Current Status and Directions of IEEE 802.11be, the Future Wi-Fi 7

DOI 10.1109/ACCESS.2020.2993448, IEEE Access

- For 8K video, Virtual Reality, Augmented Reality, Gaming, Remote Office, and Cloud Computing
- Extreme high throughput (ETH)
- Throughput at MAC more than **40 Gbps** in ≤ 7 GHz channels
- features:
  - forward-compatible physical layer (PHY)
  - scalable sounding
  - Multiple Access Point (Multi-AP) Cooperation
- Many concepts are discussed in this paper not approved yet.

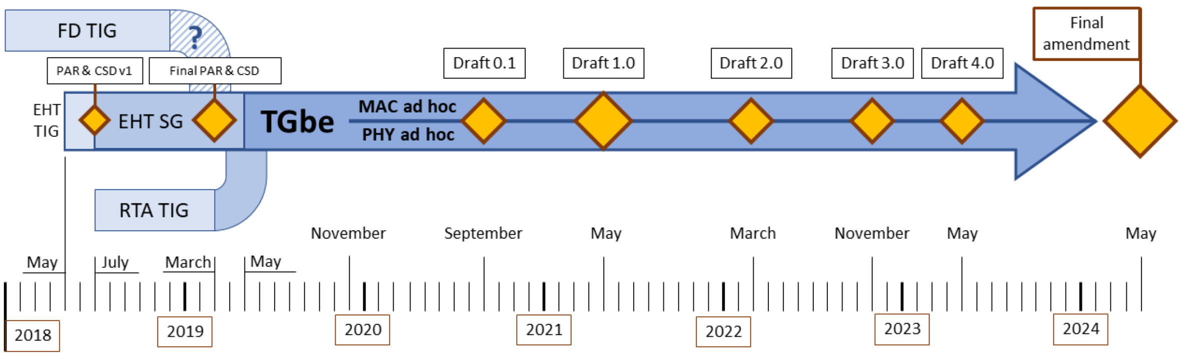
IEEE 802.11BE IN THE WI-FI LANDSCAPE

WI-FI EVOLUTION

- first Wi-Fi standard : 2Mbps, not able to replace 100M ethernet
- 802.11a/b/g: increased data rates up to 54 Mbps, in both 2.4G and 5G
  - OFDM
- Wi-Fi 4(802.11n): data rate up-to 600Mbps,
  - 5/6 coding rate, short GI
  - BW to 40MHz
  - MIMO 4SS
  - MAC: Aggregated MAC Service Data Unit (A-MSDU) and the Aggregated MAC Protocol Data Unit (A-MPDU),
- Wi-Fi 5(802.11ac): 10x increasing
  - 256QAM,160MHz, 8SS
  - DL-MU-MIMO
  - TP up-to 7Gbps
- Wi-Fi 6(802.11ax): improve efficiency of Wi-Fi networks
  - DL-OFDMA
  - UL-MU-MIMO/OFDMA: parameter full controlled by AP, Trigger frame based uplink.
  - 4x symbol duration, shorten GI ratio, reduce overall 10% overhead vs 11ac.
  - +1024-QAM: overall increase 37% efficiency.

- Skeptics(懷疑論者) claim:: focusing on the **quality of operation** and ignoring the **quantity performance** indicators may **slow down** the sales of Wi-Fi 6 devices
- Wi-Fi 7(802.11be):
  - back to increasing the nominal throughput.
  - deals with the Quality of Service (QoS) of RTA

IEEE 802.11BE DEVELOPMENT TIMELINE



- Primary goal: define new features of 802.11 on bands between 1 and 7.125GHz with
- primary objective of increasing **peak throughput** by scaling the PHY of 11ac and 11ax
- Wi-Fi Time-Sensitive Networking (TSN): to support real-time application (RTA) as a part of the activities of the 802.11 Wireless Next Generation Standing Committee
- 802.11 WG agreed to provide support of RTA as a part of the future 11be amendment.
- Parallel ad-hoc discussion group of PHY and MAC features.
- Release1: Y2021
  - 320 MHz, 4K-QAM, obvious OFDMA improvements, multi-link
  - complexity change of phy and mac would postpone to R2
- Consider **Coexistence** with 3GPP technologies of cellular networks operating in the same unlicensed frequency bands
- IEEE 802.11 Coexistence Standing Committee(Coex SC)
  - establish contact with 3GPP to set up synchronous work
  - **no technical solutions** have been approved yet in joint workshop in July 2019 in Vienna.
    - no change each technics to align the concurrency.
  - not clear which of the solutions discussed within Coex SC will become a part of Wi-Fi 7

WI-FI 7 AT A GLANCE

Target / Innovation	Nominal Throughput	Interference Mitigation	Spectrum Effeciency	Real-Time Applications
EHT PHY	4096 QAM, 320 MHz, 16x16 MU-MIMO		EHT Preamble	
EDCA with 802 TSN Features				IEEE 802 TSN, Faster Backoff, New Access Categories, TXOP capturing
Enhanced OFDMA		Preamble puncturing	Multi-RU, Direct links	Enhanced UORA
Multi-link Operation	Multi-link Architecture	Synchronous Channel Access	Virtual BSS	Asynchronous Channel Access, Packet Duplication, Queue Management, Dynamic Link Switching
Channel Sounding Optimization			Implicit Sounding, Explicit Feadback, Channel Estimation	
Advanced PHY	Full Duplex		HARQ, NOMA / SOMA	
Multi-AP Cooperation		Null steering, Co-OFDMA, CSR	Distributed MU-MIMO, Multi-AP Sounding	Joint Reception

1. EHT PHY
    - 2x BW and nSS in MU-MIMO => 4x increasing
    - 4K-QAM => 20% increasing
    - overall 4.8x increasing vs Wi-Fi 6, i.e. $9.6 \times 4.8 \approx 46$Gbps
    - generalization of PHY headers and developing a **forward-compatible** frame format.
2. EDCA with 802 TSN Features
    - TGbe examines the main findings of IEEE 802 TSN and discusses how to improve EDCA
3. Enhanced OFDMA
    - Wi-Fi 6 OFDMA drawbacks: reduce spectrum efficiency
        - allows the AP to allocate only one resource unit (RU) of a predetermined size to a client STA
        - not support direct link transmissions
    - Lack of flexibility of the legacy OFDMA
        - degrades performance in dense deployments and increases the latency
    - TGbe addresses these OFDMA challenges
4. Multi-Link Operation
    - native support of the multi-link operation
    - current chip can use multiple link but independent. limited efficiency.
    - novel sync between the links for increasing channel efficiency.
5. Channel Sounding Optimization
    - Huge overhead from high-dimensional CSI feedback
6. Advanced PHY Techniques Improving Spectrum Efficiency
    - HARQ
    - Full-duplex (HD)

