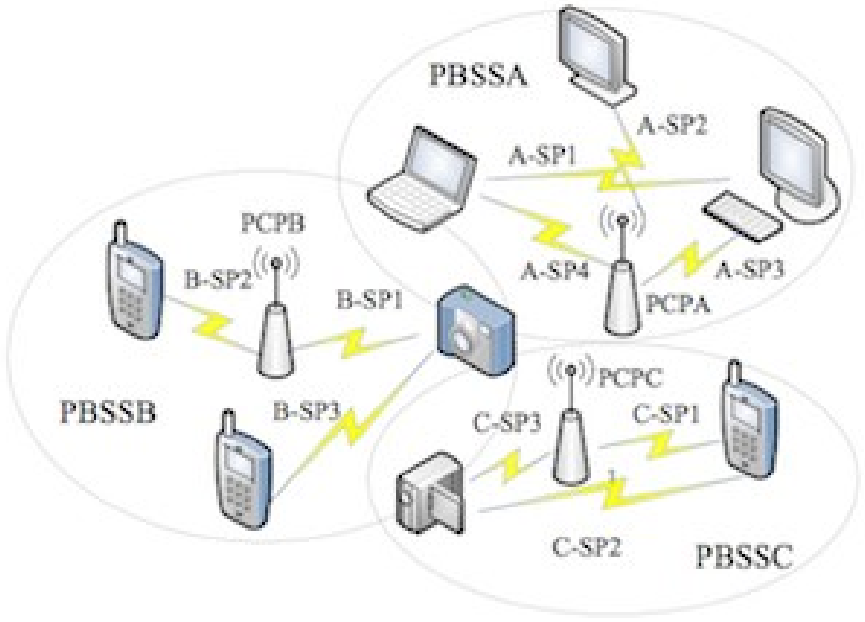
- TDMA based
  - An experiment involving 2 links
  - Update interference map at either beacon intervals or packet level (fine-grained), or not at all (fixed TDMA)
  - Interference mapping may be even worse due to huge overhead
  - A tradeoff between responsiveness and overhead



