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Future Indoor Networks: The role of Wi-Fi and its evolution

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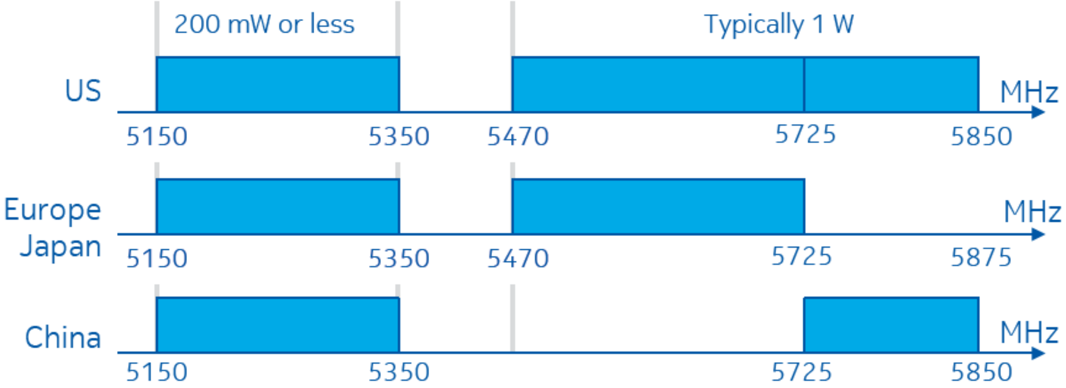
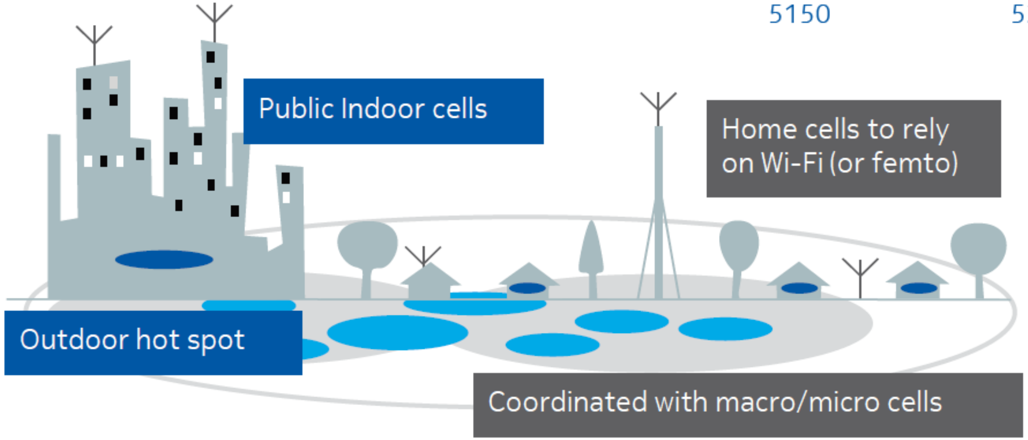
Unlicensed spectrum bands

Plenty of spectrum …

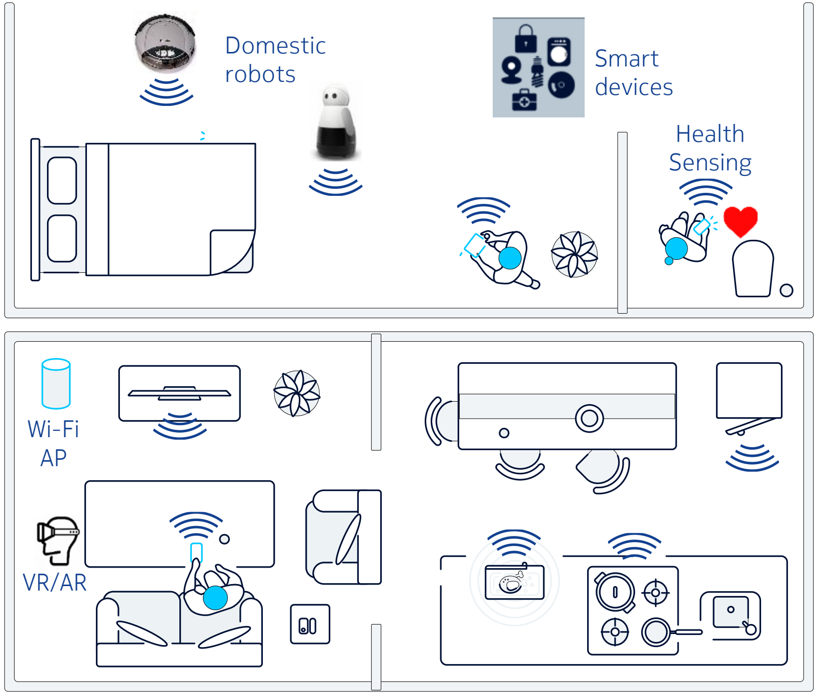




… to be used anytime, everywhere

Future Indoor Networks

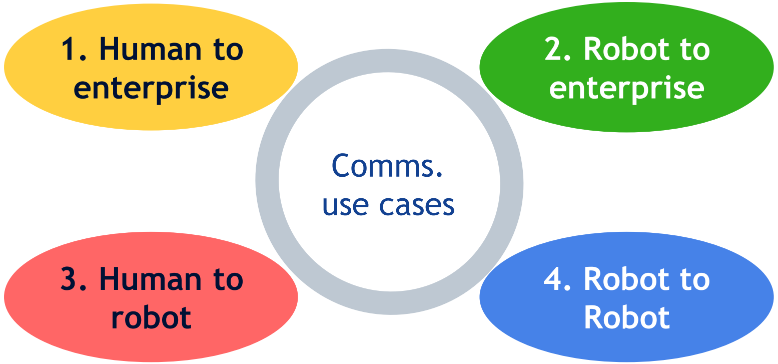
Residential



Enterprise

AR/VR (remote) live support

Sensor-based robot control



Video-based remote operation

Cooperative tasks

Industrial seminar Outline

1. The good old (and new) Wi-Fi [30 mins.]
2. 802.11 standardization status and directions [20 mins.]
3. Performance overview: massive MIMO benefits [25 mins.]
4. Q&A [10 mins.]

