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Behind Wi-Fi’s success story:

Fundamentals, deciphering 802.11ax, and roadmap towards the next generation

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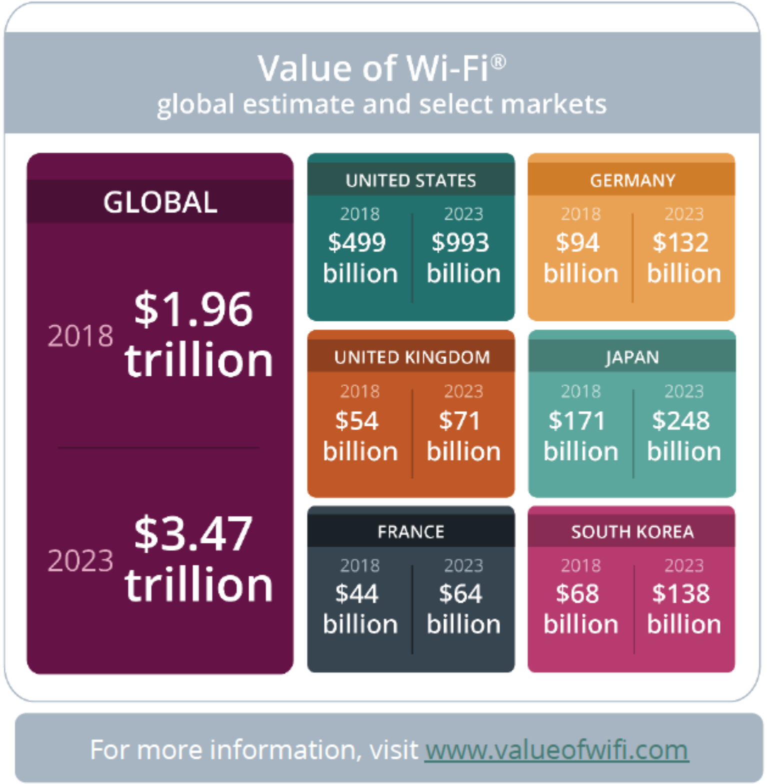
Next Generation Wi-Fi

Advantages

- Free unlicensed spectrum
- No need to involve Mobile Operators to manage and operate indoor private networks.
- Wi-Fi devices are widely diffused, 13 Billions installed
  - grown by 4 Billions only this year

Challenges

- Satisfy next generation requirements
  - higher capacity
  - lower delay
  - more reliability



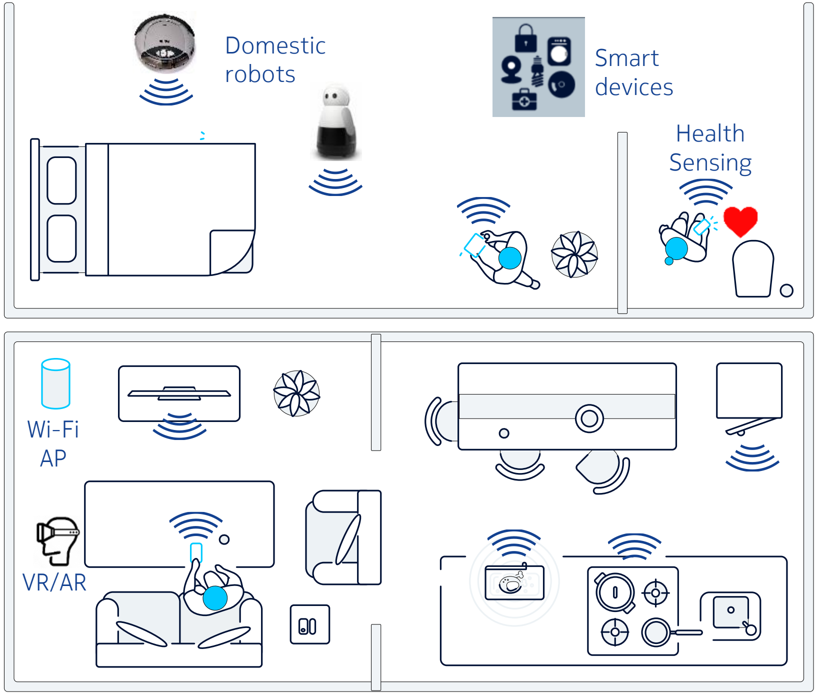
Future Digital Home

A safe space

- Home monitoring
- Security

An automated space

- Energy management
- Home robots
- Anticipate needs



A healthy space

- Health monitoring
- Fall detection
- Aging in place

An augmented reality space

- Professional applications
- Entertainment

Future Enterprise

High Reliability	Ultra-low latency	High capacity
Communication service availability >99.999%	End-to-end transmission latency < 1ms	Average link capacity >1Gbps

Human aware	Seamless integration	Safety & Security
Intelligently adapt and customize access to each individual	Seamless interplay with current industry solutions	No compromises, tailored/optimized solutions

Industrial seminar Outline

1. Fundamentals and state-of-the-art Wi-Fi [60 mins.]

2. Next Generation Wi-Fi, IEEE 802.11be [45 mins.]

3. Performance evaluation [45 mins.]

4. Q&A [15 mins.]

The speakers

David Lopez-Perez

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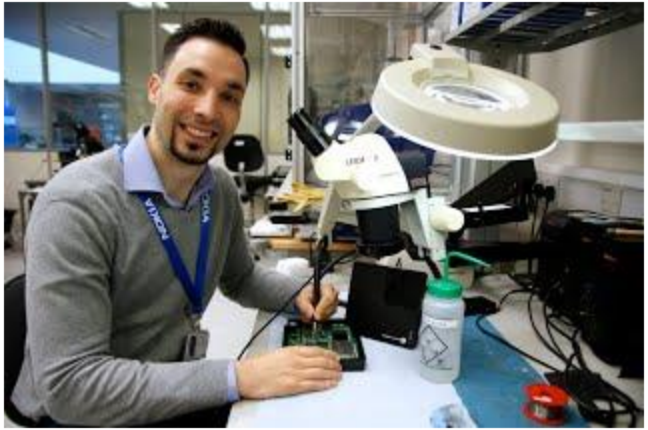
Background

- Distinguished Member of Technical Staff at Nokia Bell Labs (2012-present)
- PostDoc at King's College London, UK (2011-2012)
- PhD from University of Bedfordshire, UK (2011)



Current research

- Future indoor networks and next generation Wi-Fi

About me

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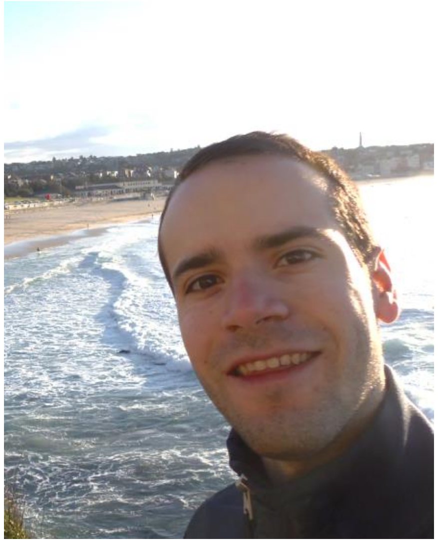
Background

- Research Scientist at Nokia Bell Labs (2016-present)
- PhD from University College London (UCL), UK (2016)

Current research

- Future indoor networks and next generation Wi-Fi
- UAV cellular communications



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Acknowledgments

Collaborators:

- Lorenzo Galati Giordano (Nokia Bell Labs, Ireland)
- Giovanni Geraci (Universitat Pompeu Fabra, Spain)
- Mika Kasslin and Olli Alanen (Nokia Bell Labs, Finland)

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The good old (and new) Wi-Fi

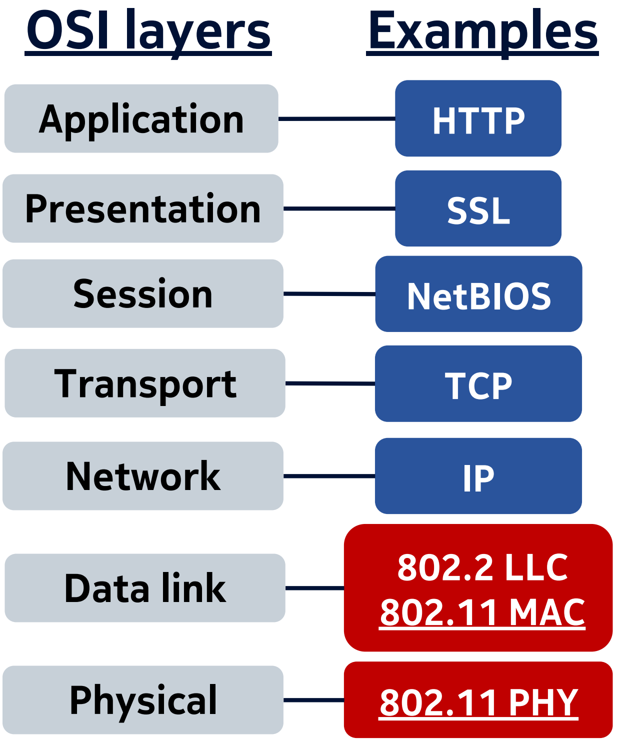
Outline: Fundamentals and state-of-the-art Wi-Fi

- Introduction
- The physical layer (PHY)
- The medium access control layer (MAC)
- Summary
- References

Introduction

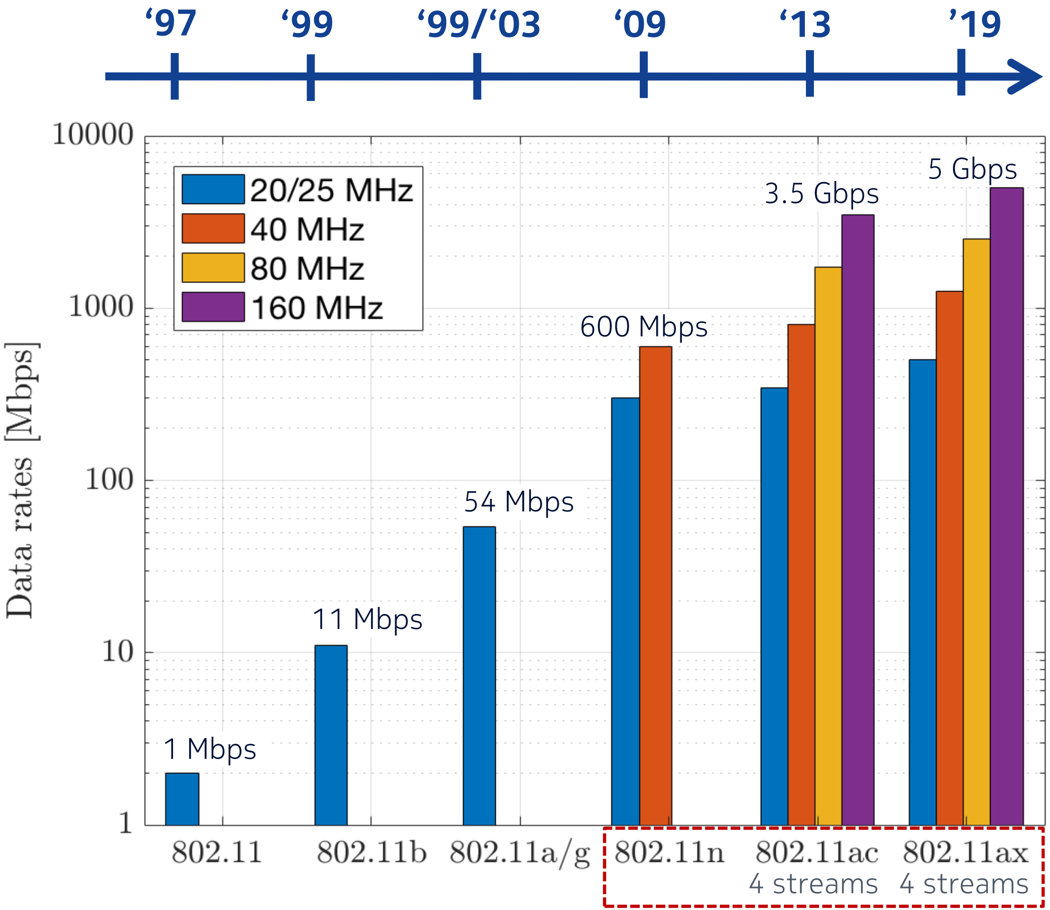
Wi-Fi (802.11) in the communications industry

