BAWMAN

Next-Next-Generation Wi-Fi

from Contention to Scheduled Access

Baw Chng
info@bawman.com

IEEE

First presented at an IEEE event on 2022 July 19

Find this presentation at bawman.com/PRESENTATIONS/

Biography

BAW CHNG @ BAWMAN LLC

- Proud Senior Member of IEEE. Founder and President of BAWMAN LLC
- Consult in the Wireless Networking and Telecommunications industry
- **Services offered**:
  - **Strategic Consulting** – business strategy, product positioning, technology roadmap development, RFI/RFP
  - **Standards Consulting** – standards development, standards & trade group representation
  - **Technology Consulting** – network system architecture, technology development, evaluation and trial
- **Clientele**: communications service providers, technology suppliers, equipment vendors, start-ups, established enterprises, investors; domestic and international
- **Expertise**: networking systems, wireless communications, standards and protocols
  - cellular, Wi-Fi, IoT, LPWAN, optical, NFV, SDN, cloud, IEEE, IETF, 3GPP, WBA, CableLabs, Broadband Forum
- **Contact**: **www.bawman.com** ; info@bawman.com

Outline

- Biography

- Next-Next-Generation Wi-Fi
  - Very brief history up to Wi-Fi 6/6E
  - Wi-Fi in the next ten years (Wi-Fi 7/8?)
    - Trends, motivations, use cases, new technological features

- Special Focus:
  - Time Sensitive Networking, Ultra-Low Latency for Wi-Fi
    - Ideas, concepts, and techniques for low/predictable latency
    - Special focus on “scheduled access” for Wi-Fi

BAWMAN

Next-Next-Generation Wi-Fi

Very brief history up to Wi-Fi 6/6E

Very Brief History Up To Wi-Fi 6/6E (1)

IEEE Std. 802.11-1997

- Initial standardization as IEEE 802.11 (derived from even earlier ALOHA protocol; includes WEP for security)
- 1 or 2 Mbps in 2.4 GHz spectrum, 22 MHz bandwidth, ≤ 100 m
- "Wi-Fi" trademarked in 1999 by the Wi-Fi Alliance ; integrated into Apple iBook as "AirPort" in 1999

802.11g-2003

- .11a-1999 : ≤ 54 Mbps in 5 GHz spectrum, ≤ 20 MHz bandwidth, ≤ 120 m (OFDM)
- .11b-1999 : ≤ 11 Mbps in 2.4 GH spectrum, ≤ 20 MHz bandwidth, ≤ 140 m
- .11g-2003 : ≤ 54 Mbps in 2.4 GHz spectrum, ≤ 20 MHz bandwidth (extended rates in 2.4 GHz)

802.11-2007

- .11i-2004 : Security (WPA2)
- .11e-2005 : QoS

802.11-2012

- .11n-2009 ("Wi-Fi 4") : ≤ 600 Mbps in 2.4 GHz & 5 GHz, ≤ 40 MHz bandwidth, ≤ 250 m (MIMO ≤ 4 streams)
- .11k : RRM ; .11v : network management ; .11r : fast roaming/handoff ; .11s : Mesh ; .11p : Vehicular (WAVE)

Very Brief History Up To Wi-Fi 6/6E (2)

802.11-2012

- .11n-2009 ("Wi-Fi 4") ... (continued from last page)

802.11-2016

- .11ac-2013 ("Wi-Fi 5") : ≤ 3.5 Gbps in 5 GHz spectrum, ≤ 160 MHz bandwidth, ≤ 8 streams (MU-MIMO DL, BF)
- .11ad-2012 : ≤ 6.7 Gbps in 60 Hz spectrum, ≤ 2160 MHz bandwidth
- .11af-2013 : TV whitespace (VHF, UHF using cognitive radio)

802.11-2020

- .11ah-2016 ("Wi-Fi HaLow") : low power, extended range, license-exempt 900 MHz spectrum
- .11aj-2018 : supports China mmWave in 45 GHz spectrum
- .11ai-2016 : fast initial link setup ; .11aq-2018 : pre-association discovery of services

802.11-202x

- .11ax-2019 "Wi-Fi 6" : ≤ 9.6 Gbps in 2.4 & 5 GHz spectra, ≤ 160/80+80 MHz bandwidth, ≤ 8 streams, ≤ 120 m
- .11ax-2020 : supports 6 GHz spectrum ("Wi-Fi 6E")
- Also introduced in .11ax: OFDMA, MU-MIMO UL, TWT, BSS Coloring

New "generation" every 5~6 years. What's next?

BAWMAN

BAWMAN

Next-Next-Generation Wi-Fi
Wi-Fi in the next ten years

Trends, Different “Dimensions” for Improving Wi-Fi

Different “Dimensions” for Improving Wi-Fi

Speed	Latency	Security/Privacy	Mobility UX	Service UX
• Single user speed • Aggregate speed • Rate vs. Range	• Low latency • Predictable latency	• Authentication • Encryption • Privacy protection	• Smoother/ faster/ smarter handoff • Faster network (re)entry	• Smarter network selection • Faster service discovery

Efficiency	Scale/Density	Spectrum	Operational	Application Specific
• Spectral efficiency • Energy efficiency	• User device density • Network/base station density	• Different frequency bands	• Mesh • Inter-op	• Media streaming, IoT, location positioning, sensing, ...