    - Non-orthogonal multiple access (NOMA)
    - not clear yet (gain vs complexity)
7. Multi-AP Cooperation
    - fully-distributed coordination between nearby APs
    - cooperation between nearby APs: scheduling, beamforming, distributed MIMO.
    - postponed to Release2
        - due to a level of uncertainty related to more complex approaches

IEEE 802.11BE CANDIDATE FEATURES

ETH PHY

4K-QAM

- 20% data rate increasing,
- 40dB SNR requirement: too high for typical Wi-Fi.
- Achieved by BF to get 40dB SNR. (many-antennas AP to few-antenna client)

320MHz

- 6GHz Band brings hundreds of MHz available to Wi-Fi.
- double the maximal nominal throughput.
- improves real data-rate for moderate distance
- 160+160/240/160+80
    - the coexistence of neighboring networks

MU-MIMO

- support up-to 16SS across all scheduled STAs
- all SS using the same MCS for complexity consideration
    - although different MCS per SS can gain more capacity.
- need to consider sounding overhead.

PHY Frame Format

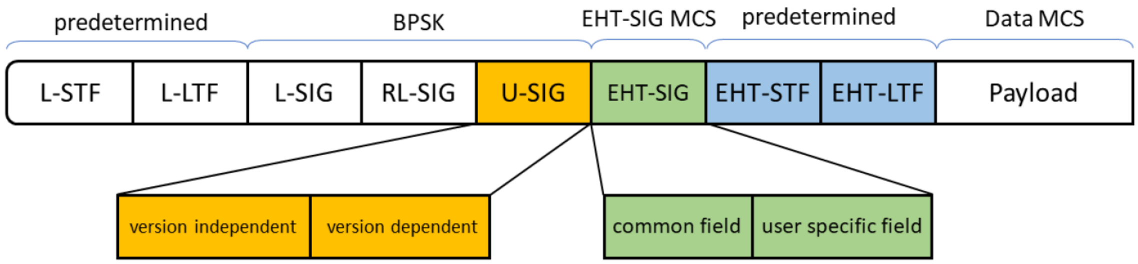
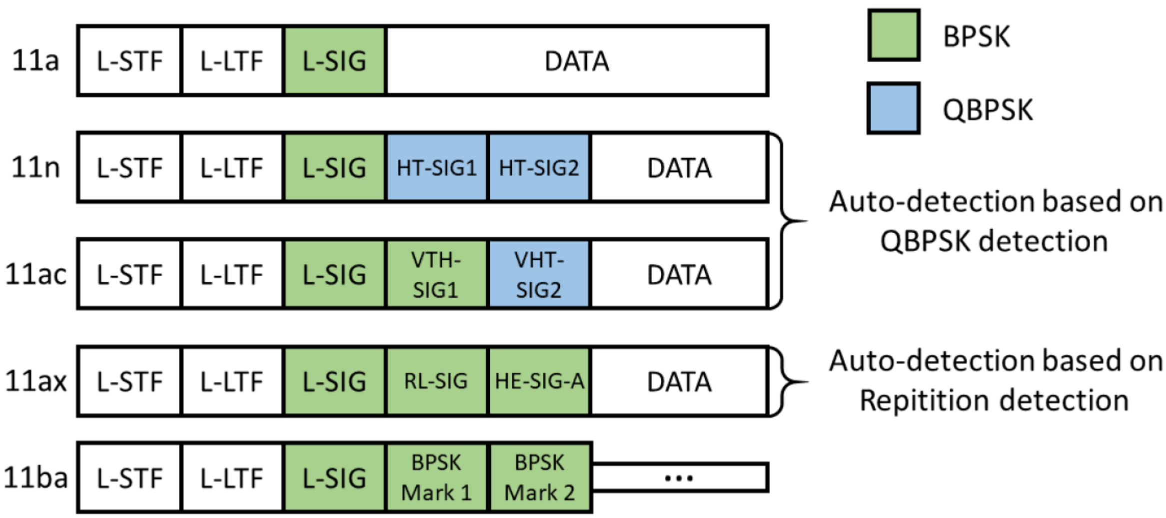


Figure 2. The EHT frame format.

- Auto detection



- 11be and beyond amendments format define:
  - the L-SIG length divisible by 3
  - stop implicit frame-format indication.
  - U-SIG:
    - two-OFDM-symbol long universal SIG
    - forward compatibility indication.
    - version independent information + version dependent information
    - version-independent contains: 3-bit phy indicator, 1bit UL/DL, BSS color, TXOP, bandwidth
    - version-dependent: LTF symbols, mid-amble periodicity, and STBC flag, and some information for 11be features.
- EHT-SIG field consists of the **common field** and a **user-specific** field
  - common field : MCS, nSS, coding, GI, RU allocation
  - user-specific: MU frames, information for individual STA.
  - Trigger frame itself not contain ETH-SIG.
- ETH STF/LTF for fine time and Fo estimation when MIMO/OFDMA is used.
- The phase of every 20 MHz copy is rotated to reduce PAPR
  - including the puncture pattern of the preamble.

Open Issues of the EHT PHY

- Sounding overhead
- Flexible OFDMA for wider 320MHz channel to handle frequency selectivity and interferences.
- long preamble for short frame.
- Scheduler algorithm complexity and robustness
  - Multiple antenna/spatial stream gain from advanced scheduler algorithm.
  - requires low computation complexity and high robustness in scenarios of variable interferences.
- Benefit of large number of SS at AP vs small number at STA for different range of AP-STA is still not clear in real application. need evaluate the new phy performance in real cases.