The speakers

Lorenzo Galati Giordano

Exploring Abu Dhabi

Background

- Member of Technical Staff at Nokia Bell Labs (2015-present)
- R&D System Engineer at Azcom Technology, Italy (2010-2014)
- PhD from Politecnico di Milano university, Italy (2010)

Current research

- Massive MIMO applications:
  - In the unlicensed spectrum
  - For UAV communications

About me

- Born in Milan (Italy), the city of design and fashion (...and good food!)

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Adrian Garcia Rodriguez

Background

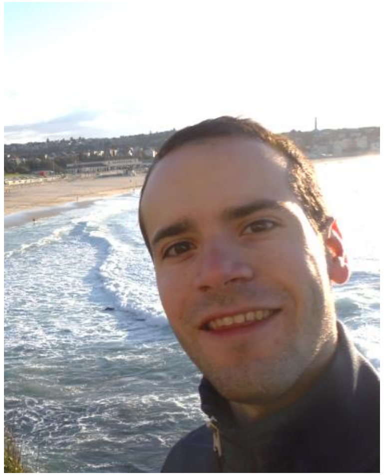
- Research Scientist at Nokia Bell Labs, Ireland (2018-present)
- Post-doctoral researcher at Nokia Bell Labs, Ireland (2016-2018)
- PhD from University College London, UK (2016)

Current research

- Unlicensed spectrum technologies (mostly Wi-Fi)
  - Both sub-6 GHz and mmWave frequencies
- UAV cellular communications

About me

- Born in Tenerife (Canary Islands), at the edge of the Atlantic



Trying to get a bit of sun in Australia

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Mika Kasslin (Nokia Bell Labs, Finland)

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The good old (and new) Wi-Fi

Outline: The good old (and new) Wi-Fi

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

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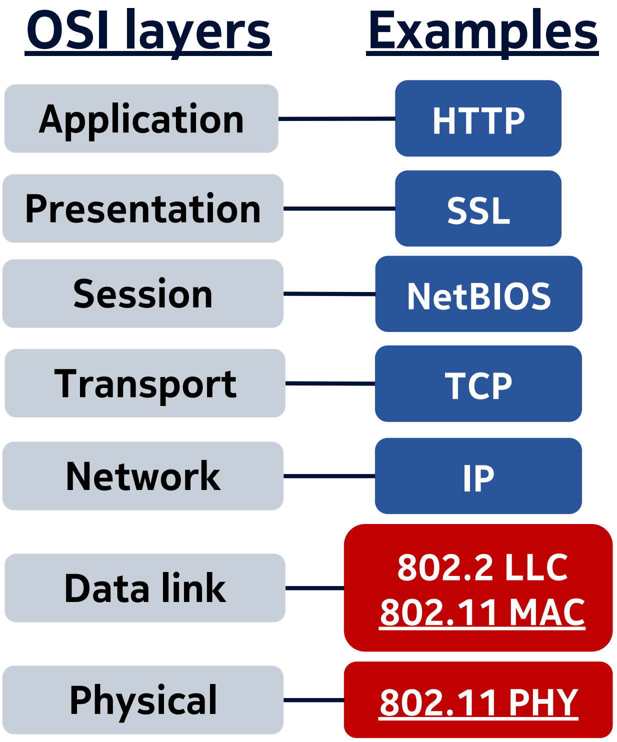
Introduction

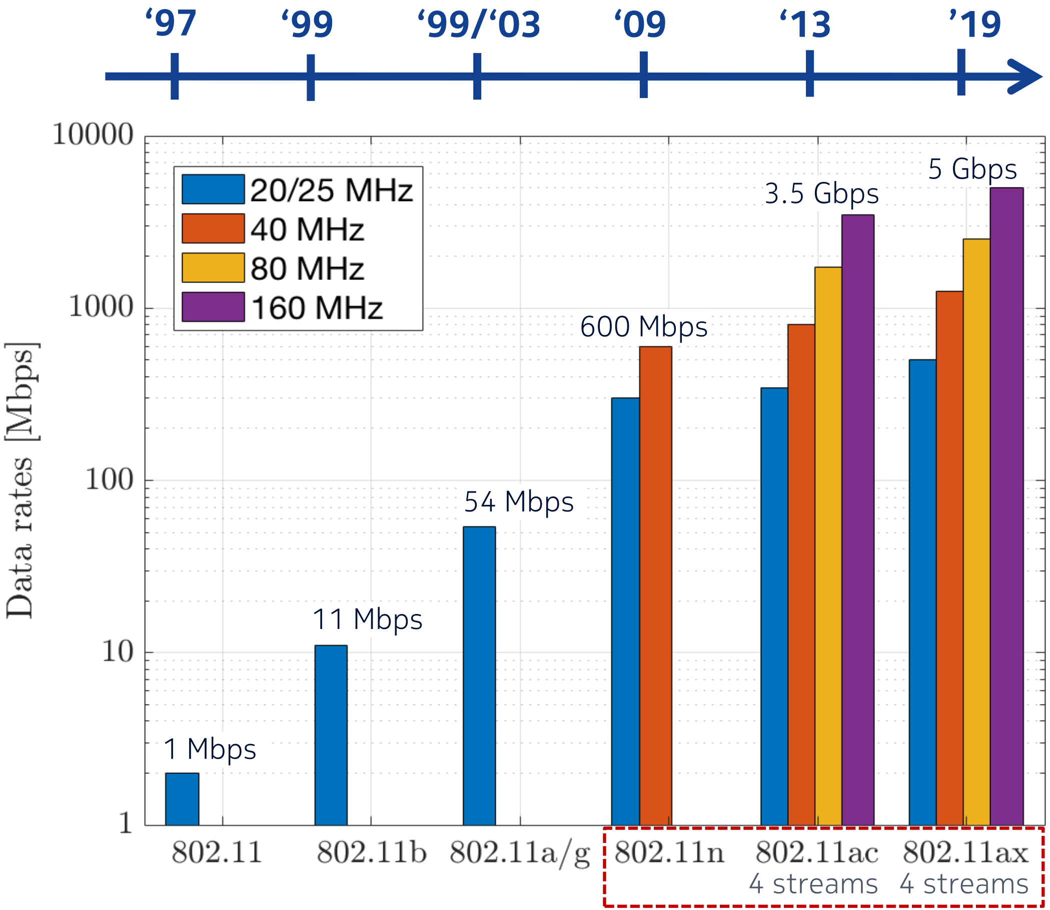
Wi-Fi (802.11) in the communications industry