- More than 13 billion devices are currently in use around the world [1]
- 4 billion Wi-Fi devices are estimated to be shipped in 2019 [1] 1 billion = 10^9
- Widely adopted indoors both for residential and industrial use
- 802.11 standard defines both the MAC and PHY layers [2]



Evolution of Wi-Fi

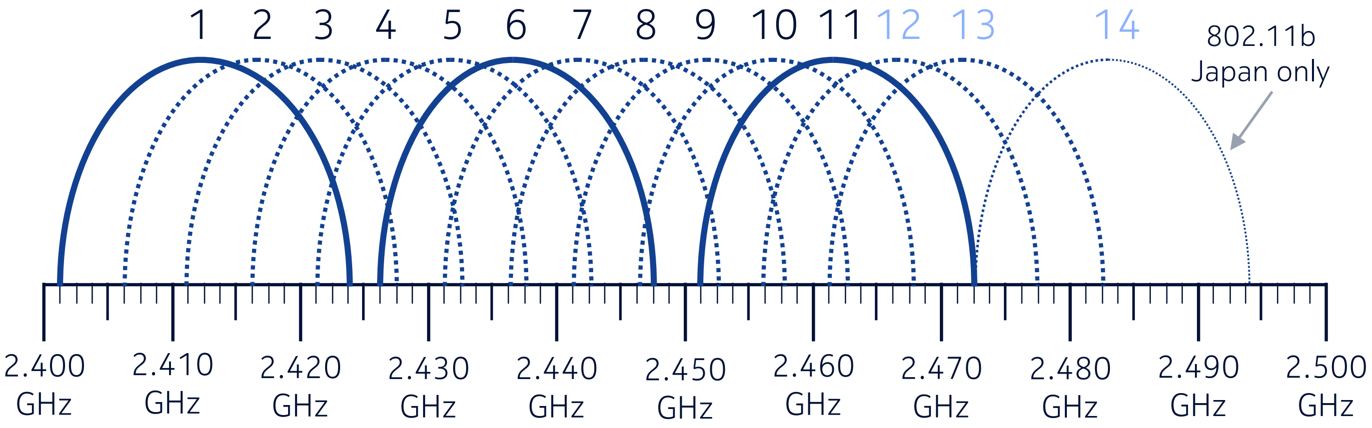
- **802.11n (Wi-Fi 4):**
  - Single-user MIMO
  - Channel bonding
- **802.11ac (Wi-Fi 5):**
  - Multi-user MIMO (Downlink)
- **802.11ax (Wi-Fi 6):**
  - Multi-user MIMO (Uplink)
  - OFDMA



The physical layer (PHY)

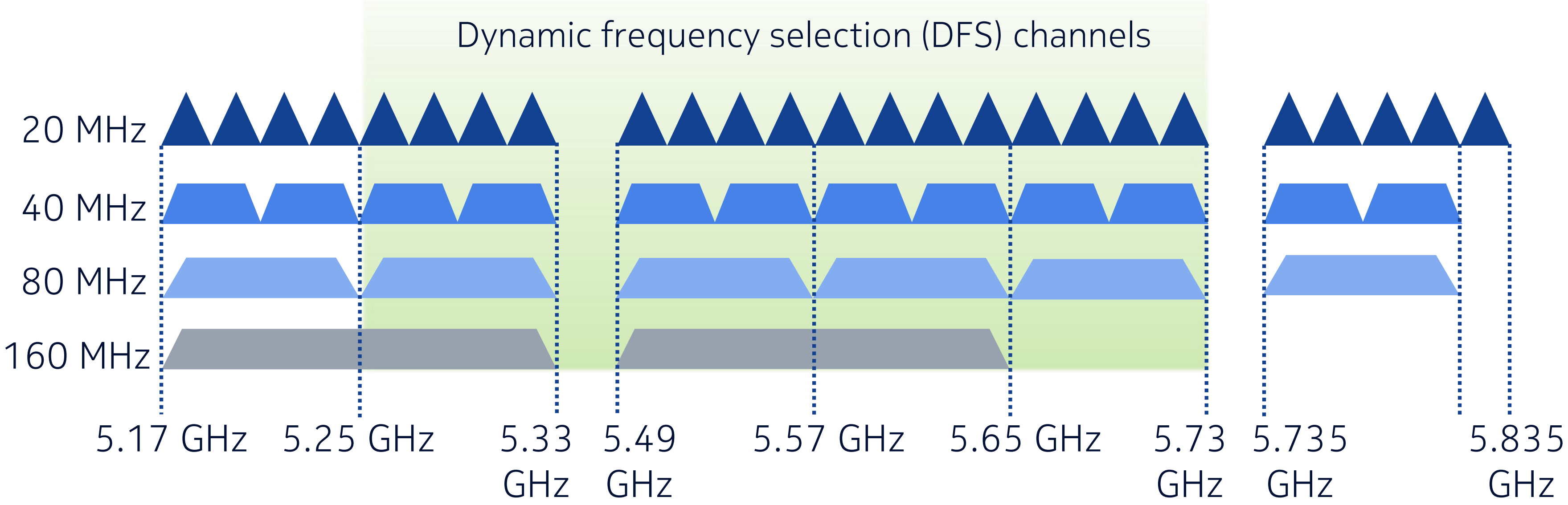
The PHY: Frequency channelization

- 2.4 GHz [3]
  - 11 channels (1-11) of 20 MHz allowed in the US
  - Only three non-overlapping channels (1, 6, and 11)



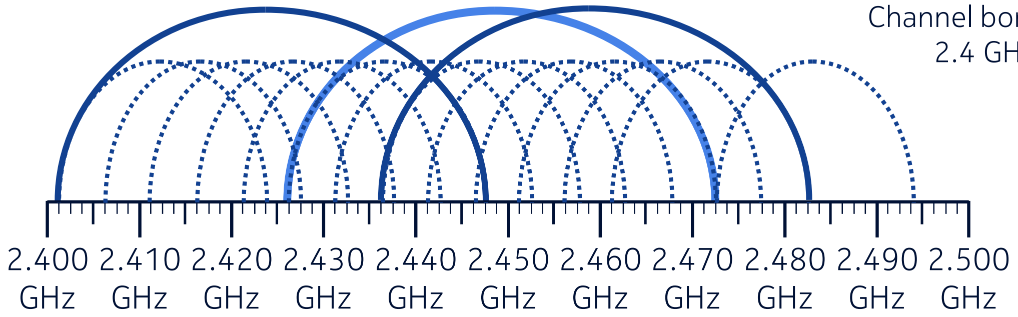
The PHY: Frequency channelization

- 5 GHz [4]
  - 25 channels of 20 MHz over 555 (semi-contiguous) MHz



The PHY: Channel bonding

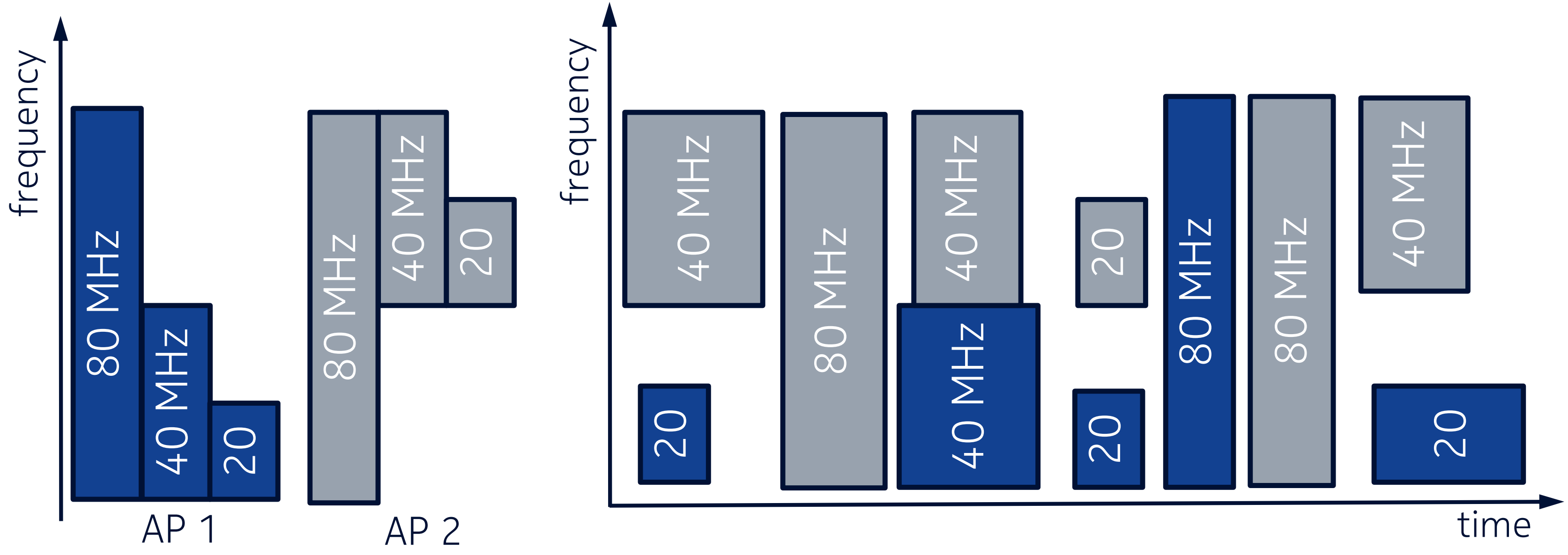
- Channel bonding is only enabled under the standard-specified stringent conditions [5, 6]
- The effectiveness of channel bonding depends on the number of coexisting devices
- Wide channels are comprised of primary and secondary channels [7]



Channel bonding in the 2.4 GHz band

The PHY: Channel bonding

- Multiple access points (APs) can use the same bonded channel with different primary channels [6]