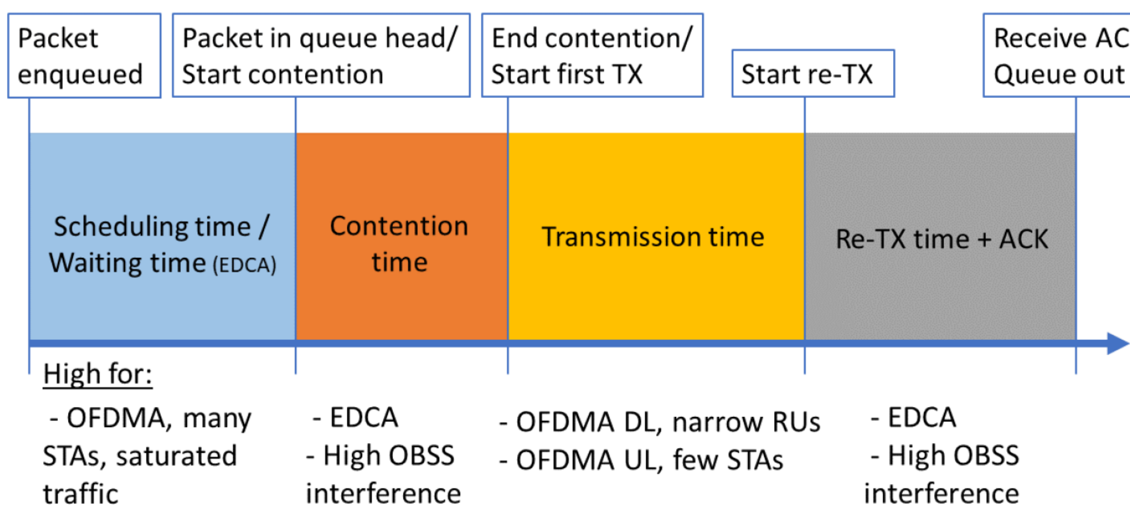
EDCA WITH 802 TSN FEATURES

Lessons from IEEE 802 TSN

- TSN network for Realtime application(RTA)
- TSN solution can not directly be applied in Wi-Fi
  - unreliable communication in unlicensed band and random access.
  - hard to guarantee latency and reliability.
- Un-managed operation scenario:
  - a typical Wi-Fi hot-spot, home or office network.
  - RTA-awareness can improve tp, latency and jitter.
    - but can not guarantee any exact values because overall performance is limited by interference.
- Managed operation scenario
  - factory or enterprise.
  - all BSSs and STAs are managed
  - interference can be controlled
  - network can provide predictable low latency, jitter,and high reliability because of no unmanaged interference.
- Enable RTA in Wi-Fi network:
  - network to detect the type of operation scenario and set relative solution.
  - Stop on-going transmission of a long **delay-tolerant packet** when an **urgent packet** arrives(QoS)
    - if same device, easily to implement.
    - if different device, need to ask the other to stop ongoing traffic.
    - if air is busy, no control packet can be sent explicitly.
  - Solution in ethernet using collection detection: 搶話、插嘴
    - urgent packet device generates a signal to induce collision at the long packet sender.
    - long packet sender stop the traffic when detecting collision.

        - Cannot directly apply in Wi-Fi since device can not sense channel when TX.
            - workaround: sent busy tone in main or separate channel when a device asking to stop transmission.
    - TSN network widely uses scheduled transmission, it improves worst-case latency.
    - Wi-Fi RTA-aware solution
        - implemented with Hybrid Coordination Function Controlled Channel Access(HCFCCA), but heavy and hardly used in practice.
        - 11ax **trigger frame** is used as workaround to allocated periodic time resource for time-sensitive frames.
        - but trigger based still works on CSMA/CA, cannot guarantee AP able to sent trigger frame in congestion environments.
        - no protection with Neighborhood interference.

Latency analysis for EHT



- packet scheduling, channel contention, transmission, retransmission
- Many STA in saturated traffic: high impact on packet scheduling
- Few STA, DL OFDMA : take more on transmission time
    - large RU improves.
- UL OFDMA: TXOP time plays major role.
    - no collision and contention in th scenarios.(which are key latency contributors)
- A shorter trigger frame duration can improve UL latency, but it is not effective in a dense environment

EDCA Improvements

- In RTA support, key performance is the worst-case latency.
    - if small and not frequent RTA, Wi-Fi can achieve without packet loss.
- Wi-Fi bad experience on gaming: suffer lag and high-ping time.

- Simulation example: video streams requires more traffic than gaming, but still keep better quality since video traffic is prioritized over gaming traffic.
- Solved by using existing Alternative Voice (A-VO) AC queue for RTA traffic or new ACs. has been done in 802.11aa

- Persistent channel allocation can reduce worst-case latency.
  - RTA is small and periodic, STA can predict next traffic avail and prepare channel beforehand.
- TGbe discuss to modifications of TXOP rules.
  - AP **temporarily** capture TXOP ownership from any associated STA to deliver RTA traffic.
  - AP grant channel access for RTA demanded STA
  - AP return TXOP to original owner when RTA traffic delivered.

Open Issues of RTA-aware MAC

ENHANCED OFDMA

- New in 11be: Assigning multiple RUs to one STA

Preamble Puncturing

- Introduced in 11ax to release the under-utilization of channel resource
  - not allocated resource in the sub-channel occupied per 20MHz.
  - allow more flexible RU allocation in dense environment.
- 11be enables punctured transmission for **single user frame**
  - exactly design is actively discussed.
- Additional puncture options considered for 6G channel where other incumbent is present.
- New TXOP mechanism for wider channel frames with puncturing.

Multi-RU

- in 11ax, an User can only assigned in a Single RU.
  - waste channel resource/capacity is some scenarios.
- 11be allows assign multiple RUs for a single user.
- Main issue: how to reduce overhead and describe the set of RUs most simple.
- Potential proposal:
  - full information only for the first RU of a set of RUs assigned to a STA
  - rest RUs, the description contains only a reference to the first RU of the set
- Coding and interleaving scheme:
  - if the aggregated size of RUs assigned to a STA is ≤ 80 MHz, **coding and interleaving** shall be done jointly
  - when size exceeds 80 MHz, they shall be done separately for each 80 MHz segment.

- Drawback: implementation and scheduling complexity.
- Proposal limited set of possible combinations.
  - with assumptions of (believe) small/limited gains in frequency diversity
  - divided into two groups : small RU (<20MHz) and large RU(>20MHz), can only combining RUs in the same group.