- More than 8 billion devices are currently in use around the world [1]
- 3 billion Wi-Fi devices have been shipped in 2017 [1][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



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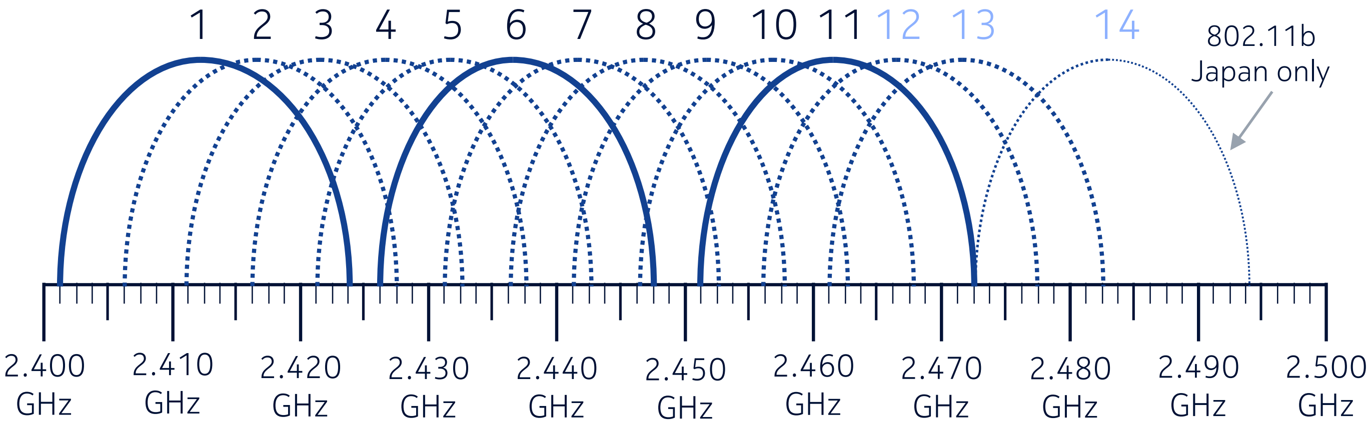
The physical layer (PHY)

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)



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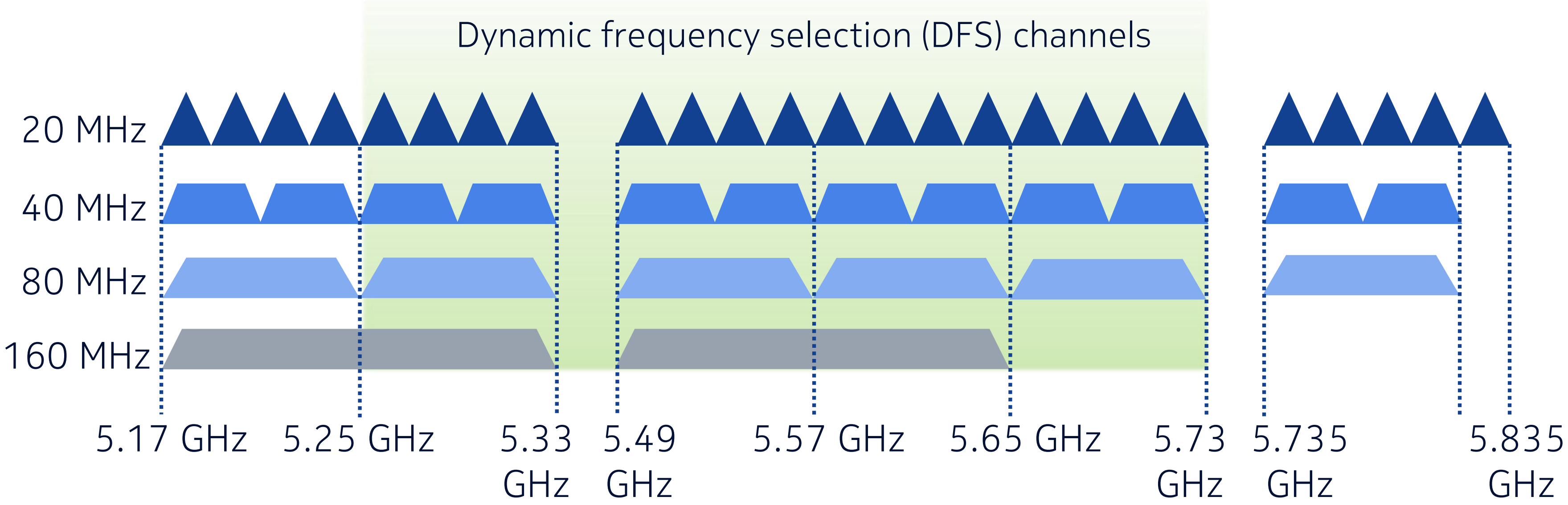
The PHY: Frequency channelization