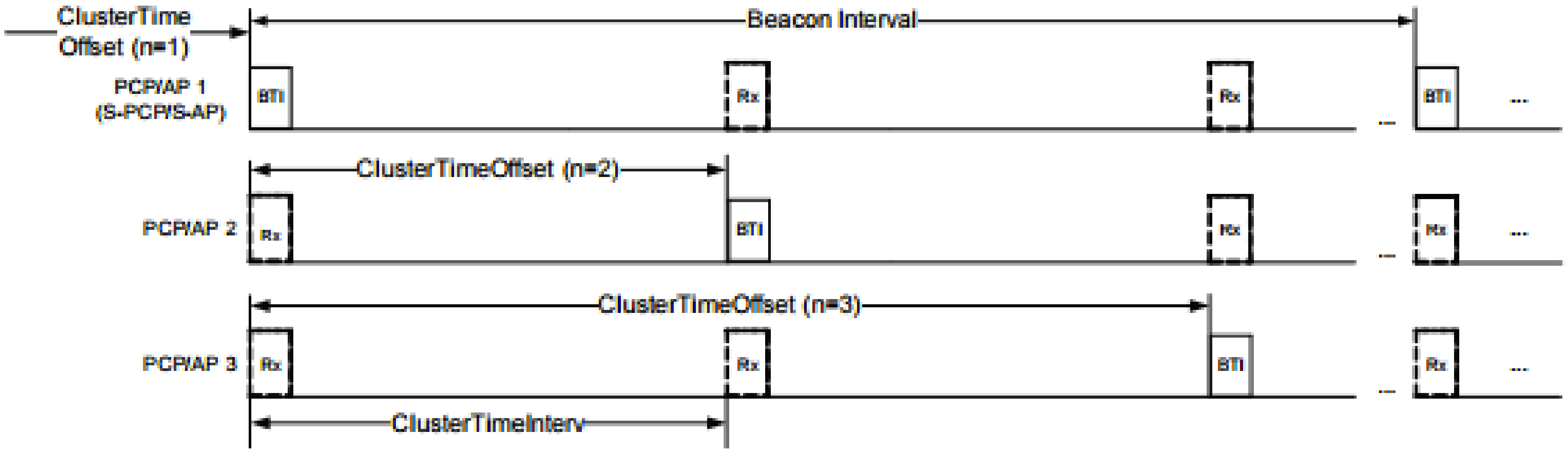
* S. Sur et al., ACM SIGMETRICS'15

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



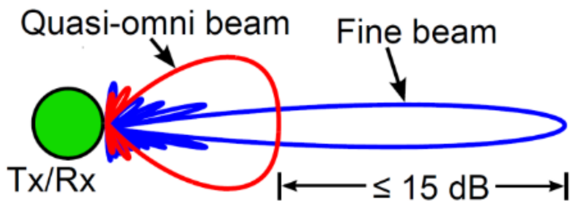
802.11ad MAC: Beamforming protocol

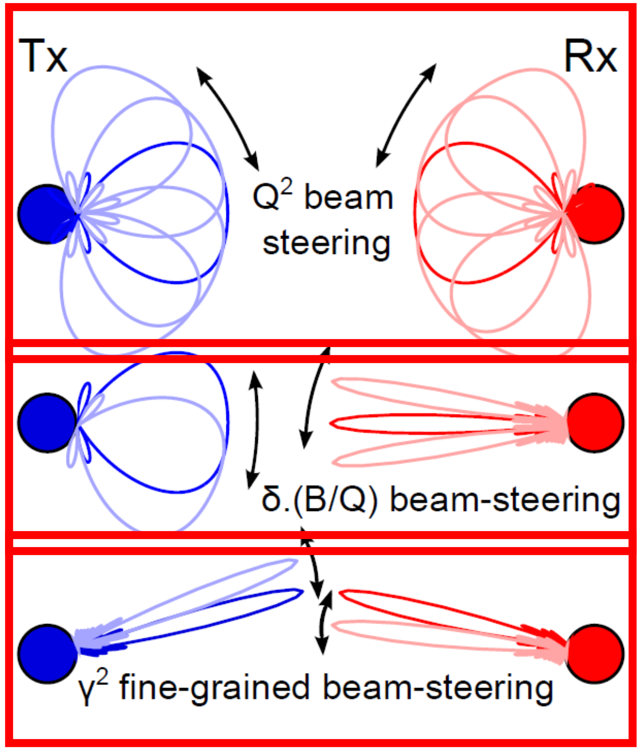
- Challenge:
  - A phased-array may have hundreds of beam directions to steer to
  - The TX&RX must decide on the beam direction of each, to maximize “alignment”, thus maximizing link SNR