OFDMA with Direct Link

- Two-hop transmission waste resource from STA to AP to STA if STAs are nearby.
- 802.11e enables the direct link from STA to STA directly.
- TGbe has agreed to design a method of how the AP can dedicate channel resources for direct link operation
  - the exact method is under development
- Extends OFDMA to direct-link can avoid collision between two neighbors STAs.
  - AP allocated dedicates RUs for direct link operation. STA ack in the same RU.
  - Proposed AP sends a trigger frame to initialize the direct link.

OFDMA for RTA

- OFDMA is a powerful tool for supporting delay-sensitive traffic, since AP can centrally manage DL and UL transmission.
- Need enhancement if need extreme low latency traffic.
- DL and UL transmissions are vulnerable(脆弱) to OBSS interference
  - occurs at a random time, causes collisions, and defers channel access
  - made latency increased even in high average SNR.
- Need to focus on following issues:
  - allocate RU for STA, important to know the traffic parameters, such as packet remaining life-time.
  - To improve random access for RTA, it is worth allocating RU for RTA packets only.
    - paper study: modify OFDMA random access so that only the STAs that have RTA UL traffic will transmit in the dedicated RU. Such a modification speeds up the collision resolution process and can increase the number of RTA STAs in the network by 50%

Open issues of OFDMA

- Flexible preamble puncturing made spectrum fragmentation.
- Efficient usage of OFDMA requires to rethink the scheduling policies implemented in Wi-Fi devices
- RUs in a complex structure in Wi-Fi, resource allocation algorithm not straightforward as LTE.
- With more flexible in RU assignment, scheduling problem will become more challenge.
- Resource allocation shall depend on the types of traffic to be delivered.

- Heavy delay-tolerant flows shall be delivered withing the RUs with the highest spectrum efficiency,
- while RTA packets require bounded delays
- 802.11 shall consider the exact required values of the QoS parameters for improve quality of user experiences.

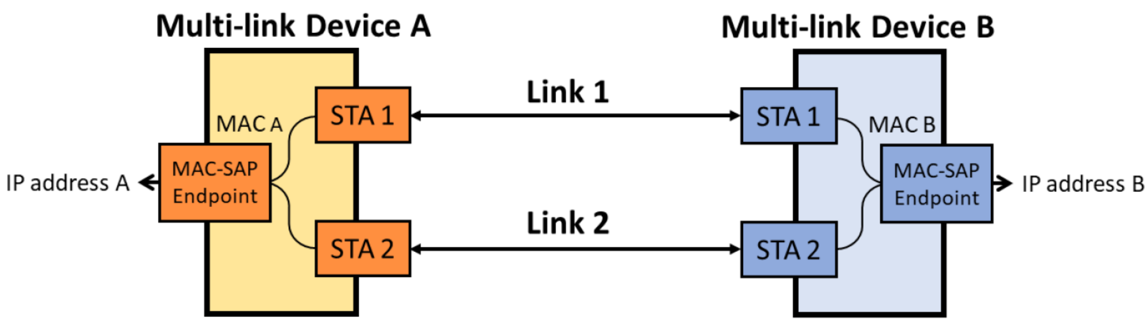
MULTI-LINK OPERATION

Legacy Approaches for Wide Spectrum Usage

- Wider channels are used to enhance throughput and reduce delay.
- not efficient due to
  - all transmission are not full Synchronized
  - channel access controlled by primary 20 band: wide channel will be blocked if primary is busy.
  - wide channels consume more power, it is crucial to mobile device.
  - increase wide channels increase the tone number and PAPR.
  - different property and interference level in the different channels, need different channel access parameter and mechanism.
- Off-the-shelf APs provides Dual- / Tri-band operation, MAC and PHY of various bands work independently and provide multiple independent link to STAs.
- 11Be try to find such a level of synchronization between various link to provide high spectrum efficiency, low delays, and low power consumption.
  - extend multiple band functionality of 11ad/11ay.
  - allow sending packet concurrently in multiple channels.
  - channels occupied in different or same band.
  - multi-link can aggregate various numbers of links with different bandwidth, such as 160+20.

Multi-link Architecture

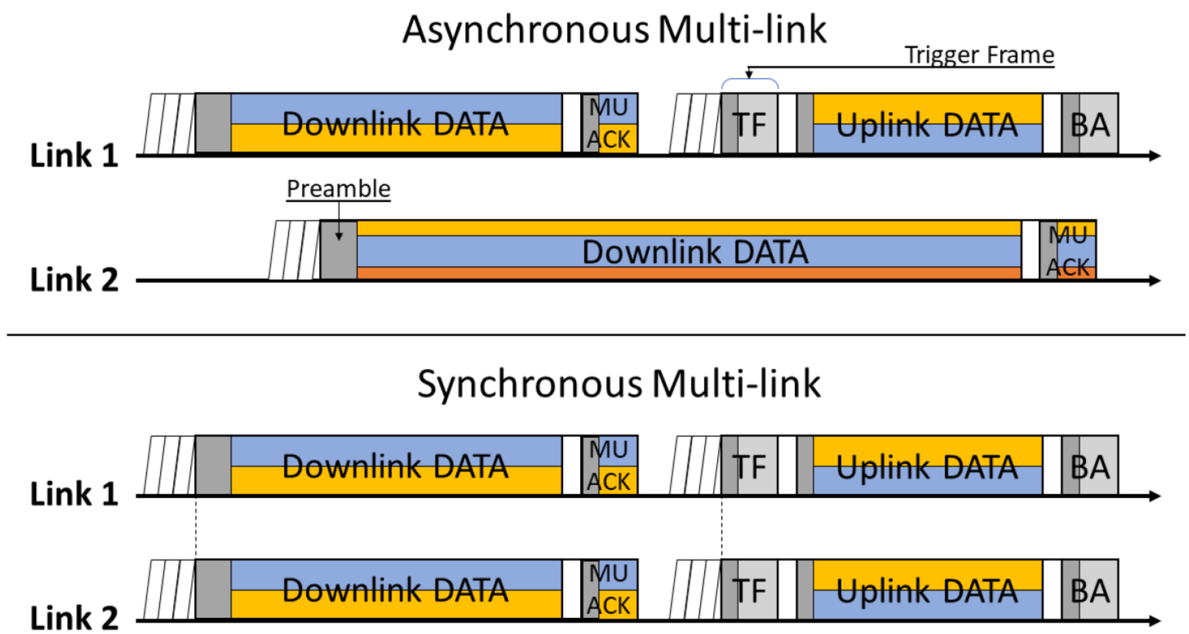
- Multi-Link Device (MLD)
  - consists of several so-called affiliated Wi-Fi devices (multiple phy)
  - single interface to LLC(link-level controller)
  - upper layer consider MLD as single device. Single MAC address.
  - Sequence number generate unique from the same sequence number space.
    - Simplified fragment, package reassembly, duplication detection and dynamic link switching.