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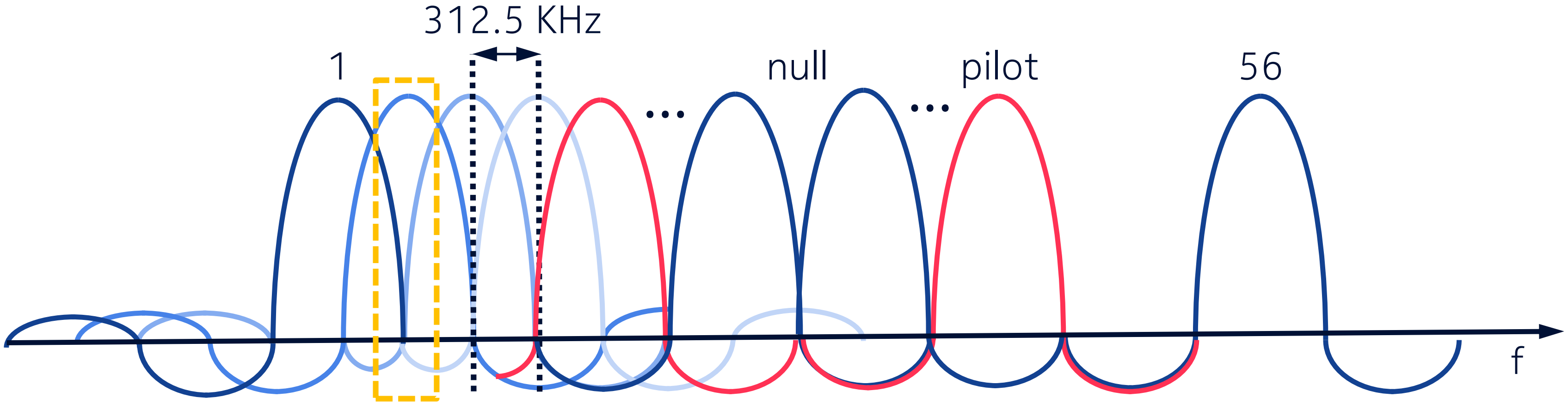
The PHY: Preamble puncturing in 802.11ax

- Current issues with channel bonding:
  - 5 GHz band is not contiguous, have different power requirements, and there might be radars occupying part of the band
  - Legacy 802.11a/n APs operate in a 20 MHz channel, making it difficult to find clear contiguous channels of 80/160 MHz

- Solution: Preamble puncturing [9]

The PHY: OFDM in 802.11a/g/n/ac

- Orthogonal frequency division multiplexing (OFDM) [2]
  - 802.11n/ac have 64 subcarriers per 20 MHz channel:
    - 52 data subcarriers (81% spectral efficiency)
    - 4 pilot subcarriers



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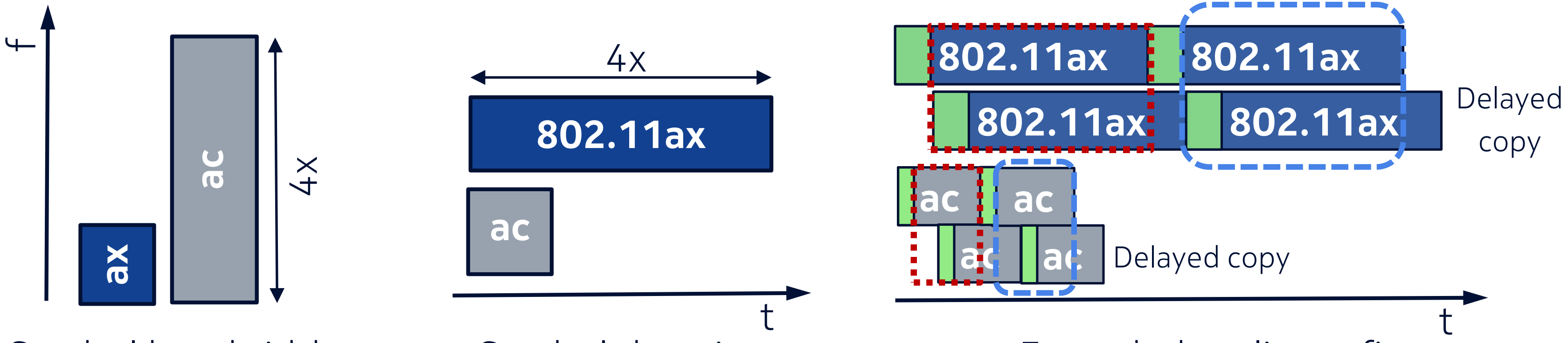
The PHY: OFDM in 802.11ax

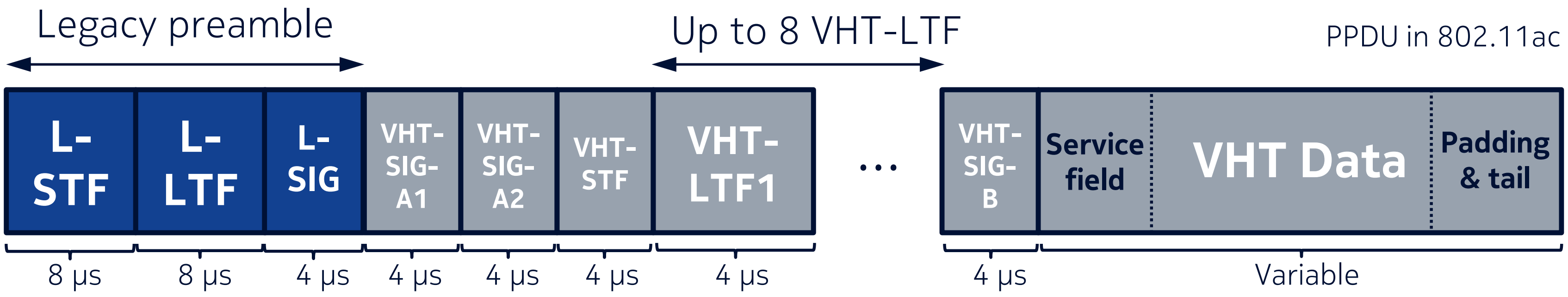
- Orthogonal frequency division multiplexing (OFDM) [9, 10, 14]
  - 802.11ax has 256 subcarriers per 20 MHz channel (234 for data)
  - Extended OFDM guard interval to enhance protection against delay spread in outdoor scenarios: from 0.8μs in 802.11ac to 0.8/1.6/3.2μs in 802.11ax



Symbol bandwidth   Symbol duration   Extended cyclic prefix

The PHY: Definition of new PPDUs

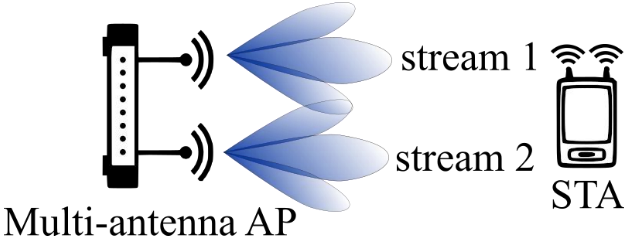
- 802.11a/n/ac/ax: frame structure with the same preamble start [9]



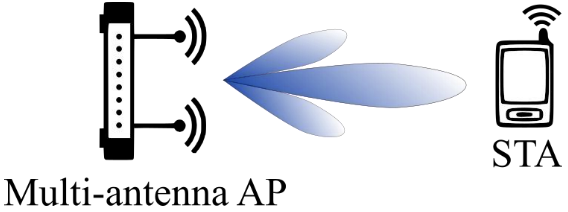
- 802.11ax defines four new PPDUs (PLCP Protocol Data Units) [9, 14]:
  - SU (Single User) PPDU (HE_SU) and HE Extended Range PPDU (HE_EXT_SU)
  - MU (Multi-User) PPDU (HE_MU) and HE Trigger-Based PPDU (HE_Trig)

The PHY: Single-user spatial processing

- Single-user techniques (802.11n/ac/ax) [11]
  - SU-MIMO
    - Up to min (N_{AP}, N_{STA}) streams
    - Only enabled for
      - High SINRs
      - Non-line-of-sight propagation



  - Beamforming
    - Regulations do not allow to focus energy on a given spatial direction [12]



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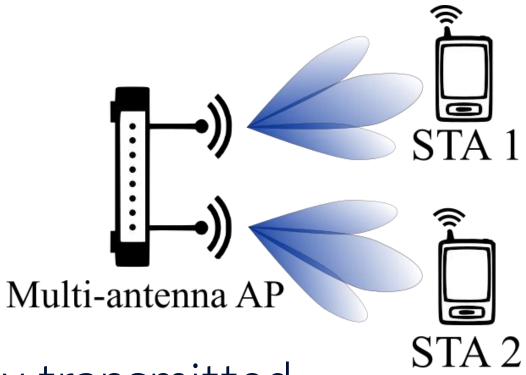
The PHY: Spatial multiplexing

- Multi-user techniques (802.11ac) [10]
  - Downlink MU-MIMO: 802.11ac allows APs to transmit 8 spatial streams simultaneously to 4 devices
  - Optional standard feature
    - Included in second-wave products
  - Current issues:
    - Many STAs are single-antenna
    - STA channel sounding responses are serially transmitted
    - Downlink TCP/IP traffic with uplink ACKs suffers because no uplink MU-MIMO is allowed



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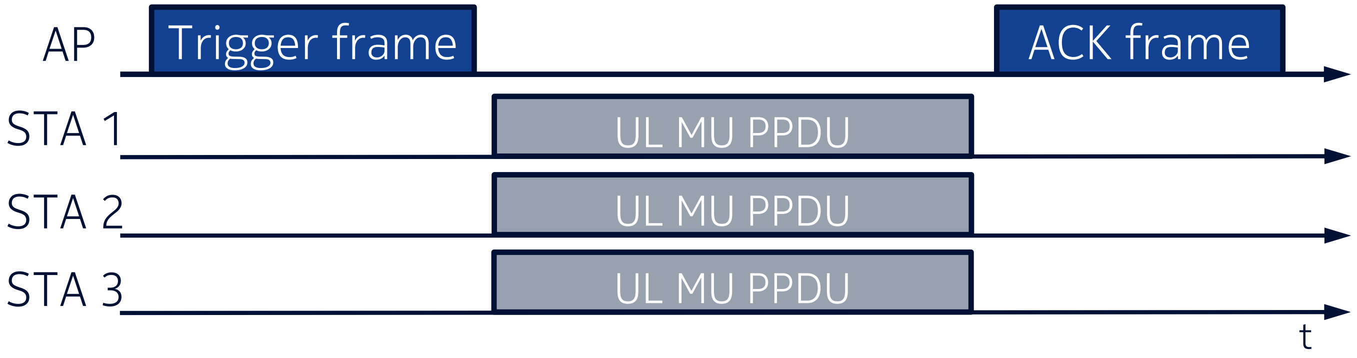
The PHY: Spatial multiplexing

- Multi-user techniques (802.11ax) [10]
  - Downlink and uplink MU-MIMO: 802.11ax allows to transmit 8 spatial streams simultaneously to 8 devices
    - UL MU-MIMO requires UL transmit power control, frequency alignment, and time synchronization