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



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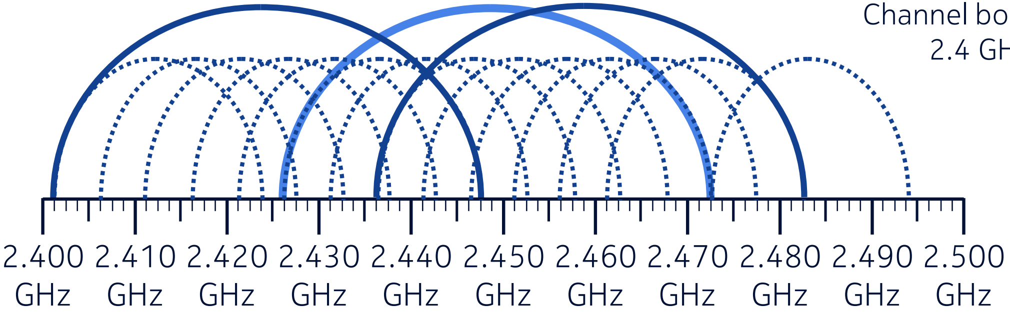
The PHY: Channel bonding

- 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

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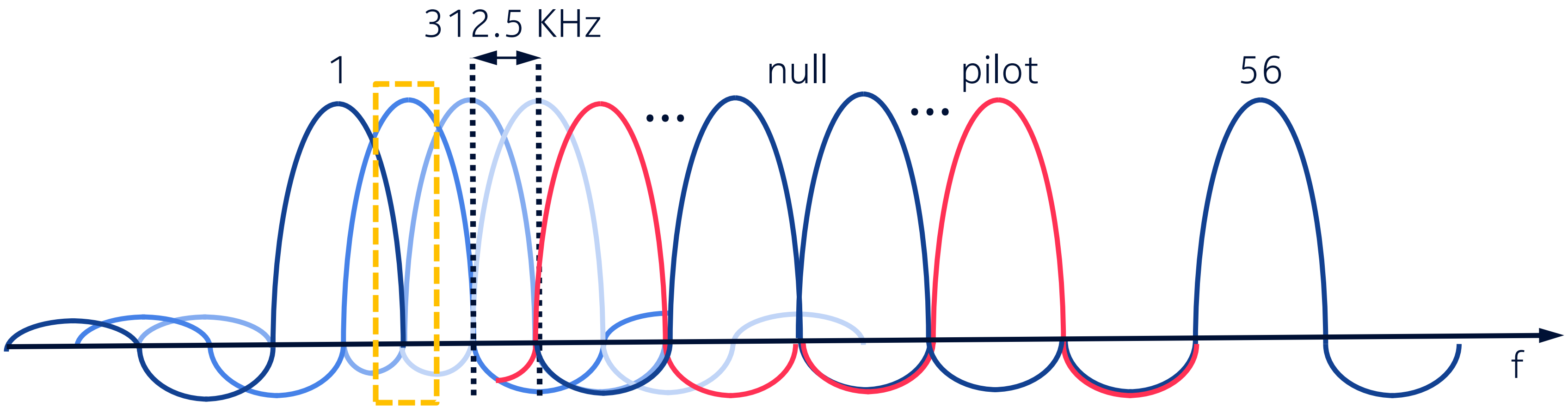
The PHY: Preamble puncturing in 802.11ax

- 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]

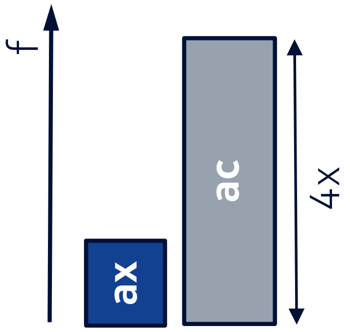
The PHY: OFDM in 802.11a/g/n/ac

- 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

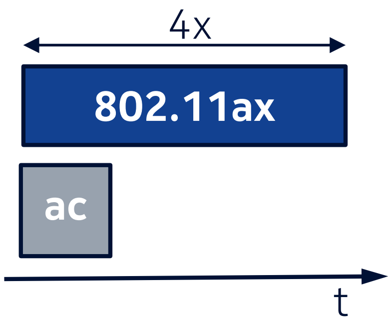


The PHY: OFDM in 802.11ax

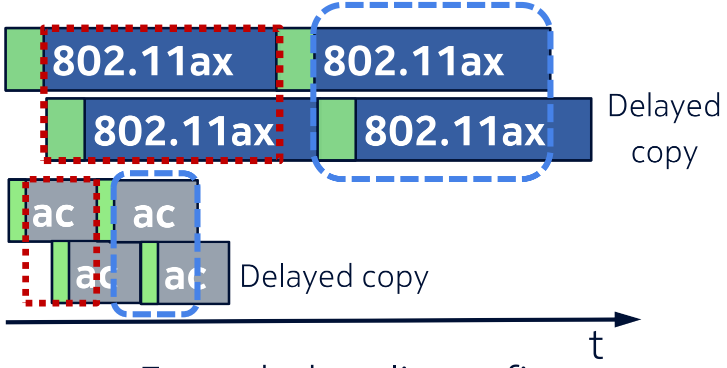
- Orthogonal frequency division multiplexing (OFDM) [9, 10, 14]
  - 802.11ax has 256 subcarriers per 20 MHz channel (234 for data)
  - Extended OFDM guard interval to enhance protection against delay spread in outdoor scenarios: from 0.8μs in 802.11ac to 0.8/1.6/3.2μs in 802.11ax