- TGBe discuss establish a connection (association, authentication) with MLD on various affiliated devices may occur indecently or jointly.
    - if jointly, all link capability should be explicitly indicated.
- Two operations: **restricted** and **dynamic link switch**
    - restricted mode:
        - data frames and ACKs are bound to one link
        - management frame over one link(power-save, security key, BA…)
    - dynamic link switch mode:
        - multiple links can be used for transmission of the same flow
        - management in one link can apply to the other link.
        - enables load balancing and congestion avoidance, improve peak, reduce latency, overhead, power consumption.
        - this mode requires reconsidering the protocol limitations of the mentioned mechanisms.

Multi-link Channel Access

- Asynchronous transmission:
    - MLD do simultaneously transmission through different bands or the same band.
    - For the same-band operation, when sharing same antenna for affiliated devices, will cause interference between the links.
- Synchronization transmission prevents the interference for co-located antenna in neighboring channels.
- Another proposal: forbidden transmission during the transmission of the intended receiver
    - transmit in one link, can not receive at the other.
    - to receive BA successfully, should stop transmission.

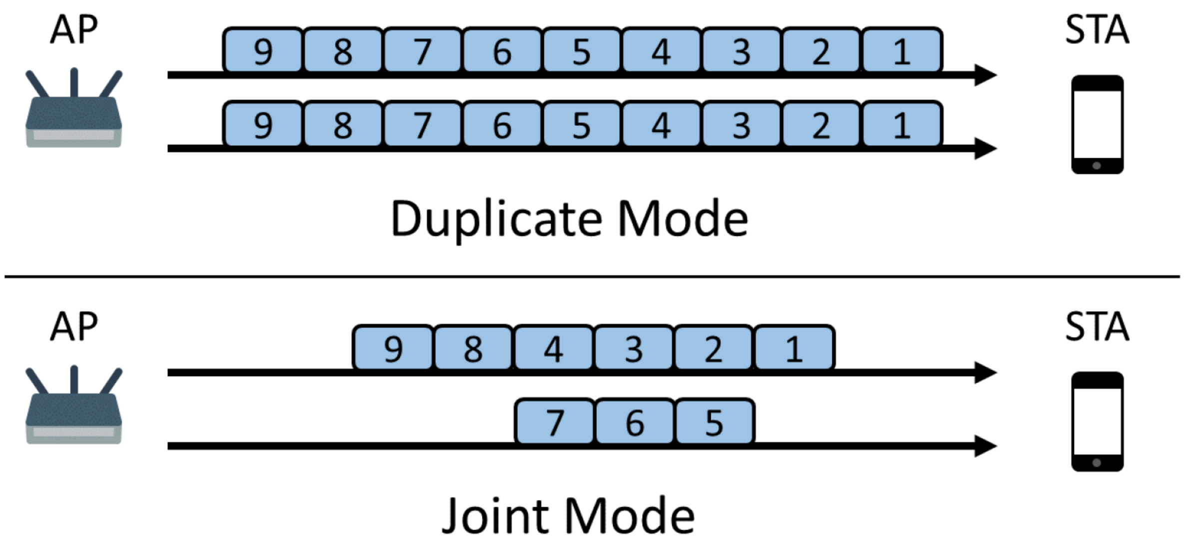


Multi-link Power Save

- At least “two device” in MLD, require good power management especially in mobile device.
- MLD exchange the power management information to each other links.

Multi-link Operation for RTA

- prospective approach to enhanced reliability and reduced latency in TGbe
- Two mode operation in RTA TIG: Duplicate Mode and Joint Mode.
  - Duplicate mode:
    - send copies to multiple links.
    - once one of the link received the data, it drops all of copies to deliver later.
    - Provide robustness transmission.
  - Joint mode: transmitter produces no copies but distributes frames over available links
    - Reduce latency.
- Conditional Packet Duplicated Mode:
  - MLD initially tries to deliver a frame only via one link,
  - if not success, it replicates the packet and deliver it via other links with the **highest** priority



Open Issues of Multi-link

- Many issues from Sync/Async transmission of the MLD.
- Asynchronous Operation: need to enhance the latency and reliability of RTA data.
- Synchronous channel access: organization of sync access is still open.
  - A primary channel: provides rare channel access
  - All links could participate concurrently: has a potential fairness issue
- Need mathematical model to evaluate and optimize their performance in case of finite flows.
- Algorithm of packet distribution among multiple links shall both **minimize channel wasting** and prevent the **head-of-line blocking delay**

CHANNEL SOUNDING OPTIMIZATION

Channel sounding induced overhead

- Channel properties significantly vary with time
- Sounding CSI data increasing by $N_c \times N_r$
- Example of ratio of overhead vs payload data
- Key challenge is to reduce sounding overhead and BF Report(BFR).

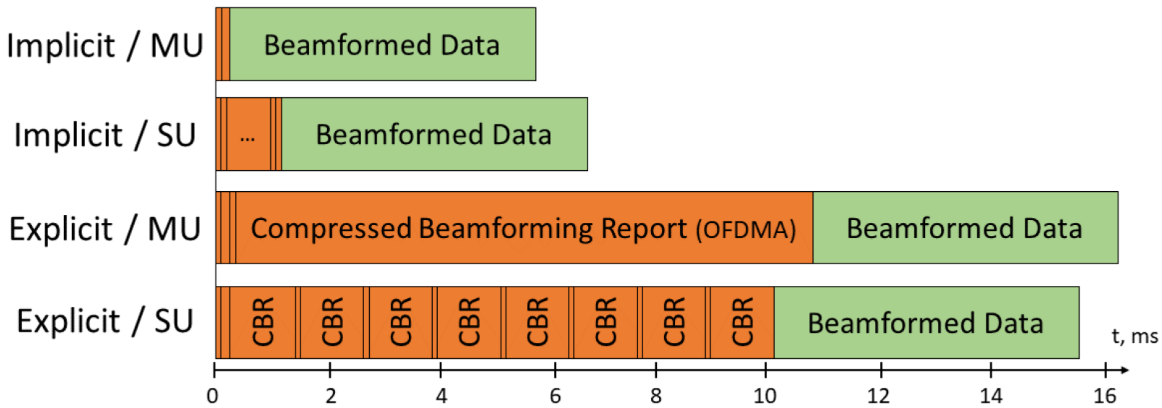


Figure 11. Data transmission vs. sounding and feedback overhead comparison, $N_r = 16$, $N_c = 2$, $N_{users} = 8$ [101].