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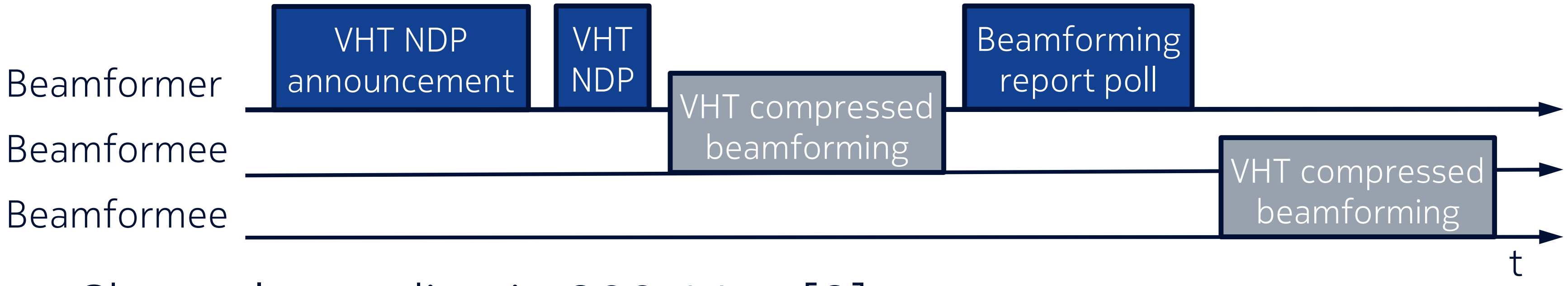
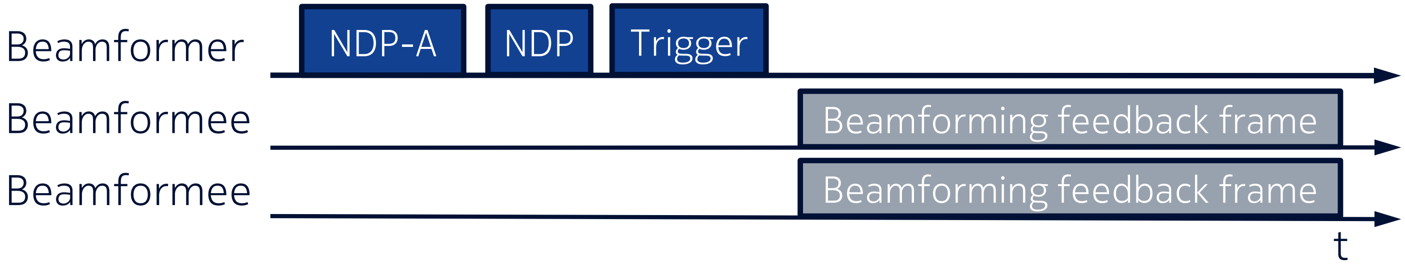
The PHY: Spatial multiplexing

- Channel sounding in 802.11ac [2]



- Channel sounding in 802.11ax [8]



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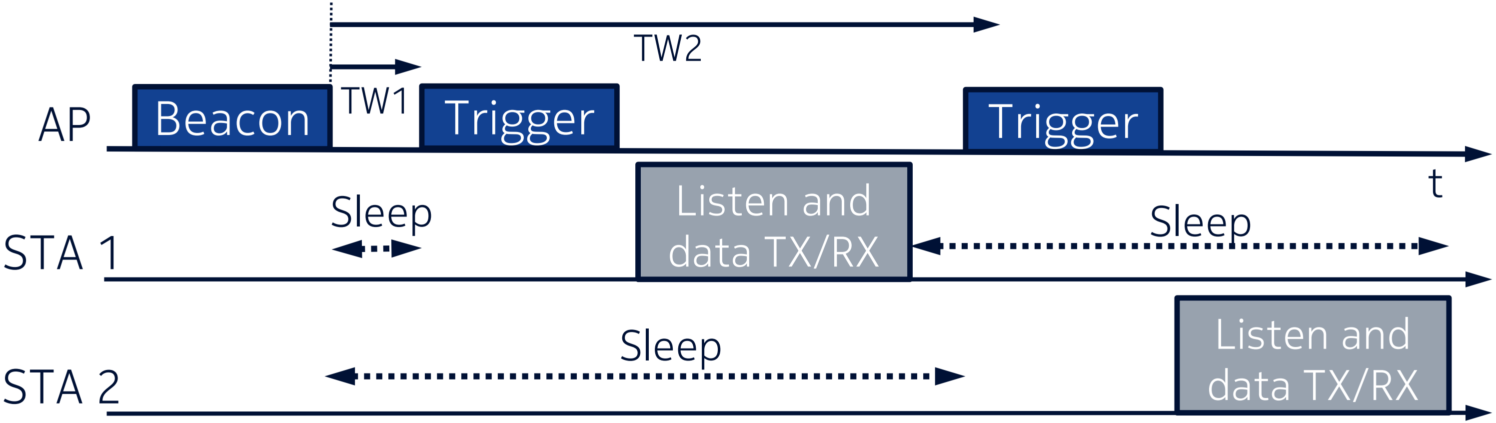
The MAC: Power saving in 802.11ax

- Target wake time (TWT) [9]
  - Both AP and devices agree on a specific time to access the medium. Meanwhile, the devices sleep to save power.
  - Reduces contention between users



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The PHY: Other features

- Forward error coding:
  - Convolutional: Mandatory up to 802.11ac
  - LDPC: Optional (802.11n/ac) and mandatory (802.11ax) [14]
- Modulation:
  - 802.11ax: BPSK, QPSK, 16-QAM, 64-QAM, 256-QAM, 1024-QAM [14]
- 802.11ax:
  - 20 MHz-only clients: Low-power devices
  - Dual carrier modulation: Repeat information in different subcarriers
  - Intra-PPDU power saving: Doze state until the end of selected PPDUs

The medium access control layer (MAC)

The MAC: Distributed coordinated function (DCF)

- Distributed coordination function (DCF) [2]
  - Carrier sense multiple access with collision avoidance (CSMA/CA) where devices only access the medium when free:
    - Physical carrier sense
      - Energy detection: -62 dBm
    - Carrier sense mechanism:
      - PLCP header: -82 dBm
    - Network allocation vector (NAV)
      - 802.11ax: Intra- and inter-cell NAVs

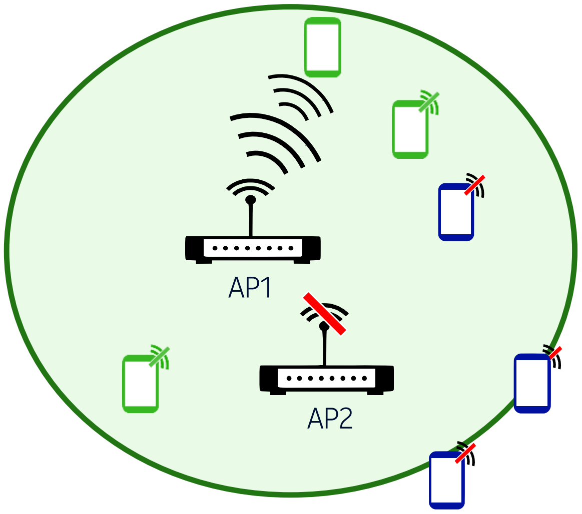

Illustration of the LBT time sharing mechanism

The MAC: Distributed coordinated function (DCF)

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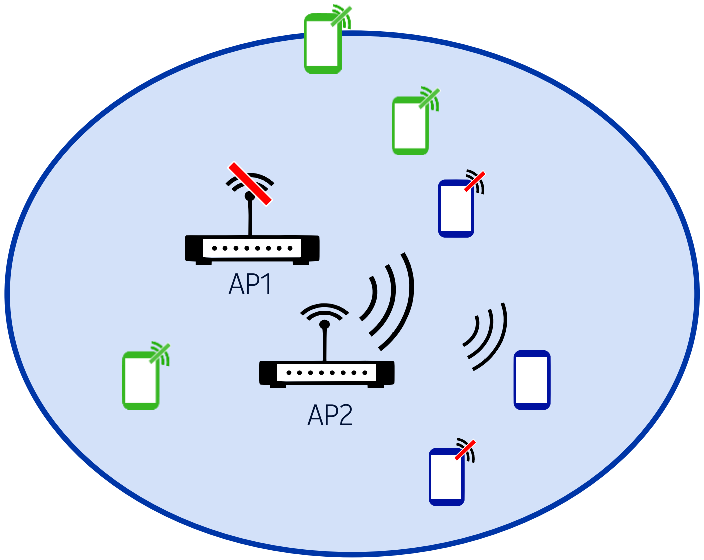
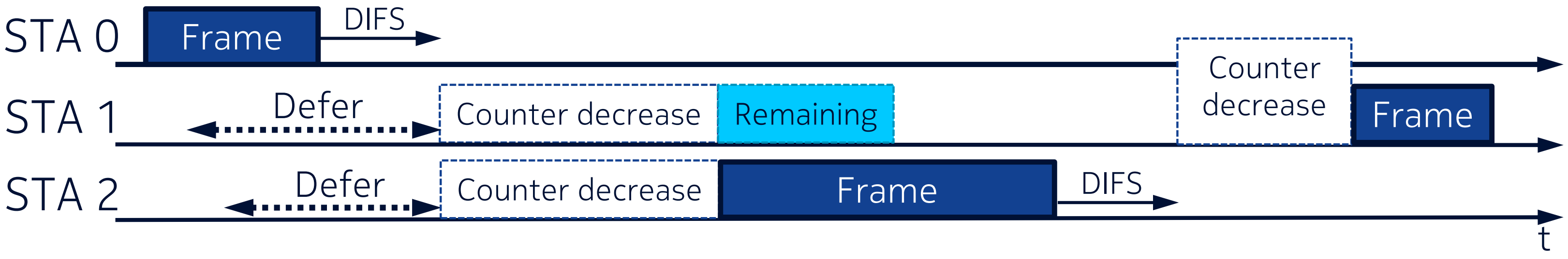


Illustration of the LBT time sharing mechanism

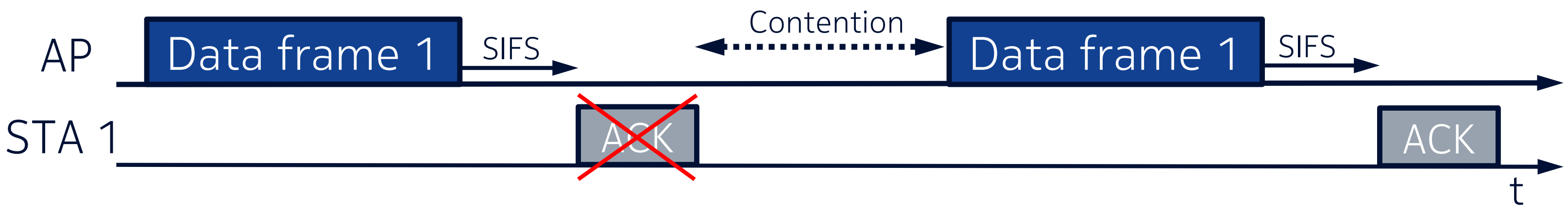
The MAC: Distributed coordinated function (DCF)