- 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 procedure



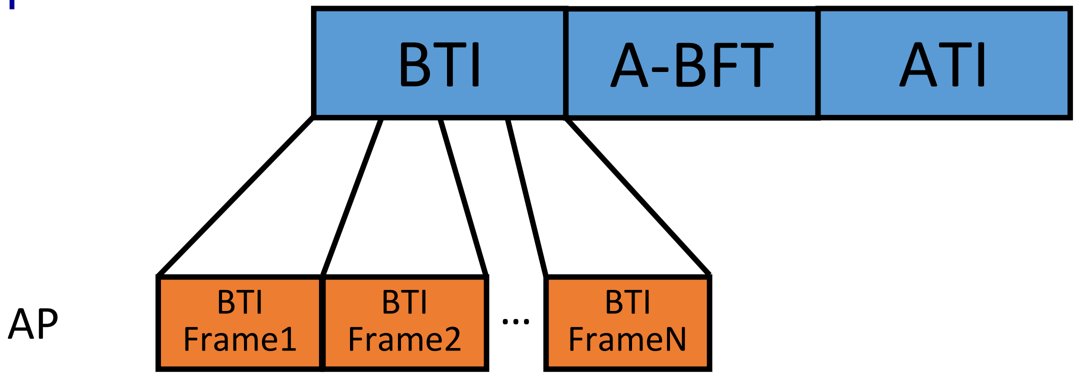


Sector level sweeping (SLS): quasi-omni beams

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

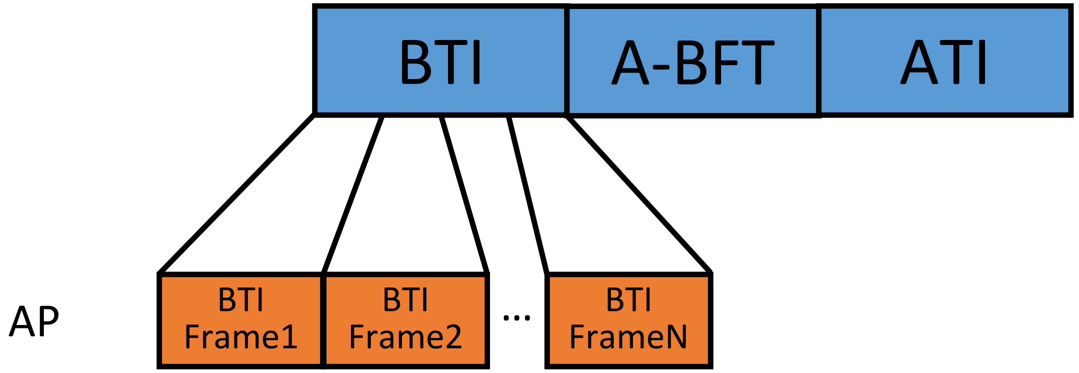
Beam Combining (BC): both TX and RX are directional

Scheduling beamforming training

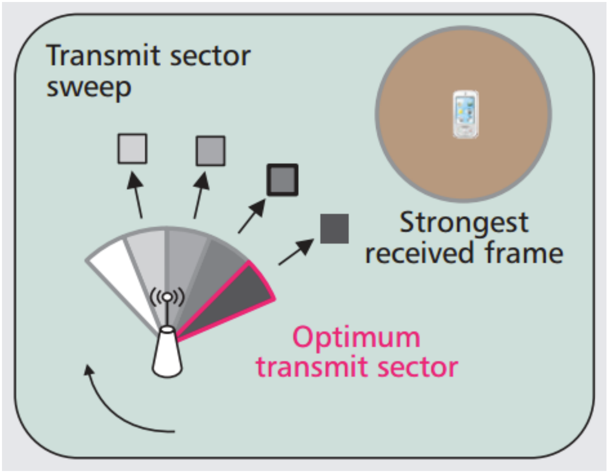


- **Training during Beacon Transmission Interval**
  - N frames
  - PCP/AP broadcasts beacon information in each frame
  - PCP/AP uses different beam patterns in different frames
  - The beam index in used is encoded in the beacon information
  - If a STA can decode a certain frame, record the beam index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