Symbol bandwidth



Symbol duration



Extended cyclic prefix

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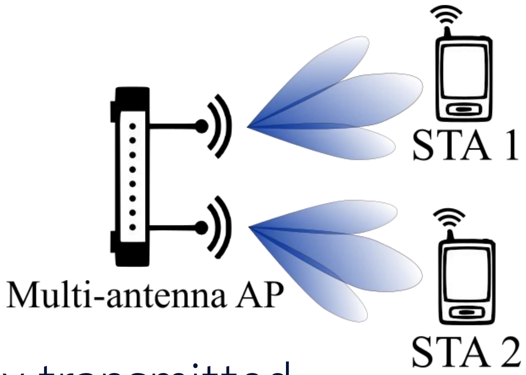
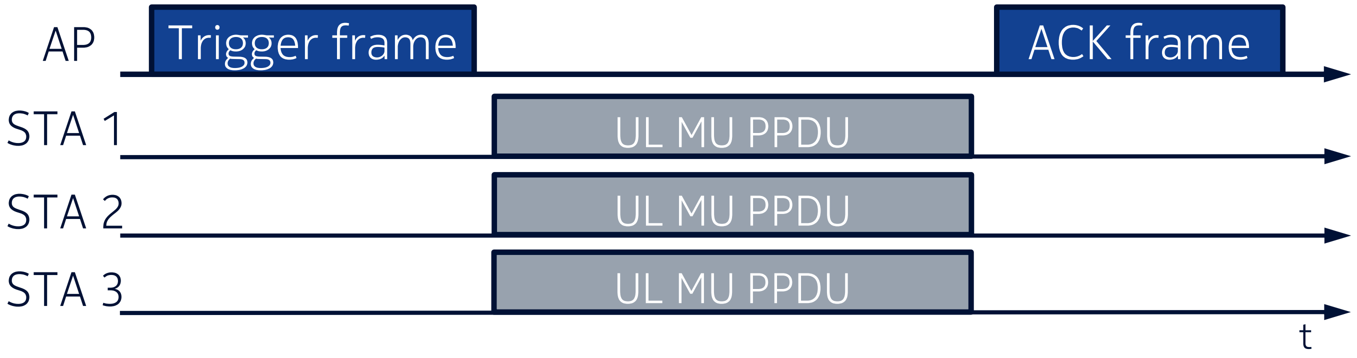
The PHY: Spatial multiplexing

- 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



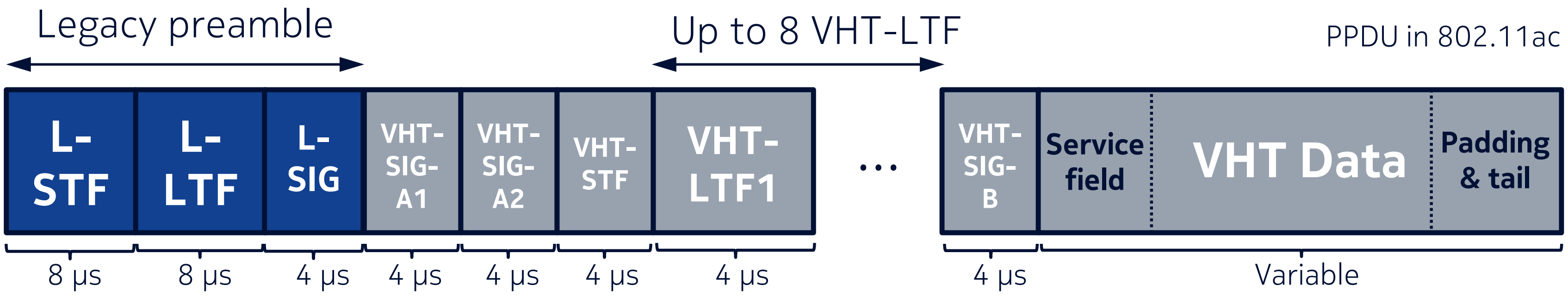
The PHY: Spatial multiplexing

- 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



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: 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
  - Target wake time (TWT): Power-saving service reservation mechanism

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)
      - <u>802.11ax: Intra- and inter-cell NAVs</u>

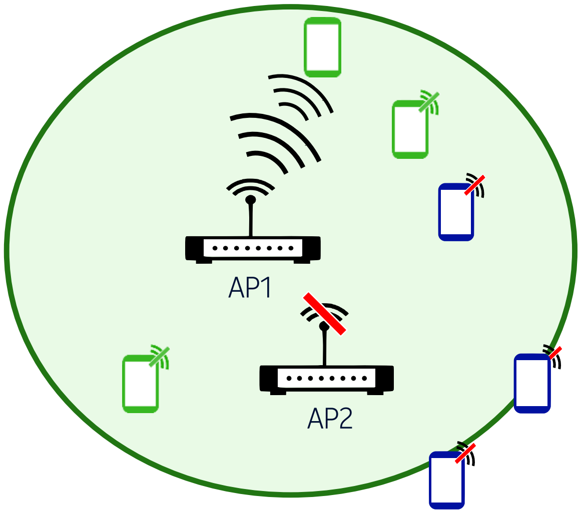


Illustration of the LBT time sharing mechanism

The MAC: Distributed coordinated function (DCF)