- Random backoff procedure [2]
  - Target: Minimize collisions by selecting a random backoff count
  - Random backoff time duration = slot time × $U[0, CW]$
  - Contention window size = $CW = 2^{\{x\}} - 1, x \in \{4, \dots, 10\}$
  - CW doubles after an unsuccessful transmission



The MAC: Data and ACK exchanges

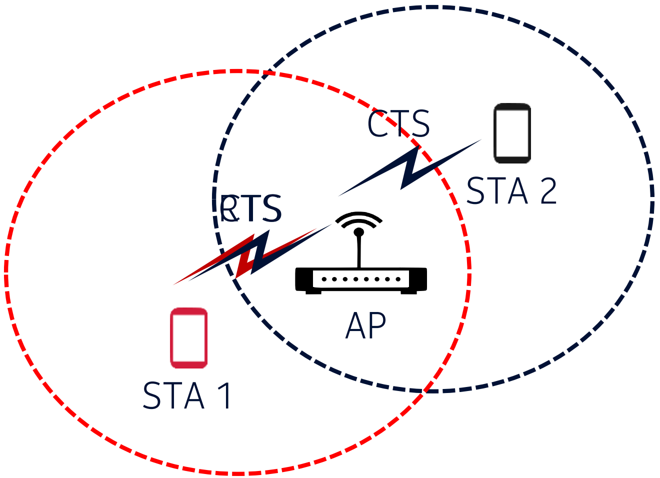
- Link level approach to quickly retransmit frames not correctly received [2]



- Frame duplicate detection through retry bit and sequence control field
- Block ACKs can be used to acknowledge multiple frames simultaneously

The MAC: RTS and CTS exchanges

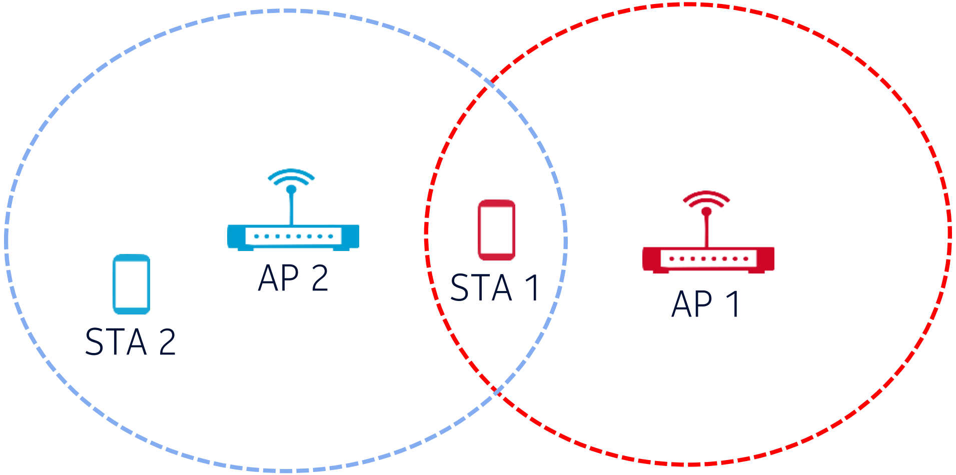
- RTS/CTS mechanism for solving the hidden node problem [2]
  - STAs and APs might initiate the transmission through a request to send (RTS) message
    - Includes a NAV covering both the CTS response and the subsequent data transmission
    - Shorter and more robust than data frame
  - The recipient responds with a clear to send (CTS) message

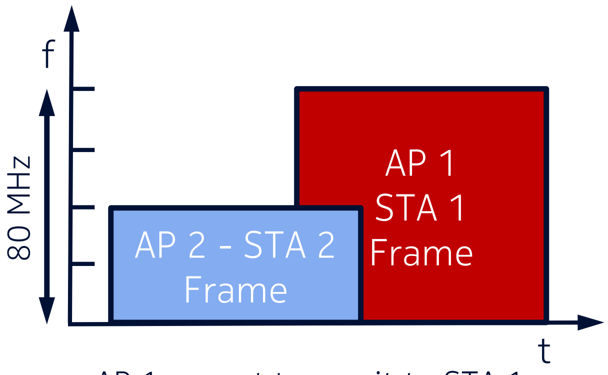


CTS message prevents the collision between STA 1 and STA 2

The MAC: RTS and CTS exchanges

- 802.11ac includes bandwidth signaling [6]
  - Problem: APs and STAs have different virtual carrier sense

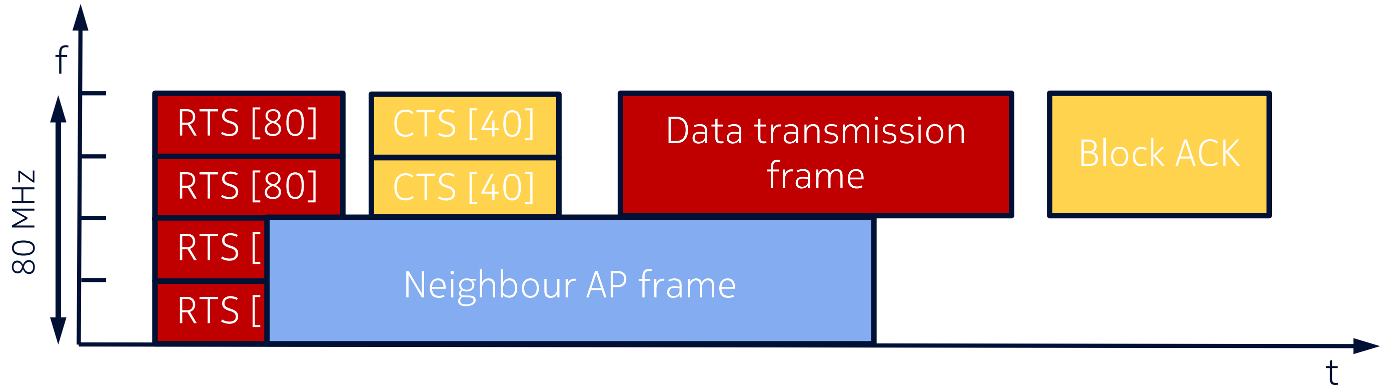




AP 1 cannot transmit to STA 1 over the entire bandwidth

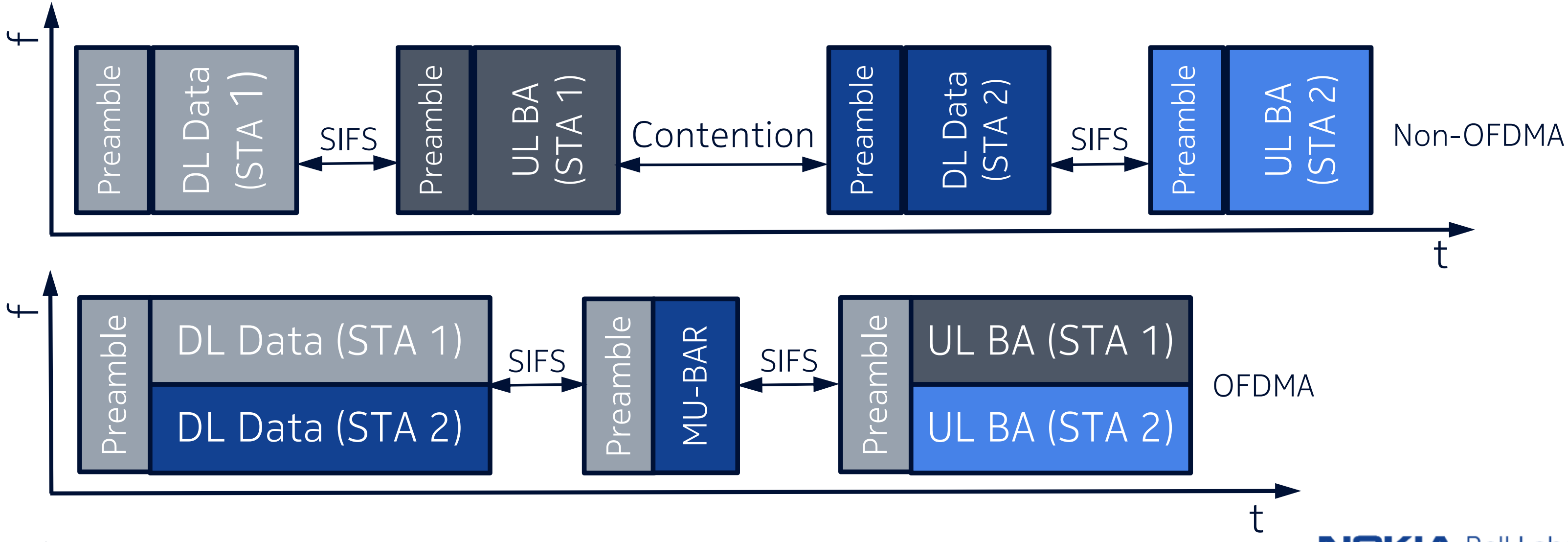
The MAC: RTS and CTS exchanges

- 802.11ac includes bandwidth signaling [6]
  - Solution:
    - RTS with BW indication over the primary channel
    - CTS is sent across the available bandwidth for transmission



The MAC: OFDMA in 802.11ax

- OFDMA: Multiple devices can be simultaneously scheduled in different subcarriers: reduces latency and better scales time/frequency resources to different types of traffic [9, 10]



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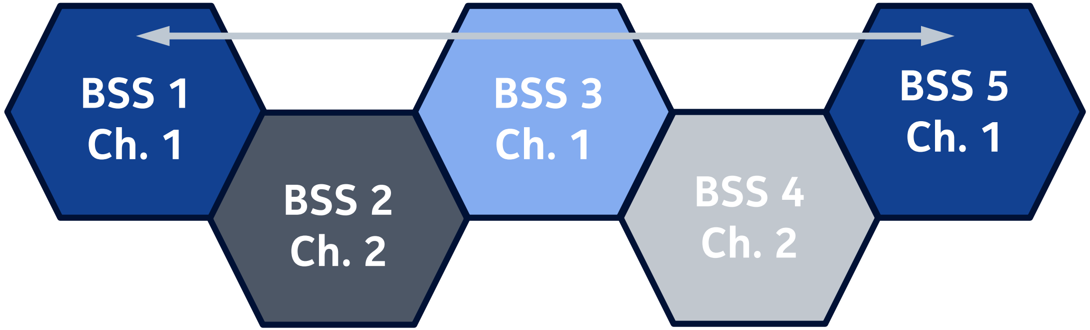
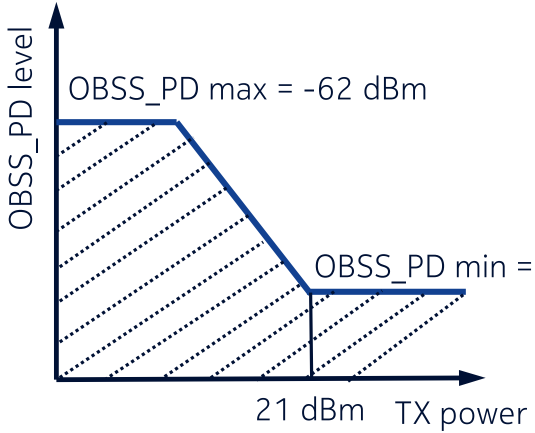
The MAC: Spatial reuse in 802.11ax