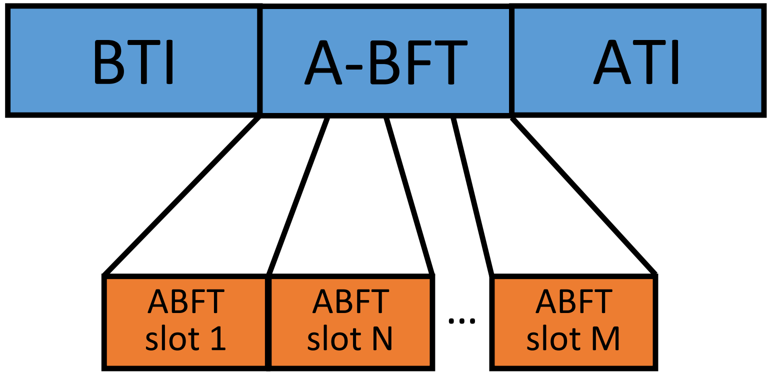
Scheduling beamforming training



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

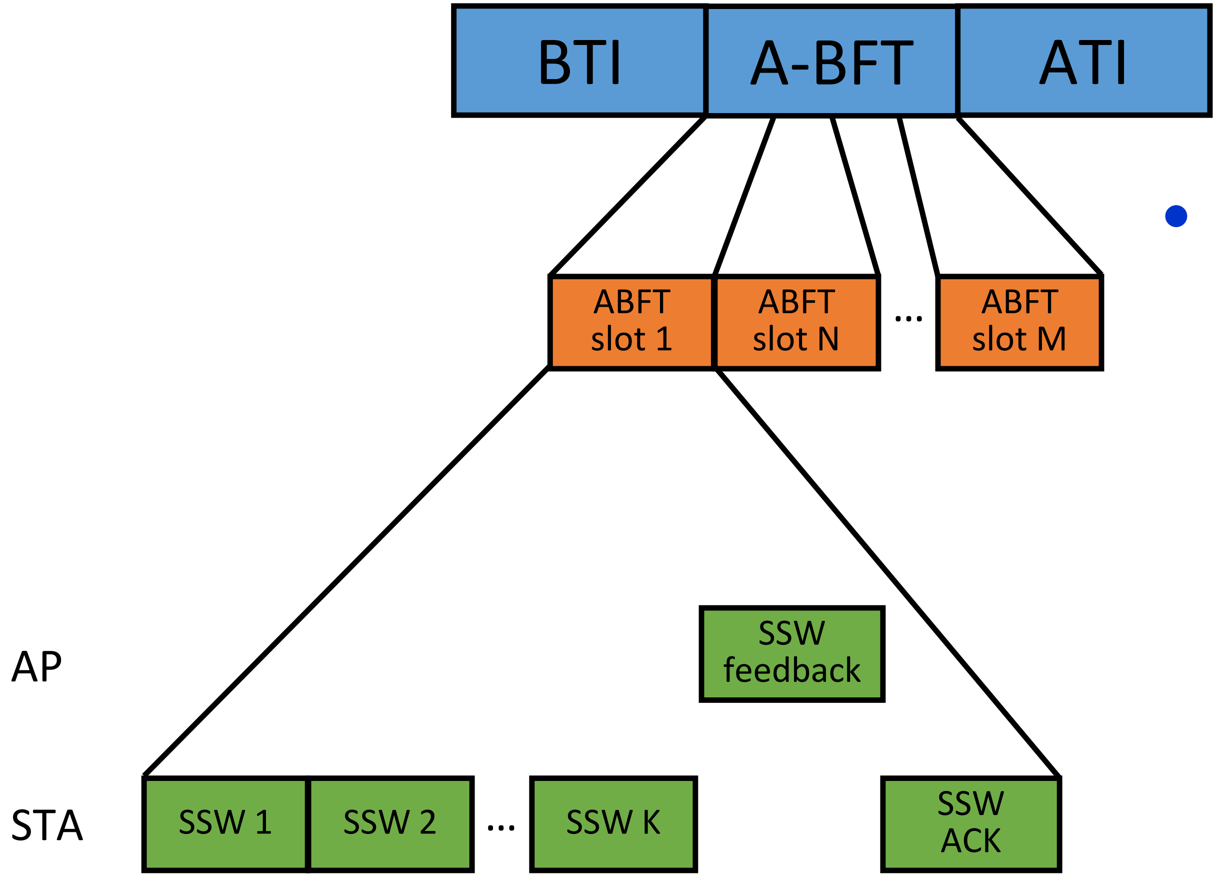


Scheduling beamforming training