Sounding Enhancements

- Sounding P matrix for high-dimension
  - Fourier transform bases as baseline.
    - no (±1, ±j)-matrices of sizes 9/11/13/15; and no (±1)-matrices of sizes 9/10/11/13/14/15
  - Large P matrix with Zero entities.
    - make fewer computations at RX.
- Shorten training period: (256us for 16ss)
  - Tone-interleaved sampling
    - a periodic sequence per SS to reduce the training sequence.
    - RX interpolates channel response per SS.
  - Orthogonal Sequence-based Reference Signal(OSRS)
    - groups of tones are orthogonal code for each streams.
    - rx to determinate the response per stream per group.
    - currently OSRS performance worst than tone-interleaving scheme due to cross-stream leakage.

Explicit Feedback Overhead Reduction

- Reduce BFR size.
- wideband precoding: implement a wideband precoder by averaging the channel over all the tones
  - shrinks the feedback information manyfold with some degradation in the accuracy and, consequently, performance
  - in high order MIMO, loss is significant.
- Narrow-band precoding at top of wideband precoding:
  - improve wideband beamforming, still keeps the precoding matrix smaller than per tone-based.
  - use the same basic HW used in legacy Wi-Fi.

    - reduces the overhead by 25-30% with 0.5dB loss and 70% reducing with 1dB loss
- Ignore very small value can furthermore reduce the overhead
    - study in TGnD channel, 20% of response < 1% total power.

Implicit Sounding

- Reintroduce implicit sounding proposed in 11n.
    - not used in off-the-shelf product due to complicated self-calibration procedure.
- Implicit sounding: STA send NDP to AP, AP measures response directly from STA.
    - improve scheduling and spectrum efficiency
    - need to calibrate non reciprocal properties of BB-to-RF and RF-to-BB.
- Self-calibration procedure: AP sent training sequence from reference antenna to the other, and derivate the relative offset/gain of the BB-to-RF .
- Trigger-based implicit sounding:
    - AP starts with a trigger frame requesting for STA UL NDPs
    - STA reply NDPs with orthogonality P matrix or subcarrier interleaving
    - save more than 60% of original airtime.

Open issues of Channel Sounding

- Tradeoff between overhead and the performance with interleaving scheme or OSRS, and the compress scheme.
- Implicit sounding is still debatable:
    - drawback: low performance caused by weak uplink
    - STA may need longer reference signals.
- Implicit sounding procedure in multi-AP operation.

ADVANCED PHY TECHNIQUES IMPROVING SPECTRUM EFFICIENCY

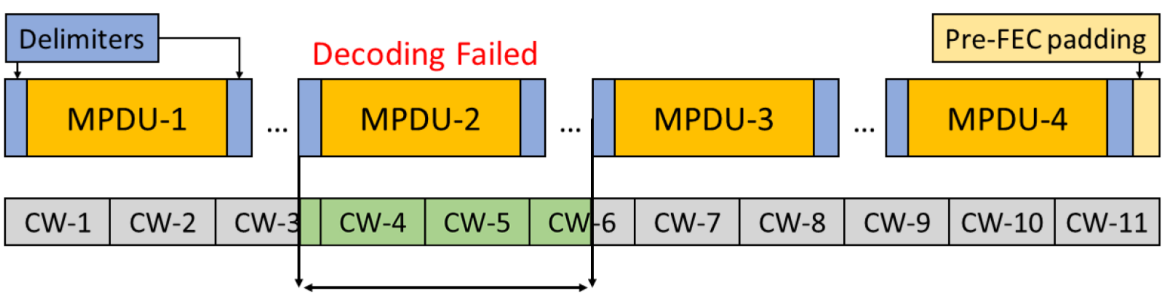
HARQ

- HARQ exploits the information from the previous tries
    - provides more robust to error and allow TX to send a higher QAM opportunistically.
    - avoids reducing MCS for such retries
- HARQ schemes: chase combining (CC), punctured CC, and Incremental redundancy(IR)
    - CC: each retry use the same info. low complexity.
    - punctured CC: TX retransmit a portion of the coded bits, reduce HARQ-induced overhead.
    - IR: every retransmission uses a different set of coded bits, every RX gain extra info. most difficult to implement, most efficient.

- HARQ introduces issues in Wi-Fi system.

Data unit

- Wi-Fi MPDU has check sum. if check failure, repeat whole MPDU.
- HQRQ inherent legacy Wi-Fi MPDU cause many issues:
    - original and re-try carry different informations: retry bit, ciphertext, CRC bits, scramblers… hard to direct combine.
    - if MDPD is encapsulated in AMPDU, LDPC codeword not align to MDPU in AMPDU, How the TX generate the failure MPDU?
        - repeat whole AMPDU ? too much overhead.
    - repeat in damaged FEC codeword :
        - receiver required to identify erroneous codewords at the PHY. Codeword has no check sum.
        - Can use parity bits with MPDU check sum, and request the associated failure codeword with MPDU.
        - need tight MAC-PHY interaction and cause implementation issues.
    - Group several codeword as HARQ block.
        - lower overhead on BA and feedback.
        - incur overhead on MAC padding.
        - HARQ Blocks could contain multiple MPDUs and their fragments: retransmission overhead will be large if a fragmented MPDU fails



Protocol

- Adopting BA mechanism, suits best for MPDU and HARQ Block units
    - feedback overhead is small, but retransmission overhead is large
- BA in codeword level is problematic because of necessary of additional MAC-PHY interaction.
- Codeword-level HARQ can bypass MAC, but need to define new protocol for PHY retransmission.
- HARQ retransmission in new TXOP or original TXOP.
    - in new TXOP, AP need to support many HARQ process. and increasing memory requirement.
    - in original TXOP, HARQ retransmission is limited by TXOP duration. Sender may need to choice long enough TXOP for both transmission and retransmission and cause wasting

resource.