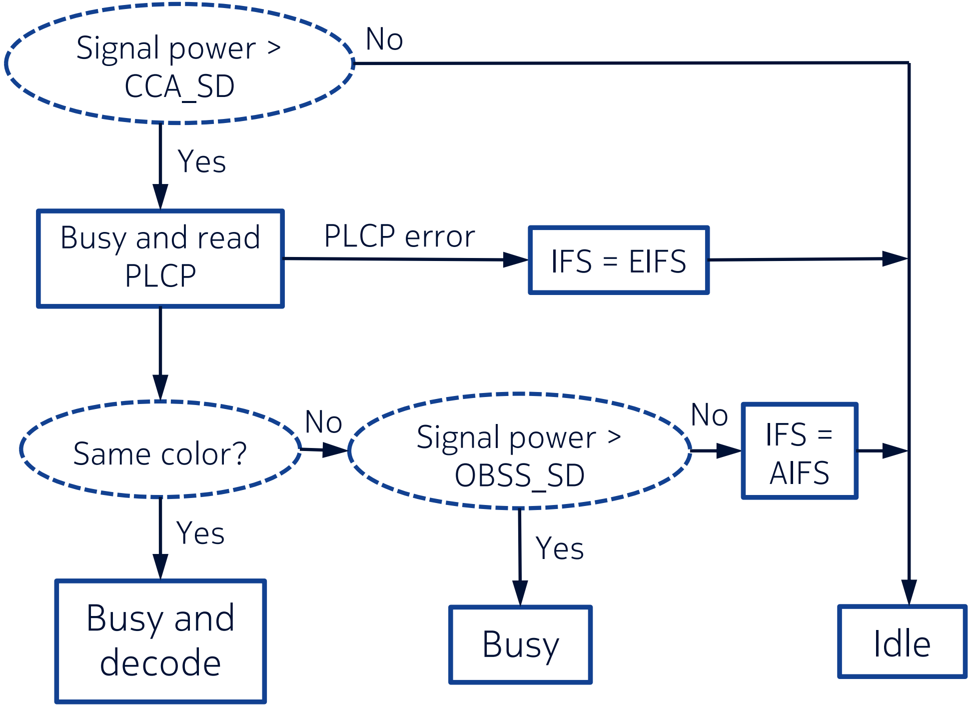
- Conventional operation (802.11n/ac):
  - Wi-Fi devices back off upon detection of a PPDU sent by any node in the same channel with received power larger than -82 dBm
- 802.11ax introduces BSS coloring for increasing frequency reuse among overlapping basic service sets (OBSSs) [10]
  - More time for data transmission at the expense of reduced SINRs



The MAC: Spatial reuse in 802.11ax

- 802.11ax STAs may adapt their signal detection threshold for OBSSs together with their transmit power to achieve better performance in dense scenarios [9, 10]





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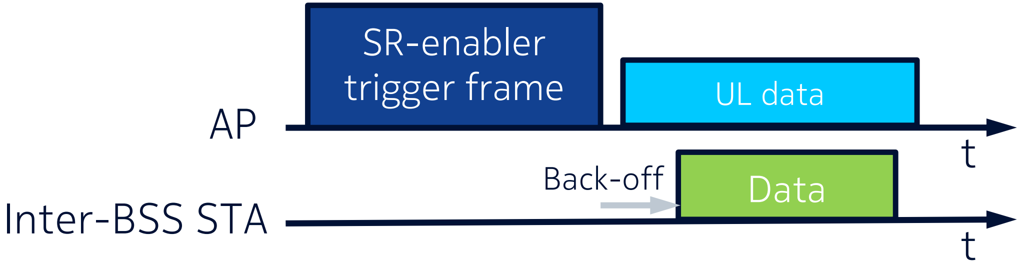
The MAC: Spatial reuse in 802.11ax

- Spatial reuse parameter (SRP)
  - Mechanism to allow APs to enable/disable spatial reuse during uplink:
    1. AP activates/deactivates spatial reuse through HE-SIG-A and/or trigger frame
    2. SRP-based SR opportunities are identified and TX power adjusted – maximum TX duration smaller than that of the SR-enabling AP
    3. Back-off procedure is performed to prevent collisions



Summary

Summary

- 802.11ax (Wi-Fi 6)
  - 8x8 downlink and uplink MU-MIMO
  - OFDMA with updated OFDM numerology
  - More flexible channel bonding through preamble puncturing
  - Enhanced spatial reuse
  - Outdoor improvements

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The next generation (future) Wi-Fi

Outline: Next Generation Wi-Fi, IEEE 802.11be

- Objective and timeline
- Potential technical features
- Summary
- References

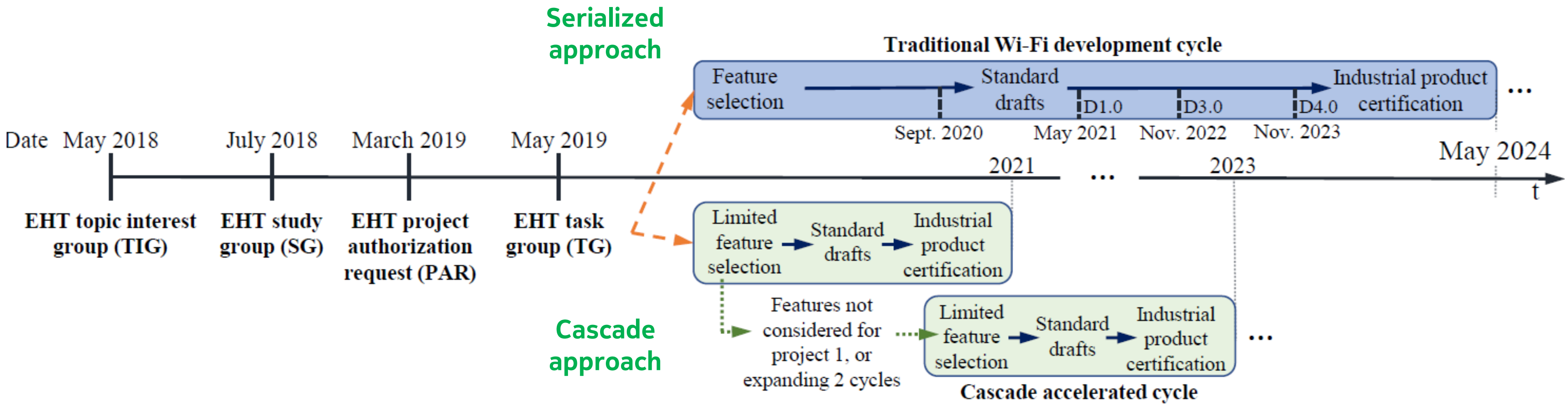
Objective and timeline

802.11be objectives

- Extremely high throughput [1][2]
  - new MAC and PHY modes of operation.
  - maximum MAC throughput of 30 Gbps/AP (4x w.r.t. 802.11ax).
  - carrier frequencies between 1 and 7.125 GHz.
- Low latency
  - At least one mode of operation capable of improved worst case latency and jitter -- no specific requirements set.
- Compatibility
  - backward compatibility and coexistence with legacy 802.11 devices in the 2.4, 5 and 6 GHz unlicensed bands.

802.11be timeline

- Two amendment development cycle proposed [3]:
  - <u>Serialized (longer period but more features) [4]</u> ➡ Selected approach in May [16]
  - Cascade (shorter period but less feature) [5]



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Potential technical features

802.11be potential features

- Set of features considered in the project approval request (PAR) [1]:
  - **Wider bandwidth:**
    - 320MHz bandwidth and more efficient utilization of non-contiguous spectrum.
    - Multi-band/multi-channel aggregation and operation.
    - If needed, adaptation to regulatory rules specific to 6 GHz spectrum.
  - **More antennas and spatial streams:**
    - 16 spatial streams and MIMO protocols enhancements.
  - **Better efficiency**
    - Multi-AP coordination, e.g. coordinated and joint transmissions.
    - Enhanced link adaptation and retransmission protocol, e.g. HARQ.

320MHZ per access point

- New unlicensed spectrum in the 6 GHz band (5925-7125 MHz), potentially adding up to 1.2 GHz!
  - Up to 320 MHz channel bonding in the 6 GHz band [6]
    - Definition of new channel access rules under discussion
  - Coexistence with incumbents needs to be managed [7]
    - Wi-Fi nodes may not be treated as incumbents as in the 5GHz band

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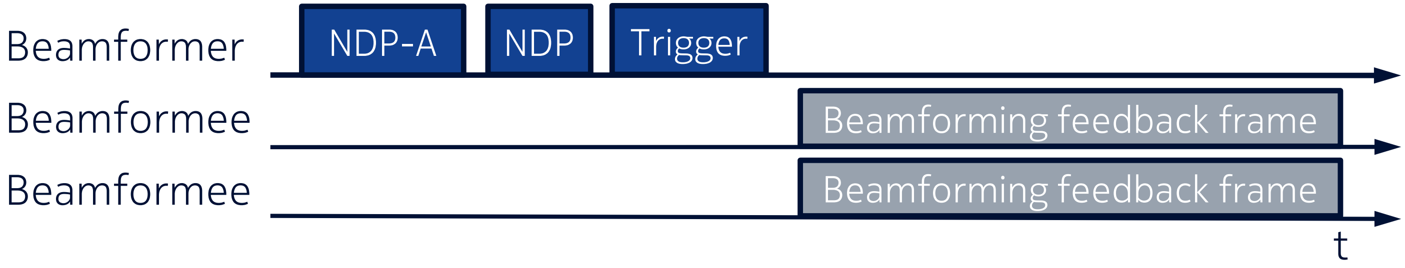
Multi-band operation

- Simultaneous use of 2.4, 5 GHz, and 6 GHz bands [8-10]:
  - Load balancing according to traffic needs
    - More channels to play with
  - Data transmission and reception separated in different bands
    - E.g. bands for uplink and high bands for downlink
  - Control and data plane separated in different bands
    - E.g. Low bands for control inf. and high bands for data tx/rx

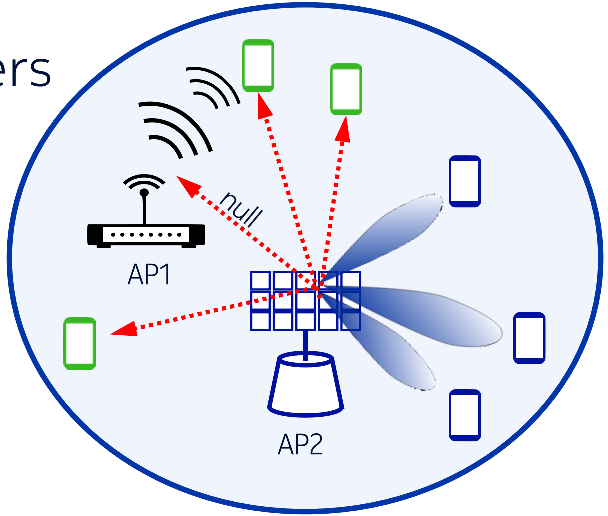
16 antenna/stream MU-MIMO

- Support of up to 16 spatial streams [11]
- Enhance channel state information (CSI) acquisition [12]:
  - Current approach based on explicit feedback does not scale well
  - Implicit CSI acquisition leveraging channel reciprocity
    - Potential improvements both for systems with 8 and 16 spatial streams