Next-Generation Wi-Fi ("Wi-Fi 7"?) (1)

- Primarily being developed in P802.11be

CAUTION: not every candidate feature will make it into 802.11be

"Needs" callouts:

- 4K/8K video
- VR/AR
- Gaming
- Remote Office
- Cloud Computing
- Improved integration with Time Sensitive Networks (TSN)

Candidate feature callouts:

- 320 MHz channel bandwidth
- Non-contiguous spectrum (efficiency)
- Multi-band, multi-channel aggregation
- 16 stream MIMO
- Multi-AP coordination
- Enhanced link adaptation/ retransmission (e.g., Hybrid ARQ)
- Adaptation for 6 GHz regulatory rules

Reference: IEEE P802.11be PAR

Next-Generation Wi-Fi ("Wi-Fi 7"?) (2)

- Translating "needs" to technical requirements

"Needs" callouts:

- 4K/8K video
- VR/AR
- Gaming
- Remote Office
- Cloud Computing
- Improved integration with Time Sensitive Networks (TSN)

"higher speed"
(e.g., "uncompressed rate of 20 Gbps")

How to increase speed?

"lower latency"
(e.g., "≤ 5 ms for realtime gaming")

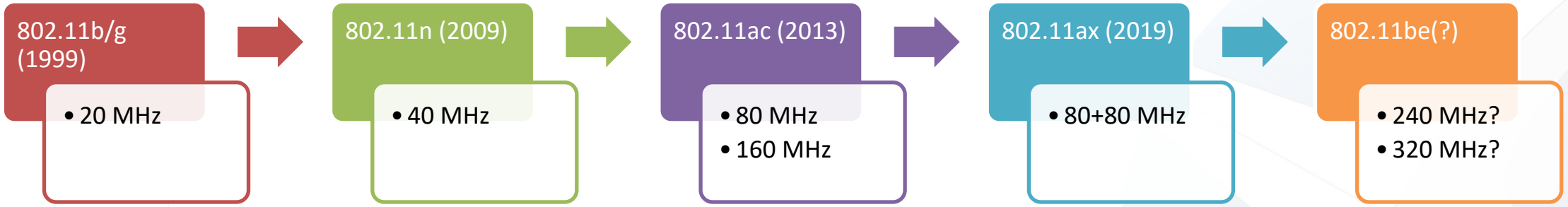
How to lower latency?

Reference: IEEE P802.11be PAR

How to Increase Speed? (1)

- … for a *single user* or *aggregate speed in a network*?

- Wider channels



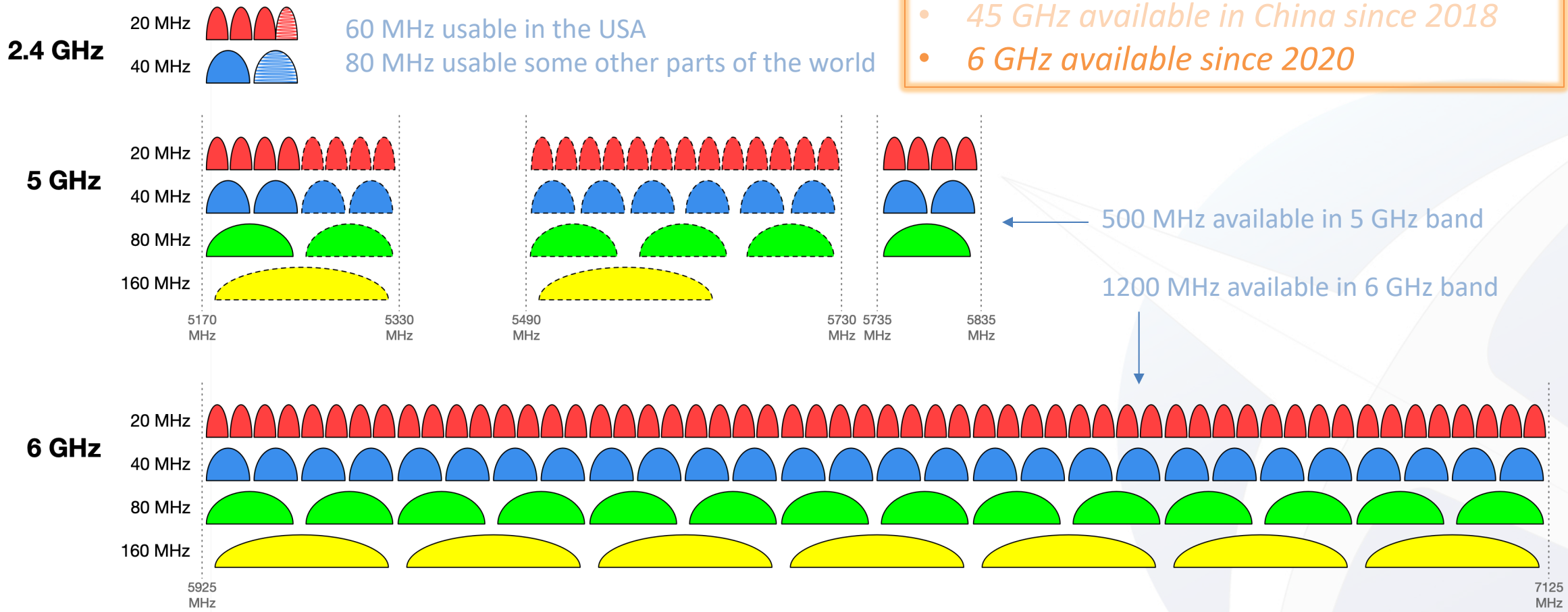
  - Effect is ***multiplicative*** (if you can use it)
  - 2x channel bandwidth ➔ 2x bits/second (all else being equal)
  - Limited in 2.4 GHz spectrum (not enough bandwidth to begin with)

How to Increase Speed? (2)

- More frequency spectra …

Brief History:

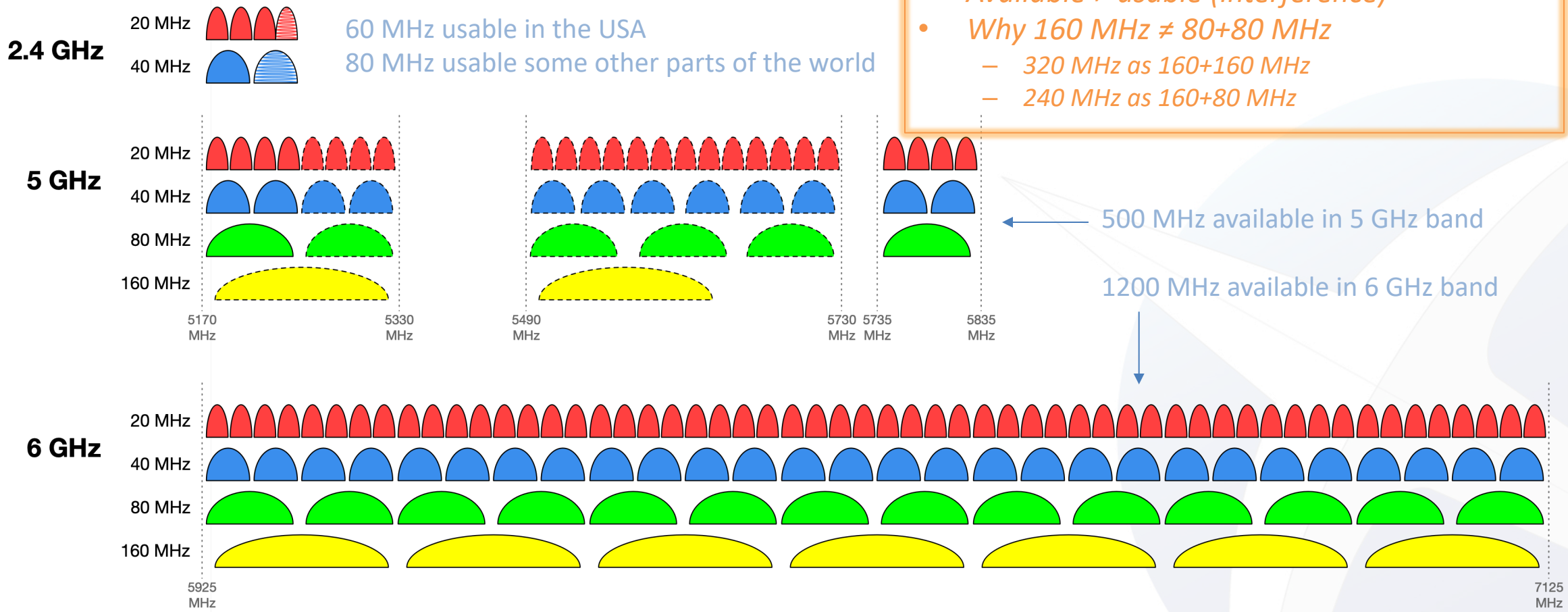
- *2.4 GHz available since 1997*
- *5 GHz available since 1999*
- *60 GHz available since 2012*
- *45 GHz available in China since 2018*
- *6 GHz available since 2020*



Not shown: sub-1GHz, licensed bands, 45 GHz, 60 GHz. Graphics not drawn to scale.

How to Increase Speed? (3)

- More frequency spectra …



60 MHz usable in the USA
80 MHz usable some other parts of the world

500 MHz available in 5 GHz band

1200 MHz available in 6 GHz band

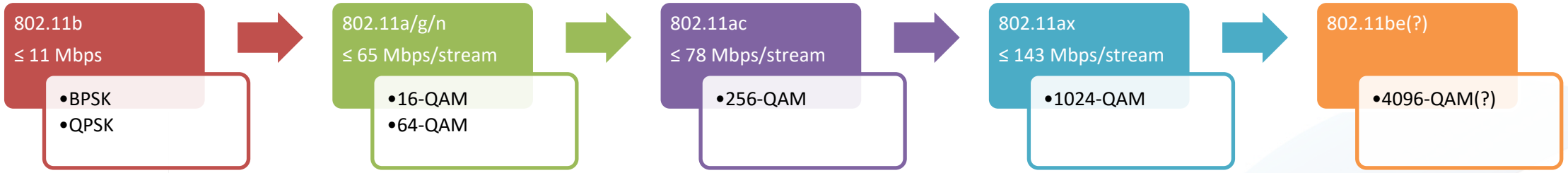
Complications with "more spectra" …

- *Depend on regulatory bodies (e.g., FCC)*
- *Demand on hardware*
  - ➔ *material cost, power, form factor …*
- *Available ≠ usable (interference)*
- *Why 160 MHz ≠ 80+80 MHz*
  - *320 MHz as 160+160 MHz*
  - *240 MHz as 160+80 MHz*

Not shown: sub-1GHz, licensed bands, 45 GHz, 60 GHz. Graphics not drawn to scale.

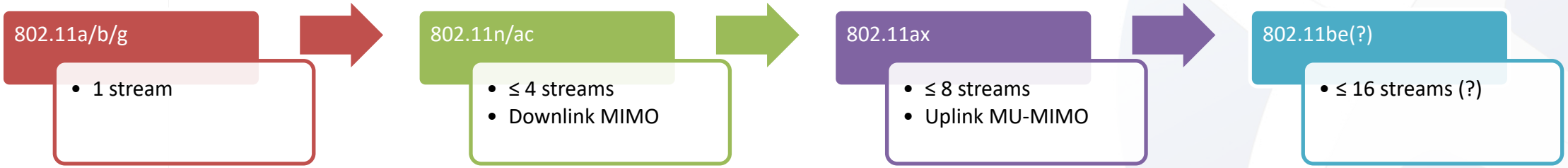
How to Increase Speed? (4)

- More sophisticated modulation schemes …



… signal-to-noise ratio permitting

- More spatial streams, MIMO …



… more streams ➔ more hardware

How to Increase Speed? (5)