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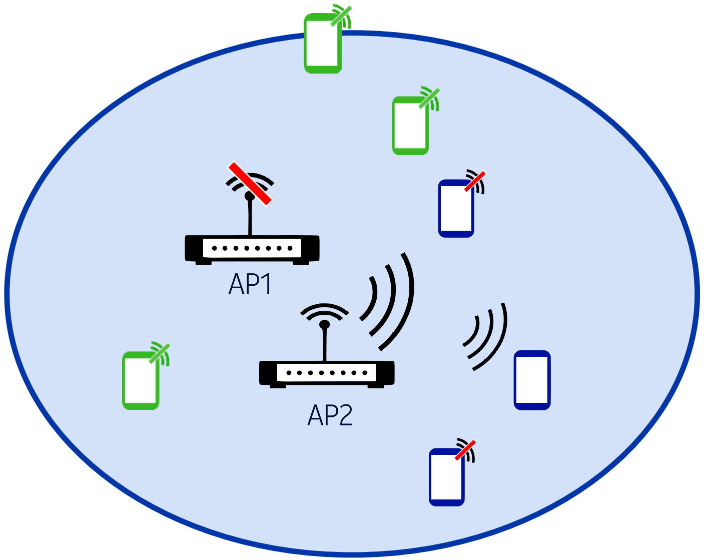
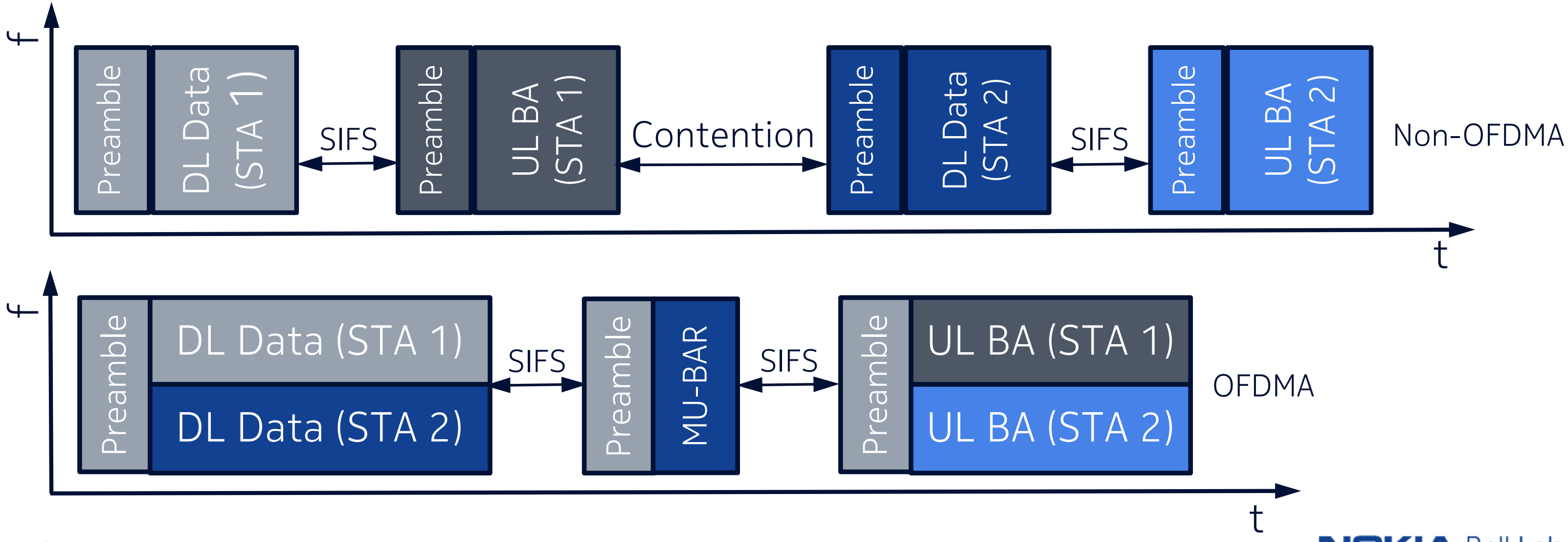


Illustration of the LBT time sharing mechanism

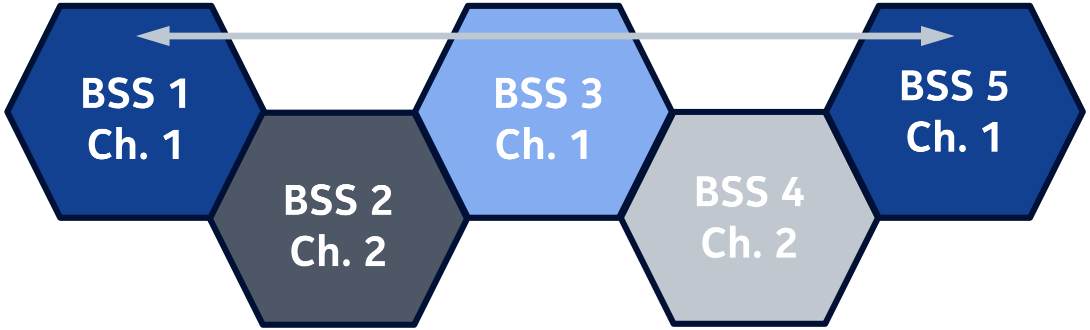
The MAC: OFDMA in 802.11ax

- 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]