- Multi-link HARQ: retransmission in different channel/link.
- Multi-layer HARQ: mapping codeword and retransmission in different QAM bits by leveraging different reliability of the bits.
    - can improve low SNR reliability.
- Evaluation of codeword puncturing and construction for HARQ is required.
- TGbe discusses introducing additional retry counter for HARQ retransmission attempts.

Implementation issues

- **Memory-hungry technique** : receiver saves log-likelihood ratios (LLRs) for received bits
- HARQ operations shall be done very quickly
    - LDPC is iteration-based solution, new info would shorten the iteration process.
    - codeword-based HARQ, MAC processing shall be accelerated.
- Performance of HARQ in Wi-Fi deployments is still an open issue
    - HARQ benefit in extreme low SNR.
    - the performance of HARQ is not well studied in dense deployments

Full-Duplex

- In-Band FD allows simultaneous UL and DL on the same spectrum
    - maximize spectrum efficiency, shorten latency.
    - collision reduction: DL signal prevents potential hidden nodes from transmitting during UL
    - relax issues for relay-based networks, multi-relay support FD can transmit simultaneously.
    - “Listen while talk”: new version of channel access schemes.
- Hard implement in Wi-Fi(Wireless): rapid channel variations and MIMO
- Successive interference cancellation (SIC):
    - mitigate internal reflections: 15-20dB lower than TX, non-linear components ~ 30-40dB, multipath ~ 50-60dB
    - Analog SIC: cancel strongest path
    - Digital SIC:interference below noise floor.
    - Operate correctly only if the STA knows the figure of its **internal reflections** and **non-linearity**.
        - need to enable calibration procedure.
- Currently, none of the FD solutions received sufficient support within TGbe because of unclear gains in real deployments.

Non-orthogonal Multiple Access

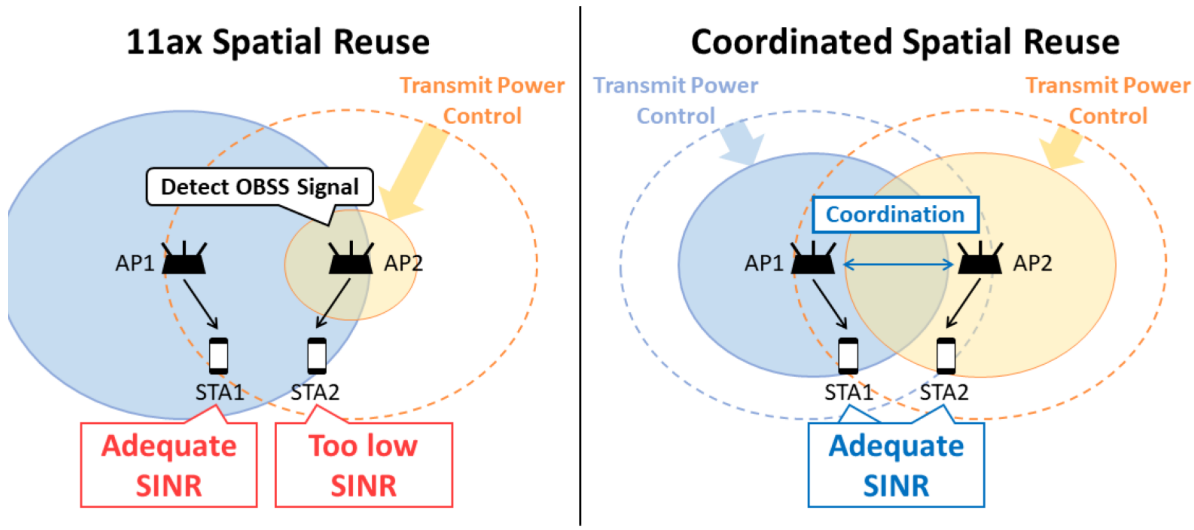
- NOMA to increase peak throughput and improve efficiency
- AP perform NOMA transmissions with the superposition coding

    - the bigger is the power, the more reliable is the component reception
    - two-STA case: the great-power component to a far STA with worse channel conditions, the other component to a near STA.
        - Far STA: composite signal as noise
        - Near STA: perform SIC
- Semi-orthogonal Multiple Access (SOMA): artificially designed gray-mapped superposed constellation
    - low-power signal component more resilient to noise
    - SIC becomes unnecessary, relax complexity.
- Performance gain:
    - in 3GPP $20-30\%$ gain of the feature is already proven in both Link and System Level
    - experimental study of NOMA/SOMA Wi-Fi systems up to 40% gain of the geometric average throughput for two STAs.
- Backward-compatible: the far STA can be legacy !!
- NOMA is complementary to MU-MIMO
    - MU-MIMO: STA in similar attenuation but orthogonal MIMO
    - NOMA: better with the STAs that have **dissimilar attenuation** and correlated channels
- There are plenty of theoretical works dedicated to MU-MIMO and NOMA cooperation.

MULTI-AP COOPERATION

Basic idea

- a paradigm shift from interference mitigation to cooperation between the neighboring APs.
- state-of-the-art enterprise Wi-Fi networks enable seamless roaming between Wi-Fi networks and simplify network configuration
- TGbe discuss to allow multi-AP system, which can have a distributed or centralized coordination
- Two type multi-AP system: Coordinated and Joint
    - Coordinated: systems send/receive each portion of data by a single AP
    - Joint: systems send/receive data by multiple APs
- Coordinated spatial reuse(CSR): an evolution of spatial reuse (SR) system introduced in 802.11ax
    - APs mitigate interference by coop-eratively controlling TX power



- Coordinated OFDMA (Co-OFDMA)
  - allows the APs to coordinate their schedules in time and frequencies
  - Nearby APs can assign the same RUs for some STAs if interfere.
- Null Steering
  - Coordinated beamforming CBF
  - AP perform beams to their STA, target to null its interference to neighboring STAs.
  - Avoid mutual interference nearby network.
  - challenge: acquire CSI from the non-served STAs associated to other APs.
- Joint Transmission and Reception
  - multiple APs to serve the same STA by creating a dynamic distributed MU-MIMO system
  - Highest profit in joint transmission and reception of all multi-AP.
  - Too complicated and has severe requests: high speed backhaul, accurate synchronization.
- Joint transmission and reception methods require joint signal processing at the APs.