- More transmit power
  - Spoiler:
    - We already transmit at regulatory maximum for unlicensed spectrum
    - To raise the regulatory maximum involves more than Wi-Fi
  - Special consideration for 6 GHz spectrum:
    - “Low power” for indoor APs
    - “Standard power” meant for outdoor APs requires Automated Frequency Coordination (AFC) support

How else to Increase Speed? (6)

- Recall from earlier slide …

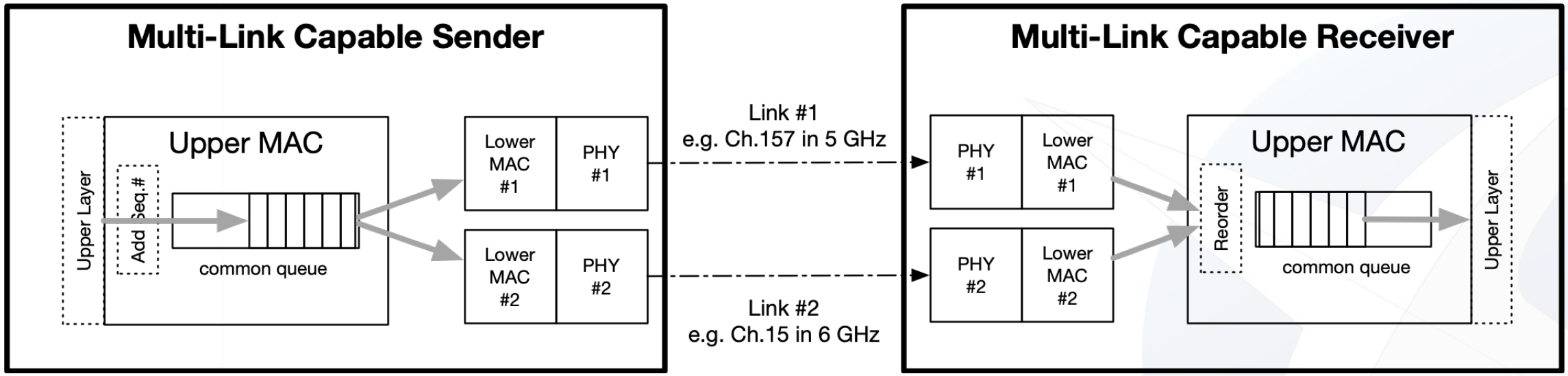
Candidate feature callouts (for .11be):

- 320 MHz channel bandwidth
- Non-contiguous spectrum (efficiency)
- Multi-band, multi-channel aggregation
- 16 stream MIMO
- Multi-AP coordination
- Enhanced link adaptation/ retransmission (e.g., Hybrid ARQ)
- Adaptation for 6 GHz regulatory rules

Multi-Link Operation (MLO)

- Maintain association over multiple channels and/or multiple bands simultaneously
- Can send data for same source-destination pair over multiple channels and/or multiple bands simultaneously
- Each "link" may carry the *same* or *different* data
  - *Different data*: increases aggregate transmission speed
  - *Same data*: lowers error rate (indirectly improves effective *goodput*)
- Opportunistic link selection
  - For time-sensitive application, opportunistically choose the first available link
- Requires substantial architectural change
  - MAC layer split into two
  - "Upper MAC" maintains legacy abstraction for higher layer & performs link selection and aggregation operations
  - "Lower MAC" takes care of legacy-like single-link operation with the PHY

Multi-Link Device (MLD) Operational Concept



Sidebar

Next-Next-Generation Wi-Fi ("Wi-Fi 8"?) (1)

- How to lower latency? (Defer to later half of this presentation.)

- What else are being considered for future Wi-Fi beyond .11be?

  – Candidate features originally called out for consideration for .11be but do not make it into .11be may be reconsidered for "next-next-generation" after .11be

  – What other *big areas* are being considered beyond .11be?

Next-Next-Generation Wi-Fi (2)

- What else are being considered for future Wi-Fi beyond .11be?

Positioning Enhancements	Light Communications	Enhanced Broadcast Services
• Time-of-Arrival (ToA) based positioning • “location guidance to product on a specific shelf” (~decimeter accuracy) • Works in “crowded metro stations and stadiums” environments • “Non-AP … peer-to-peer” • Ref: 802.11az	• Use light waves (800nm~1000nm) for Wi-Fi communications • ≥ 10 Mb/s single link throughput • Solid state light sources • Ref: 802.11bb	• Info announcement systems (e.g., airports, stadiums) • Sensor info collection (e.g., asset tracking) • Non-safety related transportation applications • Multi-media broadcast • Ref: 802.11bc

Next-Next-Generation Wi-Fi (3)

- What else are being considered for future Wi-Fi beyond .11be?

Next-Gen V2X Enhancements

- V2X: “vehicle to everything”
- Updates V2X-related provisions to take advantage of PHY/MAC advances since 802.11-2016
- 5.9 GHz & 60 GHz bands
- 2x speed at MAC layer
- Longer range (3 dB lower sensitivity)
- Ref: 802.11bd

WLAN Sensing

- Use channel measurements to “characterize the environment”
- “presence detection”
- “gesture classification”
- Think “motion sensor” using Wi-Fi
- Ref: 802.11bf