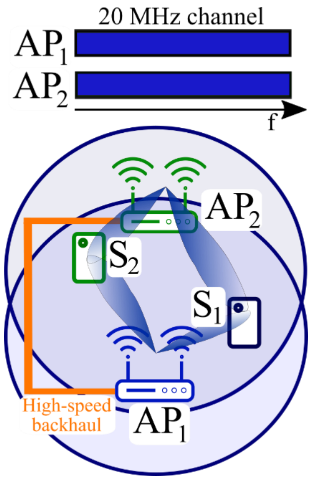
Multi-AP coordination

- Coordination approaches with different degrees of complexity [10, 13-15]:
  - Multi-AP association to facilitate handovers
  - Time/frequency coordinated scheduling
  - Coordinated transmissions
    - Beamforming/null steering
  - Joint transmissions
    - Distributed MIMO



Different degrees of complexity

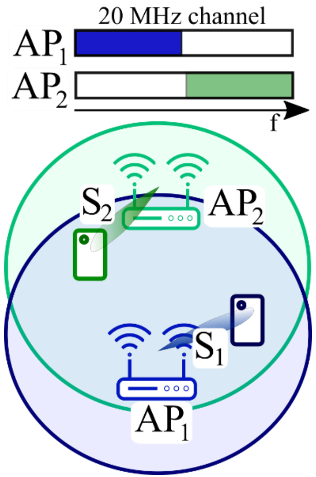
Joint Distributed MIMO



Reuses time/freq. resources via joint spatial multiplexing [16, 17]

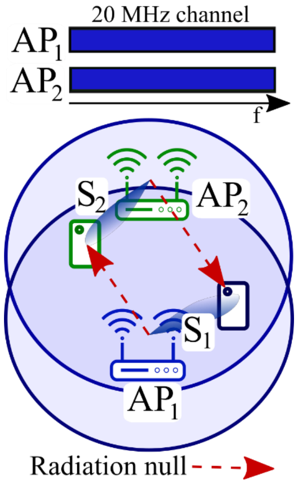
Solution with the most demanding sync. and backhaul requirements

Coordinated OFDMA



Coordinates time/freq. resource allocation [18, 19]

Coordinated null steering



Reuses time/freq. resources by placing spatial radiation nulls

Solutions with simplified requirements

Null steering offers an appealing complexity and performance trade-off

When is coordinated OFDMA effective?

- Medium to large AP densities [19]
  - Coordinated transmissions enable a more efficient time/freq. resource utilization
  - Resource splitting among APs could suffice to provide a satisfactory performance
- Also for STAs having high interference [19]
  - Interference mitigation is possible through an intelligent resource unit assignment

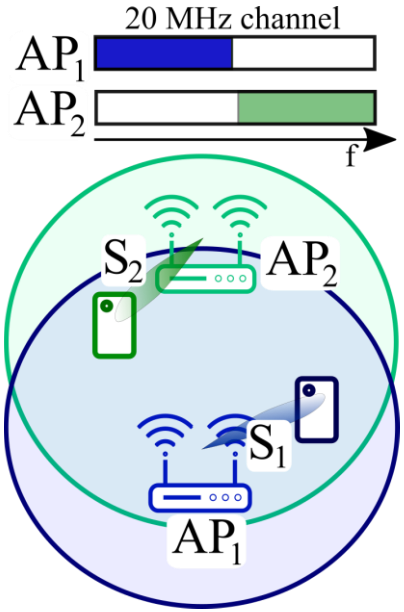


Illustration of coordinated OFDMA

Coordinated OFDMA for short packets and highly interfered STAs

When is coordinated null steering effective?

- Medium to large AP densities and APs with multiple antennas [19]
  - Coordinated transmissions enable a more aggressive time/freq. resource utilization
  - Spatial reuse could be necessary to provide a satisfactory performance
- Also for STAs having high interference and medium to high SNRs [19]
  - APs dedicate spatial resources for interference suppression purposes

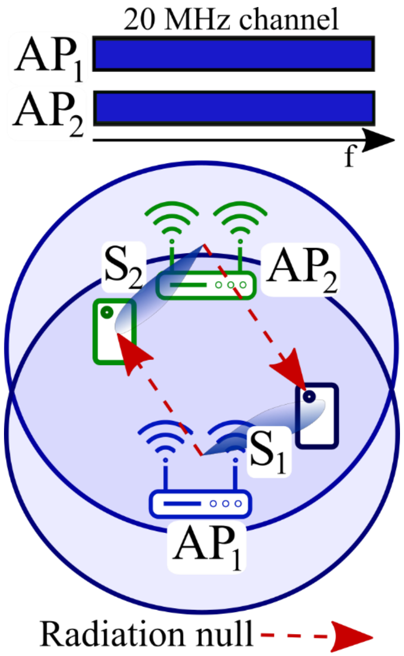
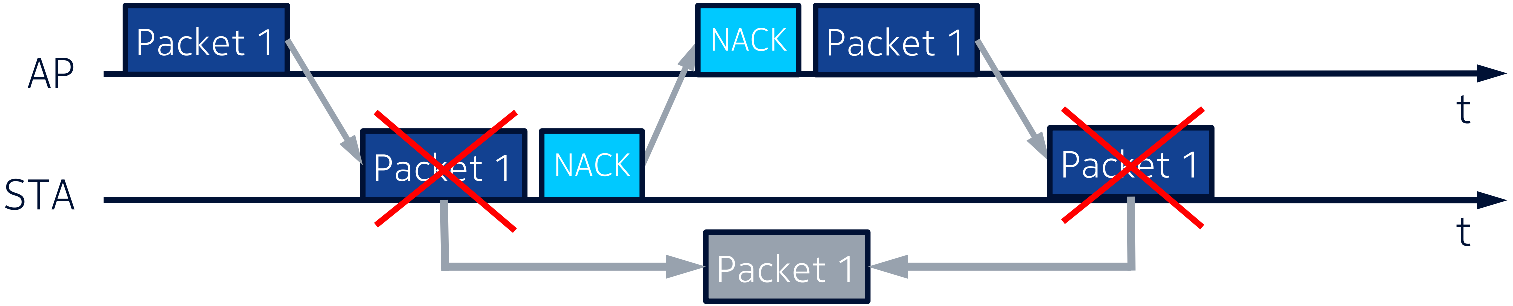


Illustration of coordinated null steering

Coordinated null steering for dense scenarios with multi-antenna APs

Hybrid automatic repeat request (HARQ)

- Boosting link adaptation via more efficient retransmission [20]
  - Theoretical SNR gains in the order of 4 to 6 dB
  - Already discussed during 802.11ac and 802.11ax standardization
- HARQ might not be robust enough against collisions caused by the unpredictable interference conditions in 802.11



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Summary

Summary

802.11be (Wi-Fi 7)

Feature	802.11ax	802.11be
Max. transmission bandwidth	80 MHz (mandatory) / 160 MHz (optional)	160 MHz (likely mandatory) / 320 MHz (likely optional)
Initial deployment bands	2.4 GHz and 5 GHz	2.4 GHz, 5 GHz, and 6 GHz
Max. number of spatial streams	8	16
CSI acquisition protocol	Explicit	Explicit and implicit
Multi-band/multi-channel data transmission	None	Available
Multi-AP explicit resource coordination	None	Time, frequency, and space
Retransmission capabilities	ARQ	HARQ

References

References

All URLs accessed on May 2019

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[6] https://mentor.ieee.org/802.11/dcn/18/11-18-1549-00-0eht-candidate-technology-review.pptx

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[12] https://mentor.ieee.org/802.11/dcn/18/11-18-1191-00-0eht-mu-sounding-improvements.pptx

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[19] Kome Oteri, "Coordinated Multi-AP Transmission for EHT," IEEE 802.11-19/0071, Jan. 2019.

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Performance Evaluation: 802.11be vs 802.11ax

Outline

- Candidate enhancements
- System evaluation set-up
- Results
- Conclusions

Candidate enhancements

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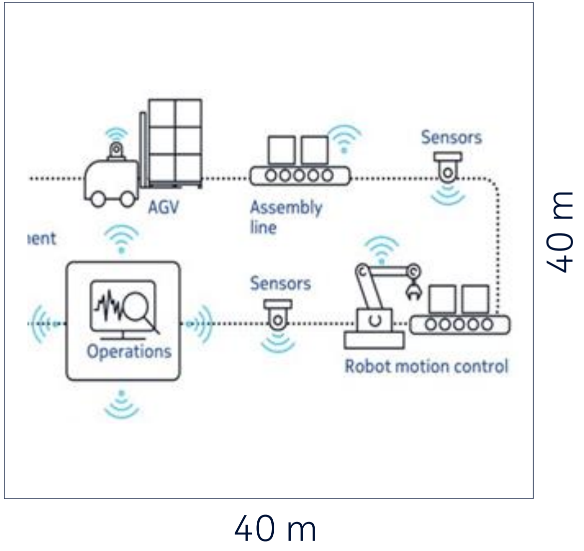
Studied 802.11be enhancements over 802.11ax

Feature	**802.11ax**	**802.11be**
Max. transmission bandwidth	80 MHz (mandatory) / 160 MHz (optional)	160 MHz (likely mandatory) / 320 MHz (likely optional)
Initial deployment bands	2.4 GHz and 5 GHz	2.4 GHz, 5 GHz, and 6 GHz
Max. number of spatial streams	8	16
CSI acquisition protocol	Explicit	Explicit and implicit
~~Multi-band/multi-channel data transmission~~	~~None~~	~~Available~~
~~Multi-AP explicit resource coordination~~	~~None~~	~~Time, frequency, and space~~
~~Retransmission capabilities~~	~~ARQ~~	~~HARQ~~

System evaluation set-up

Indoor enterprise scenario

- **Enterprise:** Single floor enterprise with an area size of 40m x 40m.
- **Channels and carrier frequency:** 4 channels of 160MHz (*802.11be*) or 80MHz (*802.11ax*) in the 6GHz or 5GHz band, respectively.
- **Channel model:** 3GPP TR38.901 InH with mixed office line of sight (LoS) probability. Internal wall losses are considered statistically.
- **Station (STA) deployment:** 512 single-antenna STAs uniformly distributed (0.1m of minimum inter-STA distance) and located at 1.0m height.