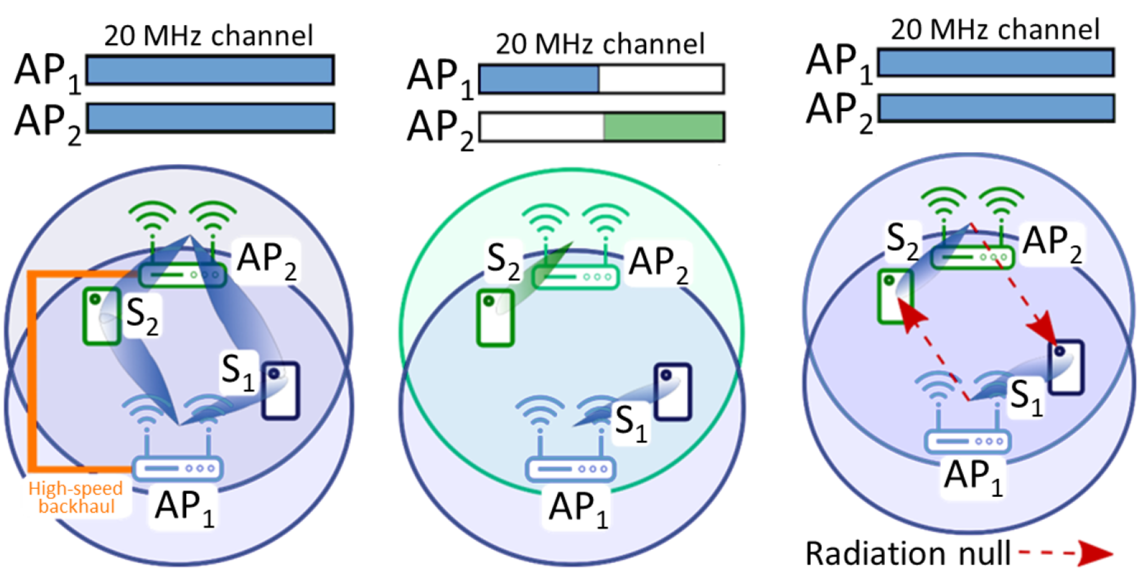
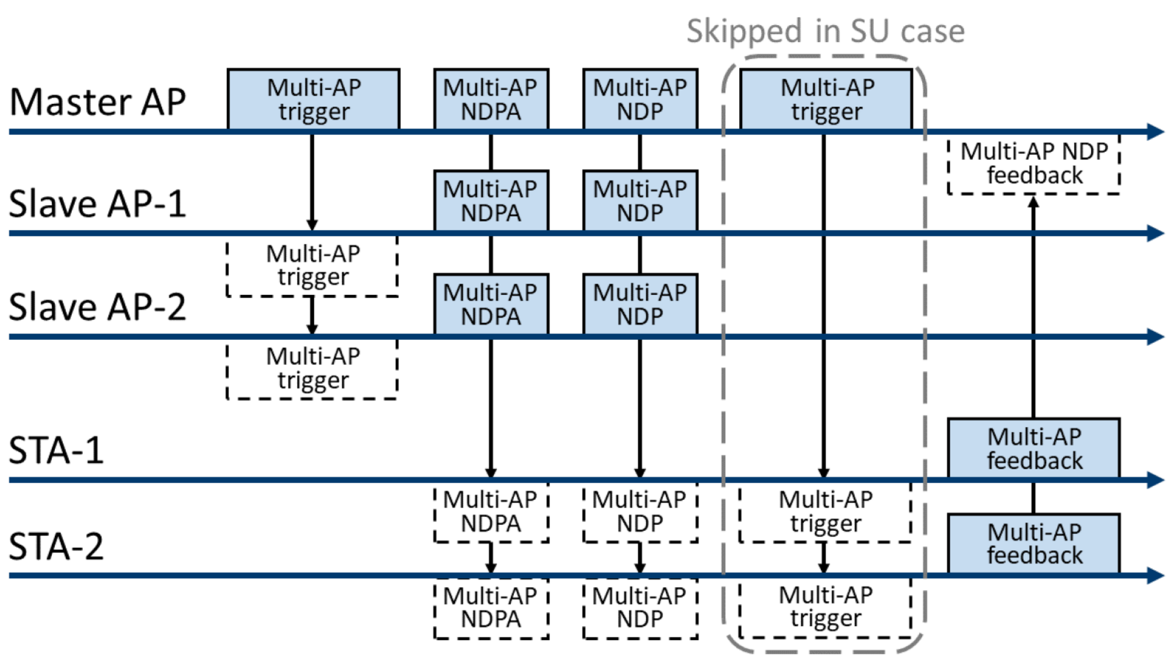


Figure 16. Joint transmission and reception (left), Co-OFDMA (center), Coordinated null steering (right) [160].

- Synchronization Requirements:
  - CSR: frame-level
  - Co-OFDMA: symbol-level timing sync
  - CFB: tight timing and phase sync.
  - JTX: additional the same data for transmission.
  - JRX: exchange signal samples.
  - CSR and Co-OFDMA the most likely to be supported in the TGbe

Sounding

- Multi-AP start with sounding procedure.



- major issue: BFR overhead for high-order MIMO.
  - interleaving scheme.
  - STA not ack for poor channel quality.
- Slave AP selection:
  - master AP select AP tp serve which STA.
  - wrong selection causes **anticipated gain**

Collecting Acknowledgments

- In JTX, APs to synchronize information about the delivery of each frame
  - each AP may listen to all the BAs
  - disseminate information about heard BAs to the rest of APs.
- Simplified approach: one AP to collect Ack and share to the others.

Virtual BSS

- Seamless exchange of frames between a STA and a group of APs without negotiation overhead
- Virtual BSS: All the APs of the set share the association/authentication and can have the same BSS ID
- STA do not need to re-association if it change physical AP serving after associated to virtual BSS.

Implementation Issues

- Coexistence with other network.
- Require tight synchronization.
- Multi-AP assumes that in an enterprise network.
- Multi-AP operation requires advanced scheduling techniques
  - Even in simple Co-OFDMA, the APs need to exchange information about channel resource demands.
- sounding mechanism not been studied for UL
- Centralized/Decentralized Multi-AP scheduling raises the fairness issue.
- JTX/JRX open issues:
  - time/frequency/phase sync.
  - midamble in long packet to reduce the negative effect.