Privacy-Related Enhancements

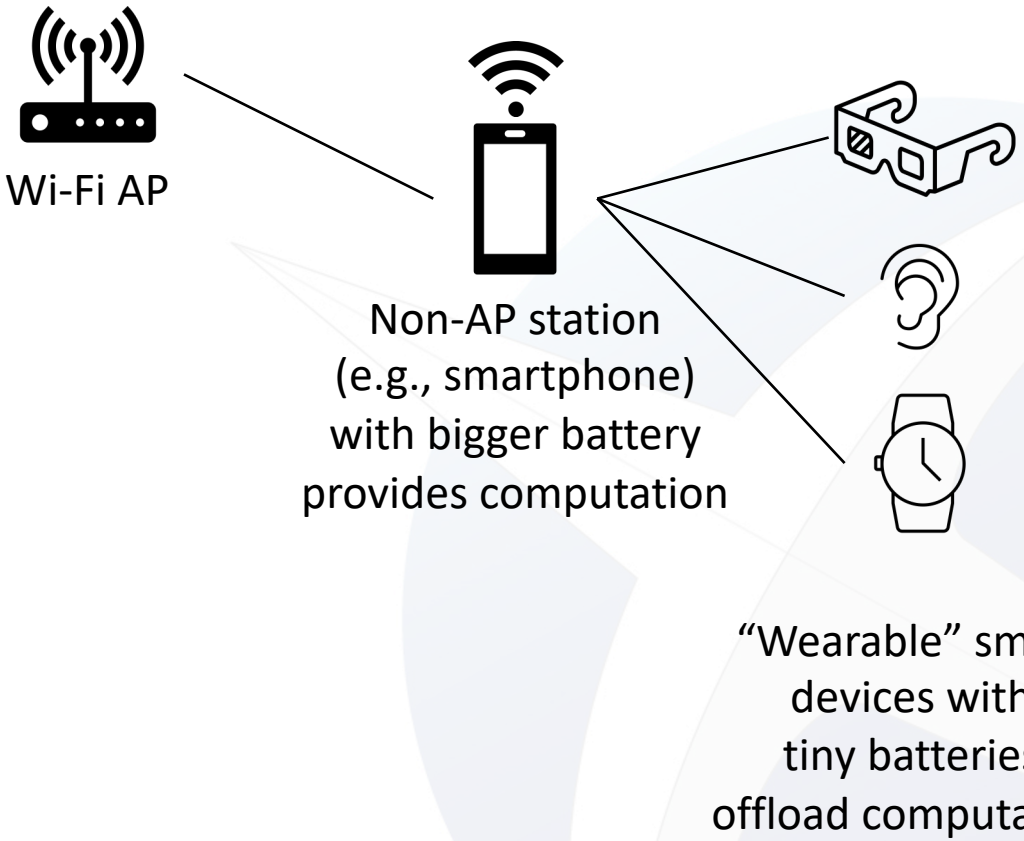
- MAC address randomization
- Protect users from “user tracking” & “user profiling” attacks
- Ref: 802.11bi, 802.11bh
- Also see “***Randomized MAC Addresses***”, presented to IEEE in October 2021, available at bawman.com/PRESENTATIONS/

Next-Next-Generation Wi-Fi (4)

- What else have been suggested for future Wi-Fi beyond .11be?

Direct Link / Tethering for Wearables

- "Wearable" devices have very limited battery capacity
- Allow "wearables" to offload energy-intensive computation to a more generously powered device
- "Wearable" connects to another non-AP station (which provides computing power) which in turn connects to an AP
  - Not "ad-hoc" network in the traditional sense
  - May need very low/predictable latency



Next-Next-Generation Wi-Fi (5)

- What else have been suggested for future Wi-Fi beyond .11be?

Artificial Intelligence / Machine Learning (AI/ML)

- (Not talking about AI/ML-enhanced management of Wi-Fi networks from a centralized controller/cloud – this is already commercially available today)
- Incorporating AI/ML into Wi-Fi stations to improve low-level functions
  - E.g., beam-forming, channel estimation, MU-MIMO resource scheduling

Cryptographic Blockchain

- Incorporate blockchain concepts/ techniques into Wi-Fi
- Examples:
  - Access control: use blockchain to prove existence of user without exposing identity of user
  - Use "proof of work" in place of exponential backoff

Next-Next-Generation Wi-Fi (6)

- Other miscellaneous areas of focus suggested for future Wi-Fi
  - Ultra High Reliability (counterpart to Ultra Low Latency)
  - Business-to-Business use cases
    - Industrial IoT, robotics
  - Wi-Fi to support AI (as opposed to using AI to improve Wi-Fi)
  - Energy efficiency
  - Energy harvesting by IoT devices (from ambient Wi-Fi signal)
  - Public safety driven wireless priority service (WPS)
    - Prioritization by user
    - Support for preemption
  - etc.

BAWMAN

Next-Next-Generation Wi-Fi
from Contention to Scheduled Access

Special Focus:

Time Sensitive Networking (TSN), Ultra Low Latency, Predictable Latency

General Attitude Towards Latency

- Quick definition: What is latency?
  - How long it takes for data to get from sender to intended receiver

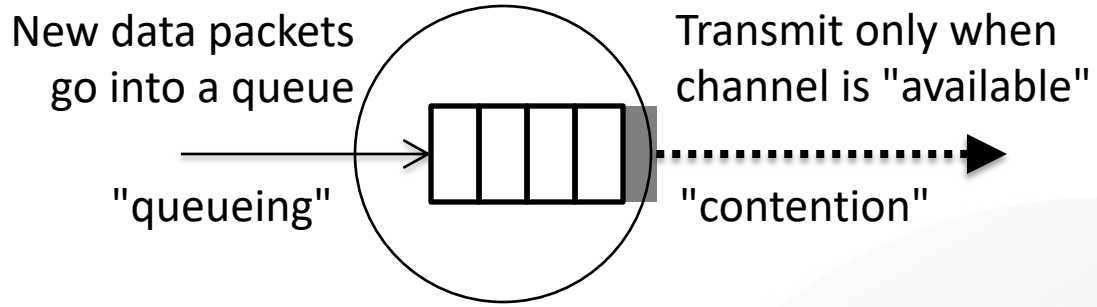
General attitude towards latency:

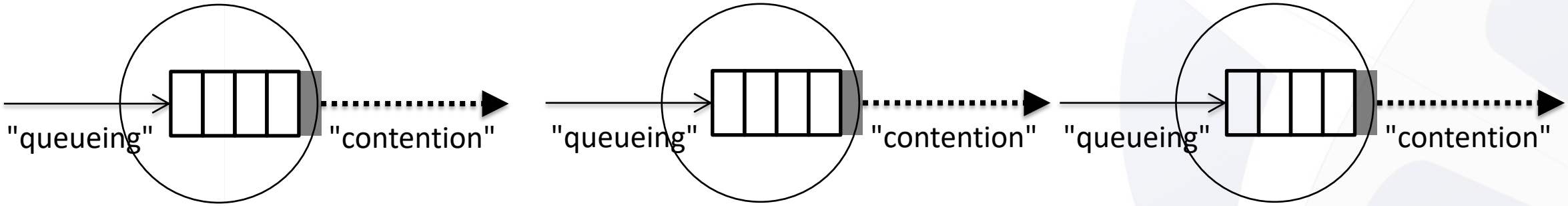
- Reduce latency as much as possible
- Where latency cannot be further reduced

  ➔ try to make it “predictable”

What Contributes to Latency (in a packet network)?

- Queueing delay
- Contention delay
- Multi-hop forwarding:
  - Store-and-Forward delay
  - Each hop adds to every type of delay

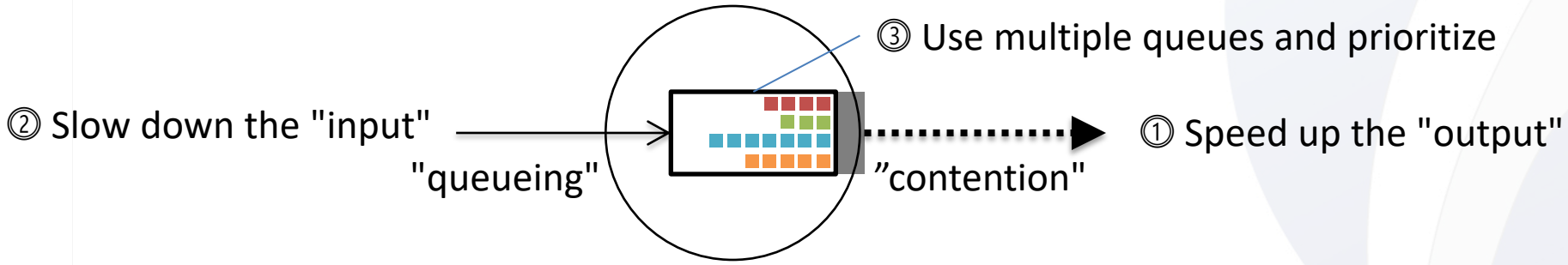




Sidebar

Dealing with Queueing Delay (concept)

- Queue develops when data come in faster than can be sent out
  - Three ways to deal with queueing delay:
    - ① Send data out faster (i.e., increase speed)
    - ② Get the data generator to slow down
      - Or "back pressure" the up-stream node
    - ③ Use multiple queues and prioritize
      - See "***Quality of Service (QoS)***", presented to the IEEE Philadelphia Consultant Network in May 2014, available at bawman.com/PRESENTATIONS/



Dealing with Contention Delay

- When multiple devices want to transmit on the same channel, they have to “take turns”

➔ All devices have to wait, some wait longer than others

Ways to Reduce Contention Delay (1)

- Make more frequencies/channels available for Wi-Fi

  ➔ Spread devices across more frequencies/channels

    ➔ Fewer devices on each channel (statistically)

      ➔ Fewer devices contending to transmit (statistically)

        ➔ Reduce contention wait times for all (statistically)

- *Assumption: Channel bandwidth not reduced*

Ways to Reduce Contention Delay (2)

- How does Wi-Fi "contention" work?
  - Technical acronym: CSMA/CA
    - Carrier Sense Multiple Access/Collision Avoidance
  - Before transmit, check if the channel is being used ("carrier sense")
    - If channel is not being used, transmit
    - Else wait a random amount of time before checking again
      - Exponential backoff … double the random wait time range after each failed check

Ways to Reduce Contention Delay (3)

- Reduce the probability of failed "carrier sense"
  - Statistically reduce the amounts of wait times

- How reduce the probability of failed "carrier sense"?
  - Clear the channel faster
    - Increase speed, finish transmission faster
      - Keep the channels wide
  - Take advantage of Multi-Link Operation (MLO)
    - Having multiple links to choose from improves the odds of finding a clear channel

Store-and-Forward Delay

- Store-and-Forward :
  - Receive an entire packet before sending it towards to the next hop
    - ➔ Have to ***wait*** for the entire packet before sending it out to the next hop
    - *What if we do not wait for the entire packet?*

- Cut-Through Forwarding :
  - Do ***not*** wait for the entire packet before starting forwarding
    - Start forwarding as soon as enough of the header has been received and decoded to determine the next hop
  - Caveats:
    - Incompatible with certain network functions, e.g.,
      - Deep packet inspection, security, content filtering (parental control)
    - Not strictly compliant with certain standards (e.g., 802.3 "Ethernet")

Sidebar

Reliability, Retransmission, and Effective Latency

- Latency is effectively increased when a transmission is corrupted
  - Receiver has to wait for retransmission to get the data
- Reduce error/retransmission ➔ reduce effective latency
  - Can reduce error/retransmission by
    - Using more conservative coding/modulation scheme ➔ lower throughput
    - Add forward error correction info ➔ lower throughput
- Hybrid Automatic Repeat Request (HARQ)
  - Use more aggressive coding/modulation scheme
    - ➔ maintain higher throughput when there is no error (no retransmission needed)
  - Retransmit only the error correction info
    - ➔ reduce the amount of data to be retransmitted when there are errors

From Contention to Scheduled Access

- Reducing latency aside …
- … can we try to make latency more predictable?