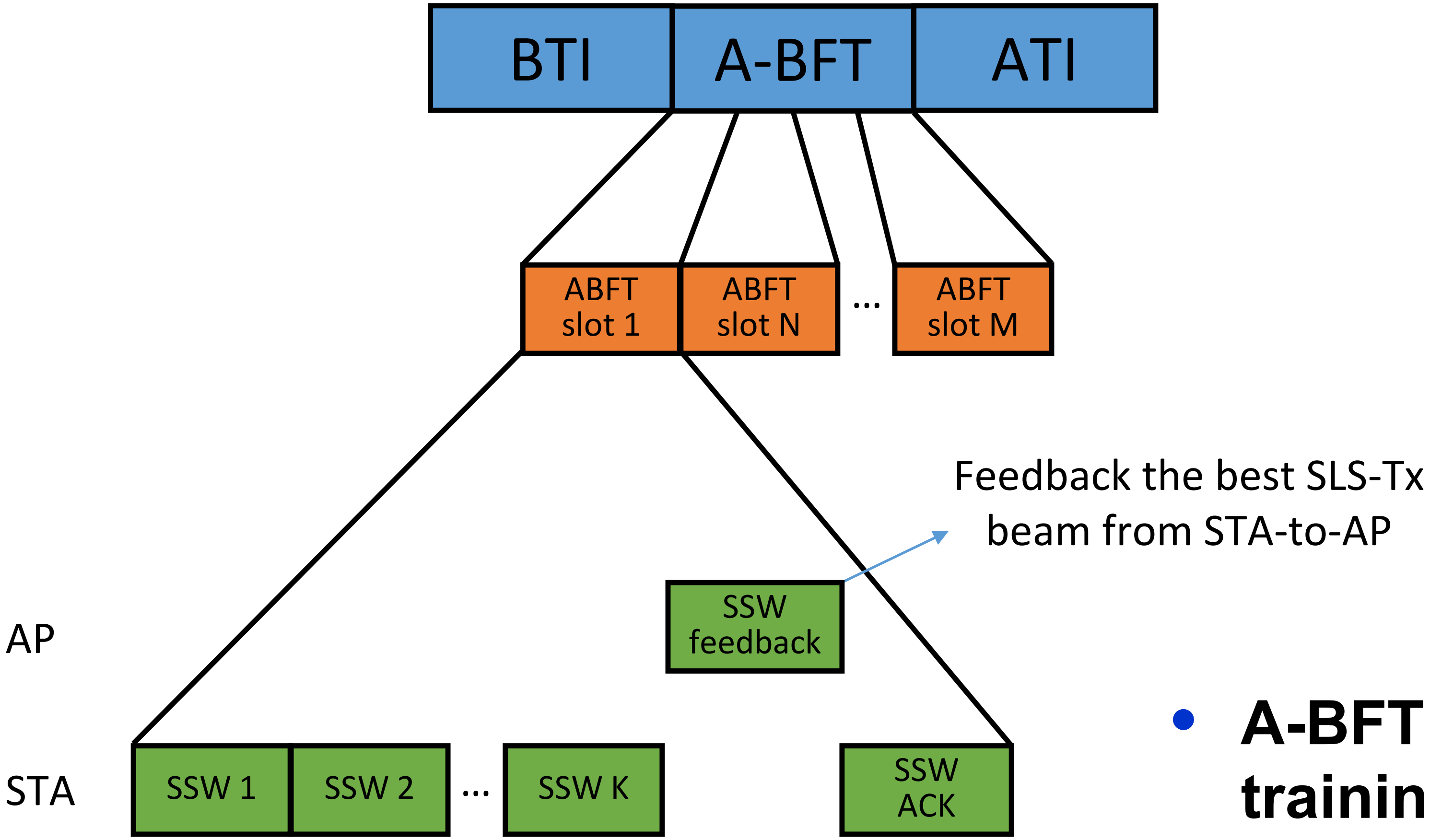
- **Beamforming training during A-BFT**
  - M slots
  - STA randomly picks one slot
  - If 2 STAs choose the same slot, they will collide
  - Collision is resolved by retry