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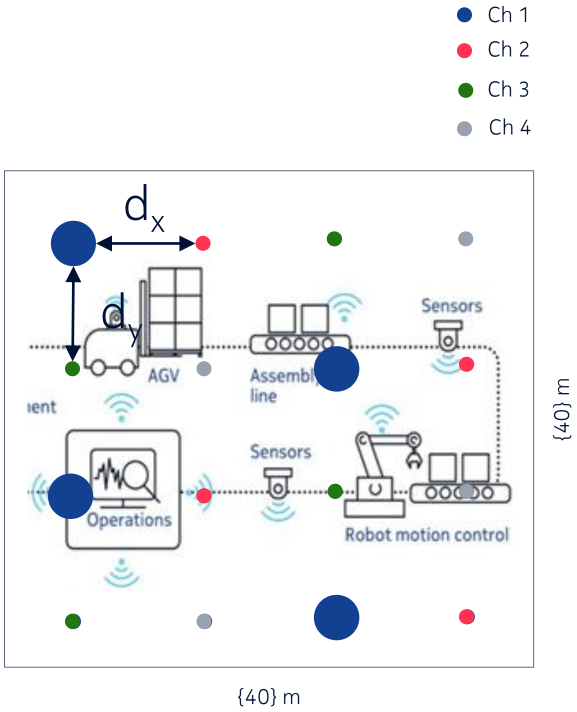
Access point configuration

- **AP deployment:** 16 ceiling-mounted APs at 3.0m height with $d_x = d_y = 10.0$m.
- **Spatial multiplexing:** 16 (*802.11be*) or 8 (*802.11ax*) omnidirectional antennas and spatial streams. MU-MIMO in downlink and uplink.
- **Channel allocation:** 1 channel per AP and optimal channel assignment, resulting in 4 APs per channel and the maximum reuse distance.
- **STA-to-AP association:** based on strongest average received signal strength.



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Detailed simulation parameters

PHY & MAC	
Carrier frequency	5.18 GHz (.11ax) / 6.2 GHz (EHT)
System bandwidth	320 MHz (.11ax) / 640 MHz (EHT)
Channel size	80 MHz (.11ax) / 160 MHz (EHT)
OFDM guard interval duration	$0.8\mu s$
AP/STA maximum TX power	$P_{\text{max}} = 24/15$ dBm
Number of antennas per AP	4×2 (.11ax) / 4×4 (EHT)
Number of antennas per STA	1
AP and STA antenna elements	Omnidirectional with 0 dBi and 0.5λ separation
CCA energy detection threshold	$\gamma_{\text{LBT}} = -62$ dBm
Signal detection threshold	$\gamma_{\text{preamble}} = -82$ dBm with -0.8 dB of minimum SINR
MCS selection algorithm	Minstrel
AP/STA noise figure	$F_{\text{dB}} = 7/9$ dB
Maximum # of scheduled STAs	8 (.11ax) / 16 (EHT)
AP spatial precoding/detection	Zero Forcing
STA scheduling	Round Robin with semi-orthogonal user selection (SUS)
Downlink power allocation	Equal power assigned per STA
MPDU payload size	1500 bytes
Medium access	Distributed coordination function
Maximum TXOP length	4 ms

Deployment	
Floor size	40 m $\times$ 40 m
AP positions	16 ceiling-mounted APs equally spaced ($d_x = d_y = 10$ m)
AP/STA heights	$h = 3/1$ meters
STA distribution	512 uniformly deployed STAs. 10 cm of min. inter-STA distance.
AP-STA association criterion	Strongest average received signal

Channel model	
Path loss and LOS probability	3GPP 3D InH (3GPP TR 38.901)
Shadowing	Log-normal with $\sigma = 3/8$ dB (LOS/NLOS) (3GPP TR 38.901)
Fast fading	Ricean with log-normal K factor (3GPP TR 38.901)
Thermal noise	-174 dBm/Hz spectral density
Traffic model	
Traffic model	FTP model 3 with a packet size of 0.5 MBytes
Traffic generated per STA	75 Mbits/s
DL/UL traffic ratio	0.5/0.5

Power regulations and implications

Downlink

- Maximum EIRP [dBm] =
  a) conducted power [dBm] +
  b) maximum antenna element gain [dBi] +
  c) maximum array gain [dB]
- Maximum conducted power = 24 dBm (U-NII-2).
- Maximum array gain = $10\log_{10}\left(\frac{N_{ANT}}{N_{STAs}}\right)$ dB.

Implications:

- Conducted power might have to be reduced in multi-antenna APs to meet maximum EIRP.

Uplink

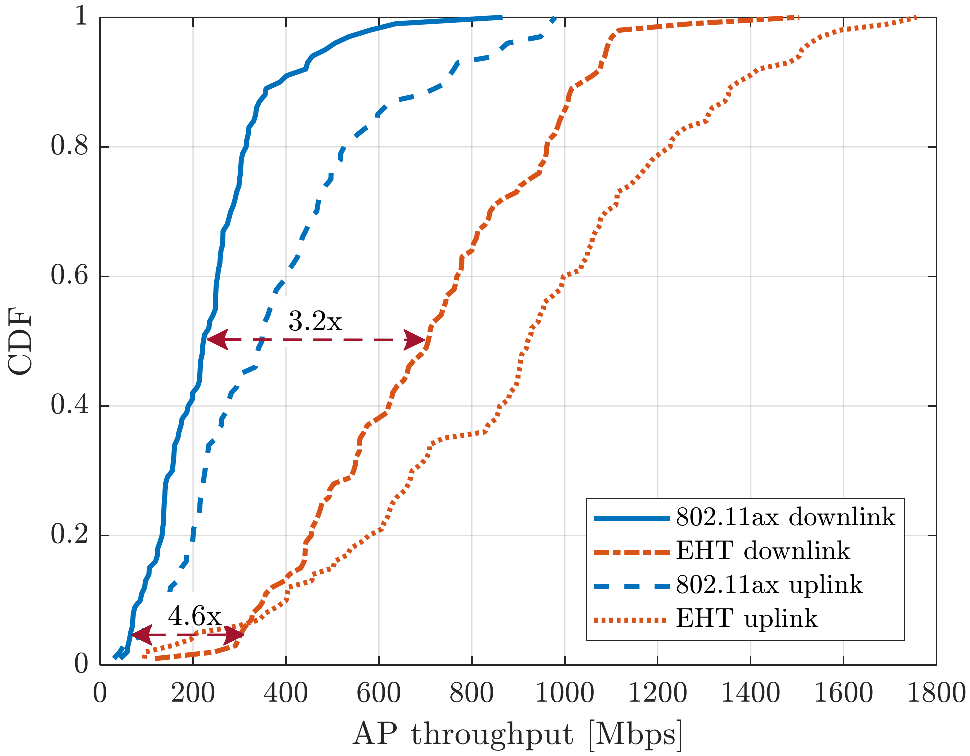
- STAs have lower conducted power (15dBm)
- STAs no or little array gain, as they have a reduced number of antennas (in our case only 1)

Implications:

- APs can leverage their beamforming gain for reception without restrictions.

Results

File throughput (I)



- **802.11be provides notable throughput gains w.r.t. 802.11ax**
  - 3.2x and 2.7x in median for downlink and uplink, respectively, and
  - 4.6x and 2.2x in 5%-tile for downlink and uplink, respectively.
- **802.11be does not reach the maximum 4x theoretical gain w.r.t. 802.11ax, since**
  - EHT cell-edge STAs do not benefit from the larger bandwidth due to power constraints and larger noise powers,
  - EHT APs do not always have 16 STAs to spatially multiplex, and
  - per-STA SINRs degrade when more STAs are spatially multiplexed, due to the reduced beamforming gain and power allocated per STA.

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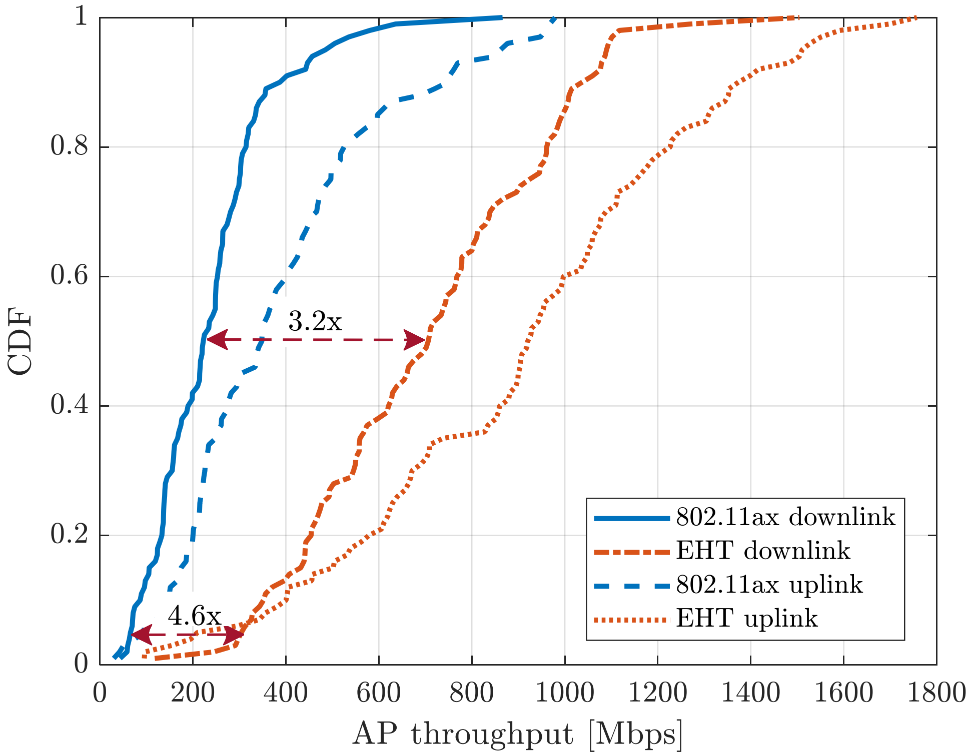
File throughput (II)



- **STAs generally experience smaller throughputs in the downlink than in the uplink because**
  - STAs have a larger noise figure than APs, which leads to reduced downlink SINRs,
  - of the power split that APs perform in downlink when performing spatial multiplexing, and
  - the uplink-to-downlink (STA-STA) interference is generally larger than the downlink-to-uplink one (AP-AP), since STAs are equipped with a single omnidirectional antenna and do not spatially suppress interference.

Summary

Summary

1. The usage of more bandwidth, more antennas, more spatial streams, and implicit feedback can significantly boost Wi-Fi performance
   - 3.2x and 2.7x in median for downlink and uplink, respectively, and
   - 4.6x and 2.2x in 5%-tile for downlink and uplink, respectively.

2. To reach a 4x performance improvement w.r.t. the state of the art Wi-Fi, we expect that
   a) multi-band/multi-channel data transmission, and
   b) multi-AP explicit coordination

   will play an important role.

3. Spatial reuse and low latency will be important drivers of the next generation Wi-Fi, and will be the subject of our next seminar.

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Behind Wi-Fi's success story:

Fundamentals, deciphering 802.11ax, and roadmap towards the next generation

D. Lopez-Perez, A. Garcia-Rodriguez,
Giovanni Geraci, and L. Galati-Giordano

IEEE EuCNC 2019
Valencia, Spain
June 18th 2019

Q&A