- What if we try to move away from "contention" based access and work towards some form of "scheduled" access?
  - What “scheduled access” mechanisms exist within Wi-Fi today?
  - What are the issues/limitations?

Sidebar

802.11ax Multi-User Uplink Capabilities

- A hint of “scheduled access” is implied within 802.11ax’s OFDMA multi-user (MU) uplink (UL) capabilities
  - How do multiple devices “know” they can transmit at the same time?
  - In infrastructure mode, the AP transmits “Trigger” frames to invite multiple devices to simultaneously transmit
    - “Trigger” frame contains information telling each invited device its individualized parameters to use to transmit uplink data
  - MU-RTS/CTS procedure to protect large MU transmissions
- *The above do not constitute a complete “schedules access” solution, but are tools that may be leveraged to achieve “scheduled access”*

Existing “Scheduled Access” Mechanism within Wi-Fi (1)

- Target Wake Time (TWT)
  - introduced in 802.11h, may leverage 802.11ax MU capabilities

- Allow devices and the AP to reach agreement ahead of time on when the devices will next get to receive/transmit data in the future
  - Original intention is to help devices conserve energy
    - Allow devices to "sleep" (go into some form of power-saving mode) and only "wake" when it comes time to receive/transmit data again
    - Meant to accommodate low duty cycle Internet-of-Things (IoT) applications

Target Wake Time (TWT) (1)

- High level TWT basics:
  - Only works in infrastructure mode
    - I.e., there is an Access Point (AP)
  - The AP provides a manner of centralized control for scheduling
  - Works within a Basic Service Set (BSS)
    - Among the AP and devices attached to that AP
  - Two types of TWT agreements
    - **Individual TWT agreements**
    - **Broadcast TWT agreements**
  - Nominally schedule with "microsecond" precision

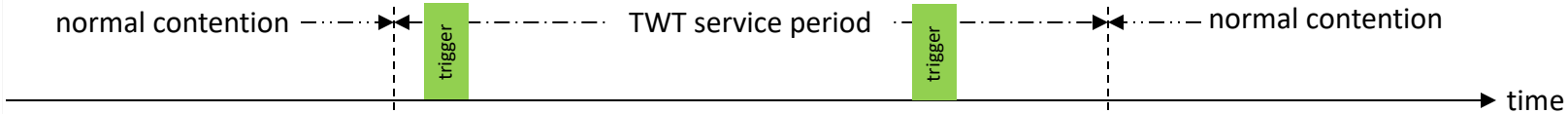
Target Wake Time (TWT) (2)

- **Individual TWT Agreements**
  - A device may ask to make a TWT agreement with the AP just for itself
  - Standard allows a device to have up to 8 TWT agreements at a time
  - A TWT agreement may allow periodic access

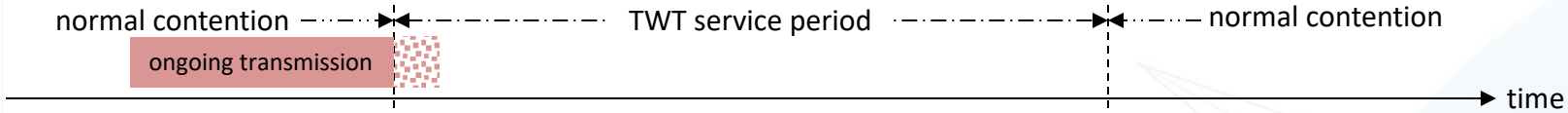
- **Broadcast TWT Agreements**
  - AP can set up TWT agreements for groups of devices
  - Use Beacon frames to convey Broadcast TWT Agreement info
  - Devices can request to participate in an existing Broadcast agreement

Target Wake Time (TWT) (3)

- Can use TWT with other 802.11ax multi-user capabilities



- Further refinement of TWT expected in P802.11be



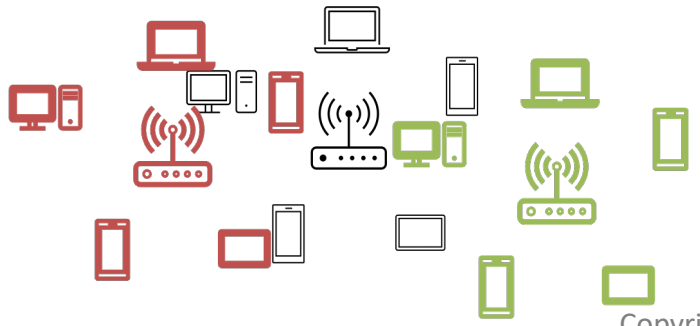
  - **Restricted Target Wake Time (rTWT)**
    - Up to 802.11ax, standard does not prohibit transmissions that started before a TWT service period to end before a TWT service period starts
      - Ongoing transmissions may prevent devices from using their TWT service periods
    - rTWT is meant to correct this oversight
      - Requires devices that implement rTWT to end non-TWT transmissions before the start of the nearest TWT service period

Target Wake Time (TWT) Limitations (1)

- Is TWT/rTWT enough to move away from “Contention”?
  - Answer: NO
  - Standard does not (yet) require the AP to guarantee that its TWT agreements for different devices to not “overlap”
    - In case of overlap, devices may still have to resort to “contention”

Target Wake Time (TWT) Limitations (2)

- Recall we noted in an earlier slide:
  - High level TWT basics:
    - …
    - The AP provides a manner of centralized control for scheduling
    - Works within a Basic Service Set (BSS)
      - Among the AP and devices attached to that AP
    - …



But the real world have many deployments where multiple Basic Service Sets overlap!