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

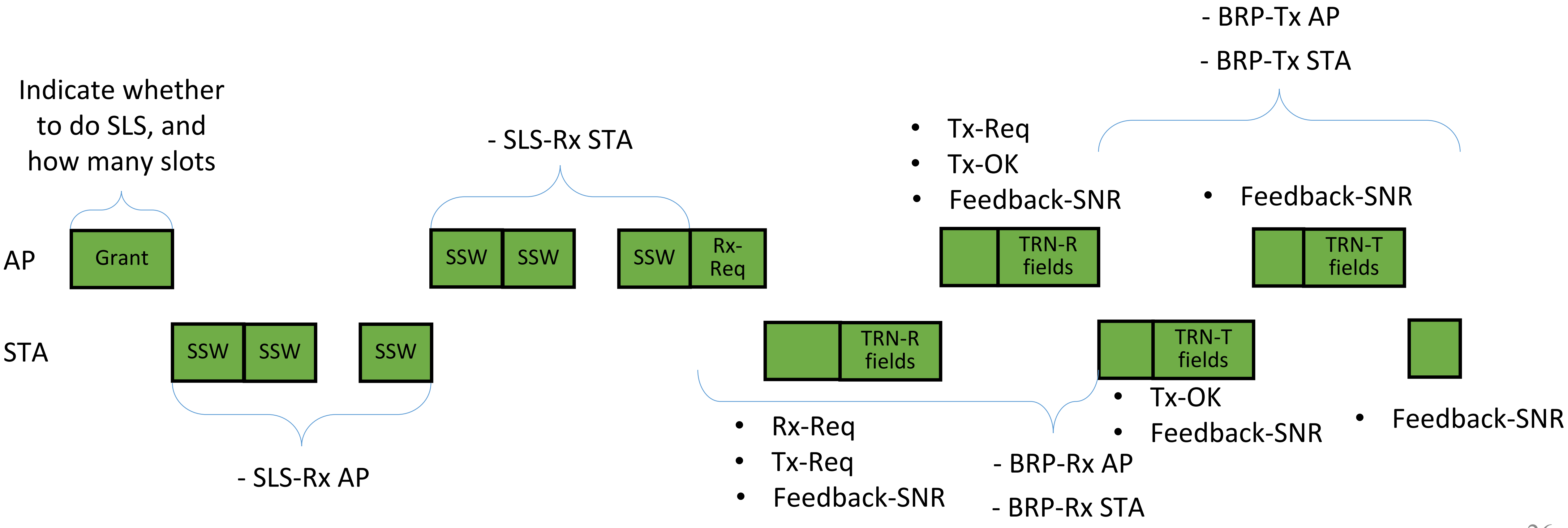
Scheduling beamforming training



- **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;
  full draft expected to be released in 2017
- 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

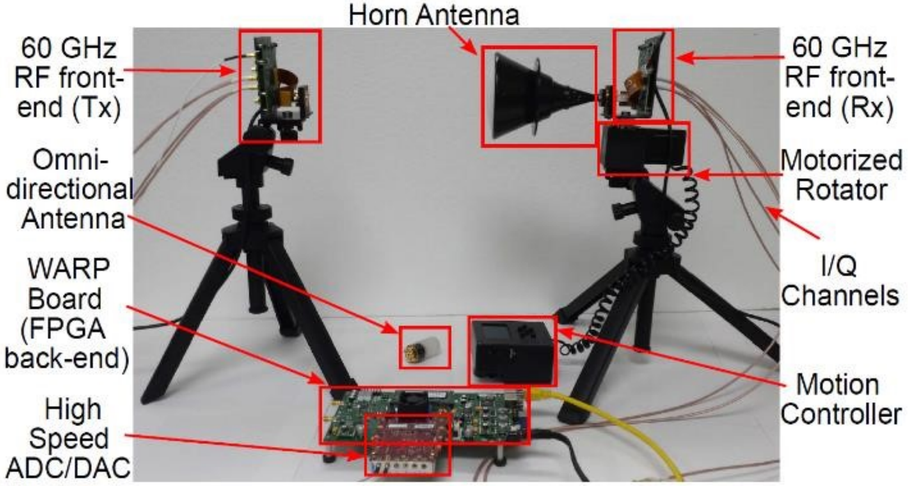
Beyond 802.11ad: 802.11ay

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

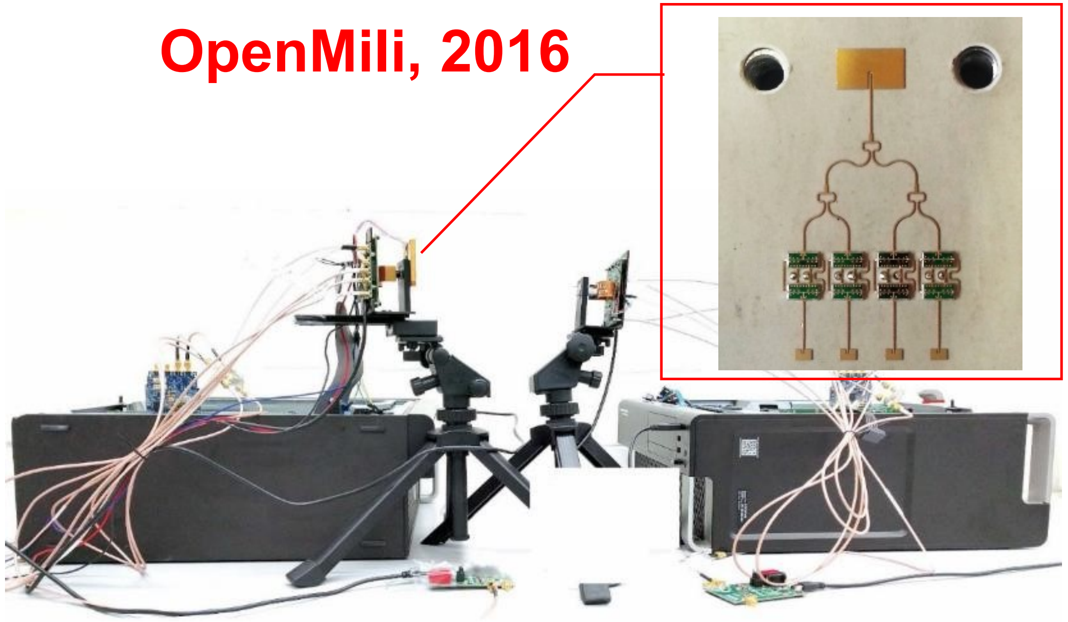
Experimental research in mmWave networking: beyond the standards