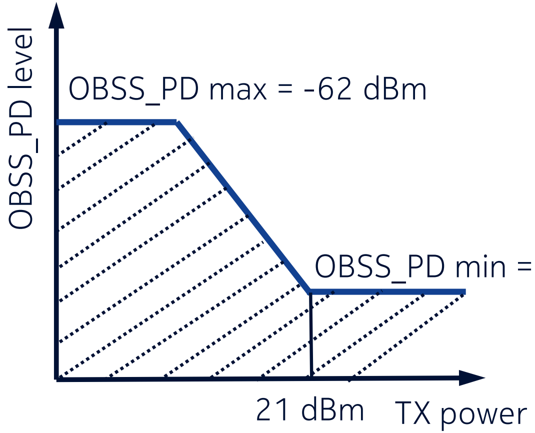
The MAC: Spatial reuse in 802.11ax

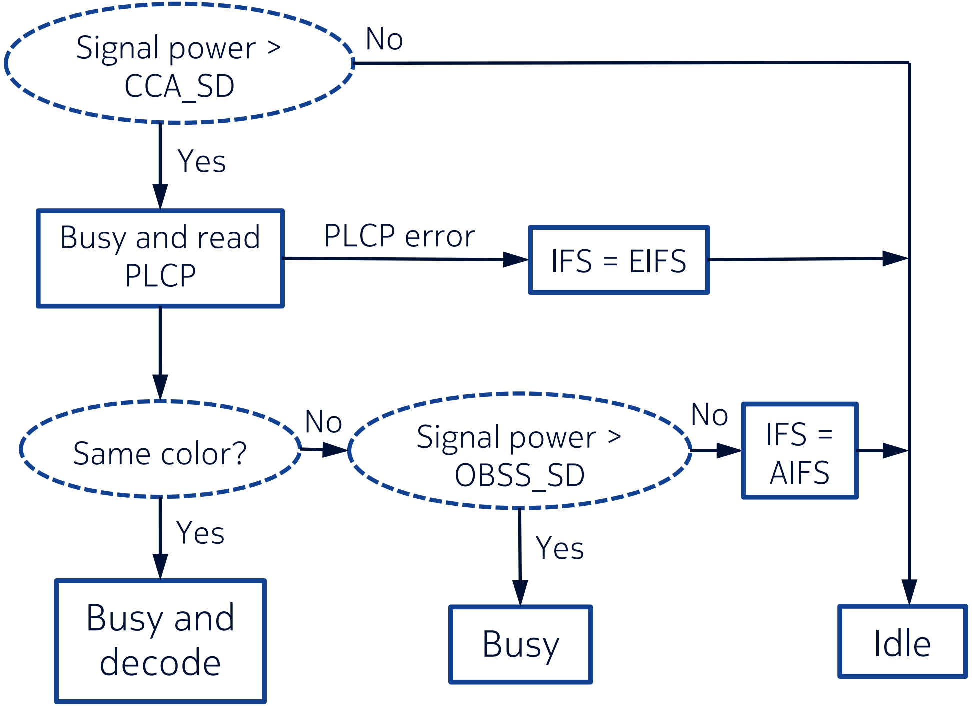
- Conventional operation (802.11n/ac):
  - Wi-Fi devices back off upon detection of a PPDU sent by any node in the same channel with received power larger than -82 dBm
- 802.11ax introduces BSS coloring for increasing frequency reuse among overlapping basic service sets (OBSSs) [10]
  - More time for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



The MAC: Spatial reuse in 802.11ax

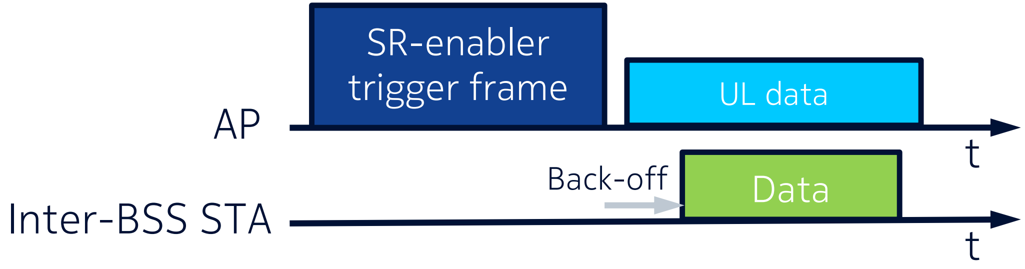
- 802.11ax STAs may adapt their signal detection threshold for OBSSs together with their transmit power to achieve better performance in dense scenarios [9, 10]





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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802.11 standardization status and directions

What is next?

- 802.11 topic interest and study groups [1]

Date	Jan. 2018	March 2018	May/July 2018	July 2018
	- TIG: Full duplex	- TIG/SG: Broadcast services - SG: Next-generation V2X	**- TIG/SG: Extreme High Throughput (EHT)**	- TIG: Real time applications

What is next?

- Extreme High Throughput (EHT) [2-4]

Date May 2018 — **IEEE 802.11 EHT topic interest group (TIG)**

July 2018 — **IEEE 802.11 EHT study group (SG)**

Early 2019 — **IEEE 802.11 EHT project authorization request (PAR)**

Extreme high throughput (EHT)

- What features are currently being discussed?* [2-5]

	Intel	InterDigital	Broadcom	Cisco	MediaTek	Marvell	LGE	Sony	Samsung	Huawei	Nokia
Single band operation	●	●		●						●	●
Multi-band operation	●	●		●		●	●				
Spatial multiplexing	●	●	●	●					●		●
Multi-AP coordination	●	●		●	●	●		●	●	●	●
Link adaptation	●	●		●						●	

*Non-rigorous list of the techniques addressed in the EHT contributions by different companies

Single band operation

- 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 [4-5]
  - Definition of new channel access rules under discussion [5]
  - Coexistence with incumbents needs to be managed [6]

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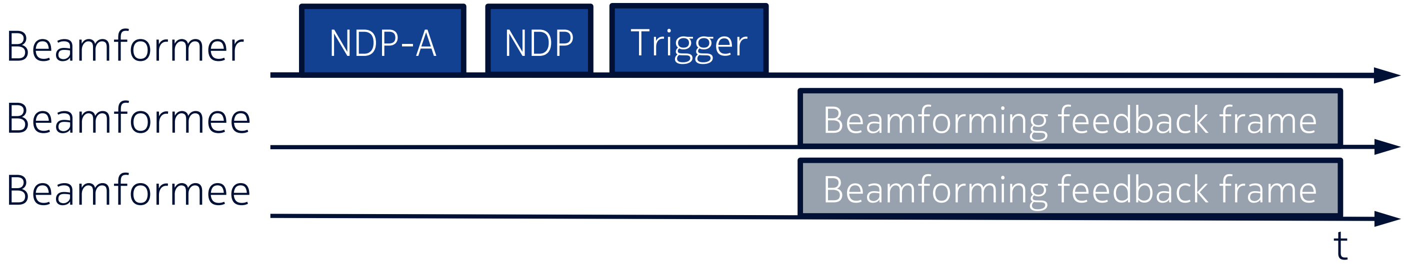
Multi-band operation