Issues & Challenges with “Scheduled Access” (1)

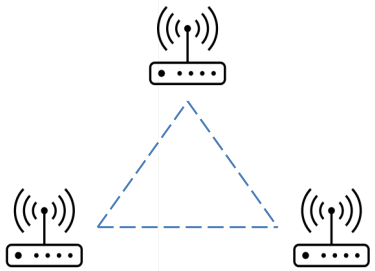
- Cross BSS (multi-AP) coordination
  - How to coordinate access schedules across multiple APs?

- Time synchronization
  - “Scheduling” implies having a common time reference
    - Within one BSS, the AP can provide that common time reference
  - Across multiple Basic Service Sets
    - How to synchronize time across multiple APs?
  - “Microsecond” precision
    - Precision impacts efficiency

Issues & Challenges with “Scheduled Access” (2)

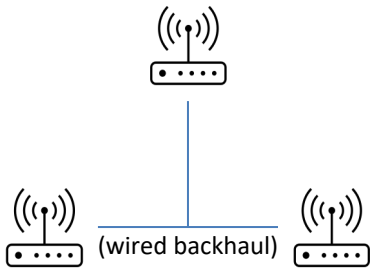
- Three approaches to cross BSS (multi-AP) coordination

Over-the-Air Coordination



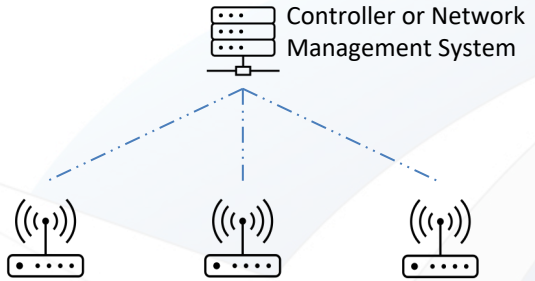
- May be solved within 802.11
- Develop additional provisions to allow multi-AP coordination strictly within Wi-Fi standard

Over-the-Backhaul Coordination



- May be solved within 802
- Security/firewall may be an issue
- Wirelessly overlapping APs may not connect to the same backhaul network
- May be good only for controlled environments

Use Centralized Controller

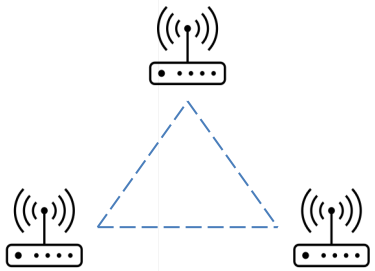


- Out of scope for 802/IEEE
- Proprietary systems like this exist today
- Wirelessly overlapping APs may not connect to the same controller
- May be good only for controlled environments

Issues & Challenges with “Scheduled Access” (3)

- Time synchronization across BSS (multiple APs)

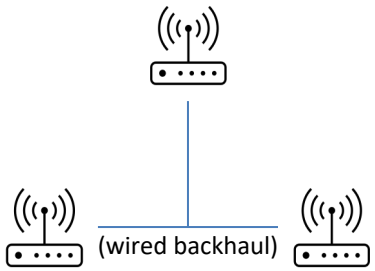
Over-the-Air Sync



- May be solved within 802.11
- Develop additional provisions to allow multi-AP time sync strictly within Wi-Fi standard

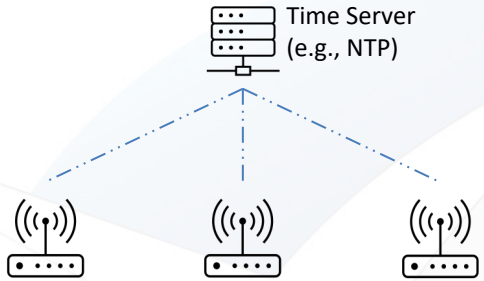
- What about GPS?
  - Expensive hardware
  - No signal in many places

Over-the-Backhaul Sync



- May be solved within 802
- Security/firewall may be an issue
- Wirelessly overlapping APs may not connect to the same backhaul network
- May be good only for controlled environments

Use Time Server(s)



- Out of scope for 802/IEEE
- Wirelessly overlapping APs may not connect to the same time server
- May be good only for controlled environments
- µs precision is hard to do!

Issues & Challenges with “Scheduled Access” (4)

- Legacy devices
  - Older devices may not implement 802.11ax, TWT, or rTWT
  - As administrative policy: AP may be configured to refuse to let devices that lack certain capabilities from joining a network/BSS.

- Legacy APs
  - Older APs may not implement 802.11ax, TWT, or rTWT
  - In controlled environments (e.g., enterprise campuses, certain government buildings), the administrator may ban the deployment of APs that lack certain capabilities
  - In uncontrolled environments, all bets are off

Issues & Challenges with “Scheduled Access” (5)

- Can we block older devices that do not support “scheduled access”?
  - For example:
    - Develop standard provisions that prohibit devices/APs that lack certain capabilities from using certain frequency bands
    - Couple with certification programs to certify devices/APs that implement certain capabilities correctly
  - Cannot be retroactively enforced; only works for new frequency bands to be made available in the future
    - Consumers need to be educated/convinced to use only certified products

Issues & Challenges with “Scheduled Access” (6)

- Unlicensed radio frequencies
  - Used also by non-Wi-Fi devices
  - Even after we solve all the issues with Wi-Fi standard and Wi-Fi product certification programs …
    - Non-Wi-Fi products/appliances using the same unlicensed frequencies can still interfere with TWT service periods

BAWMAN

Next-Next-Generation Wi-Fi
from Contention to Scheduled Access

Thank you!

Questions and Answers, Discussion …