- Key challenge is a programmable platform with phased-array
- Some existing platforms: open-source software-radios

WiMi 1.0, 2015



OpenMili, 2016

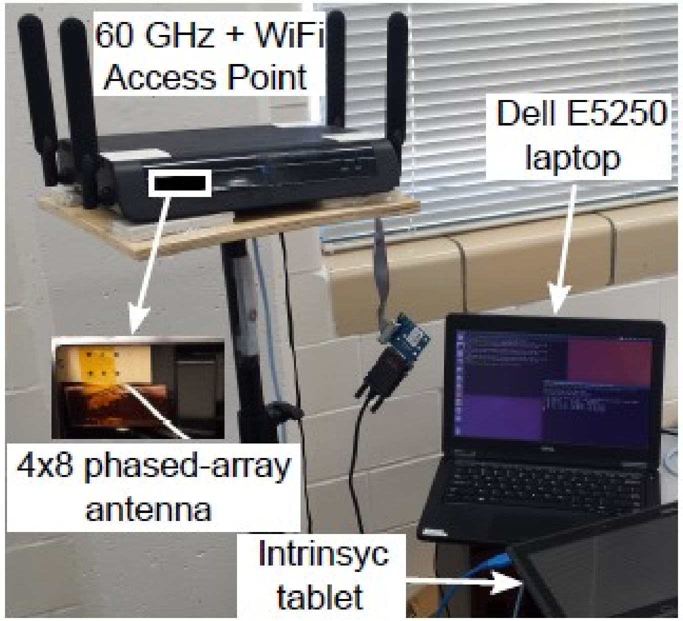


* “*60 GHz Indoor Networking through Flexible Beams: A Link-Level Profiling* ”, Sanjib Sur, Vignesh Venkateswaran, Xinyu Zhang, Parameswaran Ramanathan, ACM SIGMETRICS’15

* “*OpenMili: A 60 GHz Software Radio Platform With a Reconfigurable Phased-Array Antenna* ”, Jialiang Zhang, Xinyu Zhang, Pushkar Kulkarni, Parameswaran Ramanathan, ACM MobiCom’16

Experimental research in mmWave networking: beyond the standards

➢ Some existing platforms: proprietary 802.11ad radios



* "*WiFi-Assisted 60 GHz Networks*",
Sanjib Sur, Ioannis Pefkianakis, Xinyu Zhang, Kyu-Han Kim, ACM MobiCom'17

* "*Object Recognition and Navigation Using a Single Networking Device*",
Yanzi Zhu, Yuanshun Yao, Ben Y. Zhao and Haitao Zheng, ACM MobiSys'17

References

* "*IEEE 802.11ad: directional 60 GHz communication for multi-Gigabit-per-second Wi-Fi*", Thomas Nitsche ; Carlos Cordeiro ; Adriana B. Flores ; Edward W. Knightly ; Eldad Perahia ; Joerg C. Widmer, IEEE Comm Magazine, 2014

* "*WiGig and IEEE 802.11ad For Multi-Gigabyte-Per-Second WPAN and WLAN*", Sai Shankar N., Debashis Dash, Hassan El Madi, Guru Gopalakrishnan, arXiv:1211.7356

* "*Millimeter Wave Wireless Communications*", Theodore S. Rappaport, Robert W. Heath, Jr., Robert C. Daniels, James N. Murdock, Prentice Hall, 2015

* "*60 GHz Indoor Networking through Flexible Beams: A Link-Level Profiling* ", Sanjib Sur, Vignesh Venkateswaran, Xinyu Zhang, Parameswaran Ramanathan, ACM SIGMETRICS'15

* "*Demystifying 60GHz Outdoor Picocells*", Yibo Zhu, Zengbin Zhang, Zhinus Marzi, Chris Nelson, Upamanyu Madhow, Ben Y. Zhao, and Haitao Zheng, ACM MobiCom'14

* "*WiFi-Assisted 60 GHz Networks*", Sanjib Sur, Ioannis Pefkianakis, Xinyu Zhang, Kyu-Han Kim, ACM MobiCom'17