- Simultaneous use of 2.4, 5 GHz, and 6 GHz bands [7-9]:
  - Load balancing according to traffic needs
  - Data transmission and reception separated in different bands
  - Control and data plane separated in different bands
    - Low bands for control information exchange and high bands for data transmission/reception

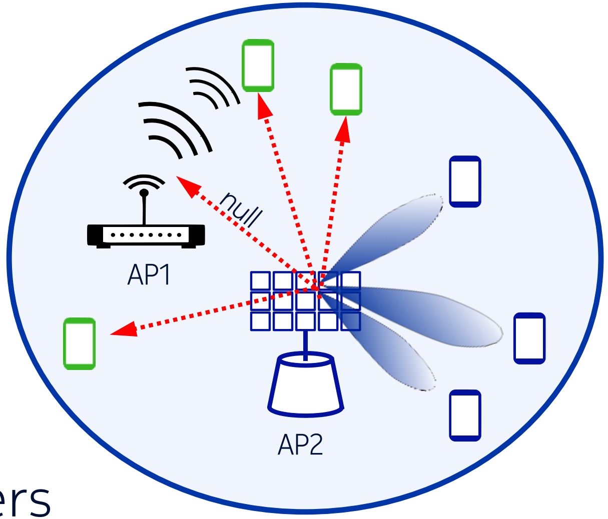
Spatial multiplexing

- Support of up to 16 spatial streams [10]
- Enhance channel state information (CSI) acquisition [11]:
  - 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



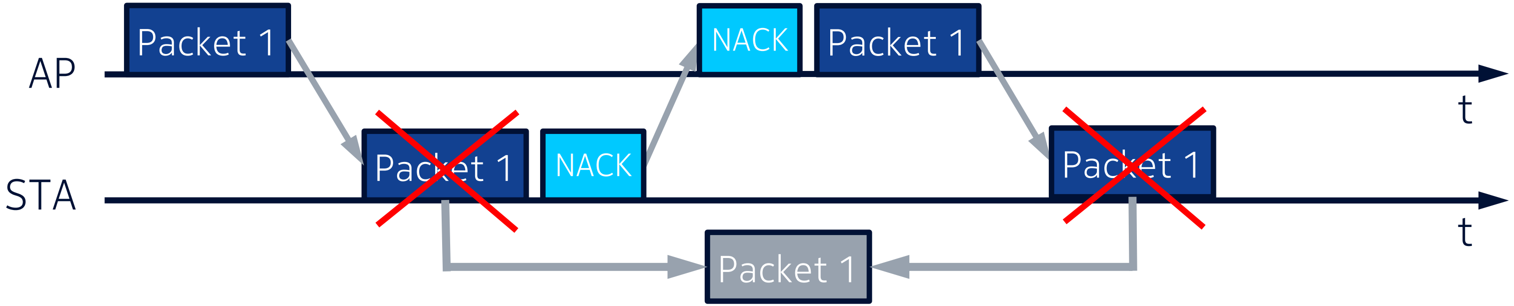
Multi-AP coordination

- Coordination approaches with different degrees of complexity [9, 12-14]:
  - Time/frequency coordinated scheduling
  - Inter-cell interference coordination
    - Null steering
  - Distributed MIMO
    - Inter-AP synchronization
  - Multi-AP association to facilitate handovers



Hybrid automatic repeat request (HARQ)

- Key objective: Help link adaptation through retransmission [15]
  - Theoretical SNR gains in the order of 4 to 6 dB
  - Already discussed during 802.11ac and 802.11ax standardization
- Drawback: HARQ might not be robust enough against collisions caused by the unpredictable interference conditions in 802.11



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Performance Overview: Massive MIMO benefits

Outline

- System evaluation set-up
- Spatial reuse
- Beamforming and multiplexing
- Throughput
- Conclusions

System evaluation set-up

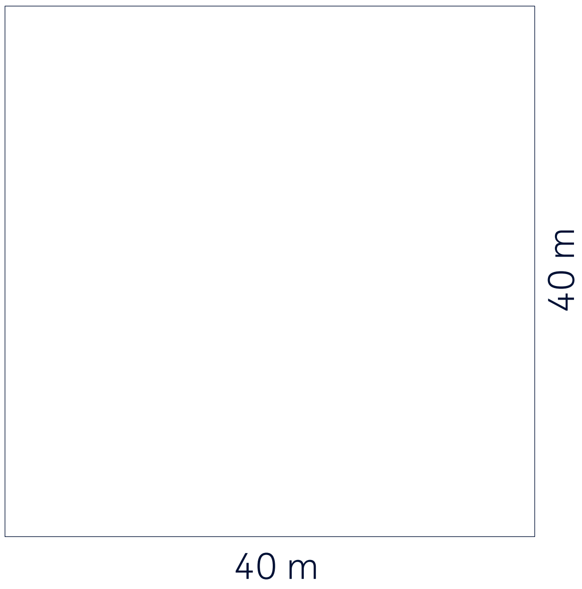
Indoor Enterprise Scenario: Main Simulation Parameters

- 1 floor with area size 40m x 40m.

- 3GPP TR38.901 InH with mixed office line of sight (LoS) probability. Internal wall losses are considered statistically.

- 256 single-antenna stations (STAs) uniformly distributed within the floor (0.1m of minimum inter-STA distance) and located at 1m height.

- 10 simulation drops of 10 seconds performed, to take into account variations caused by stations (STAs) locations, shadowing, LoS/NLoS probabilities, etc.



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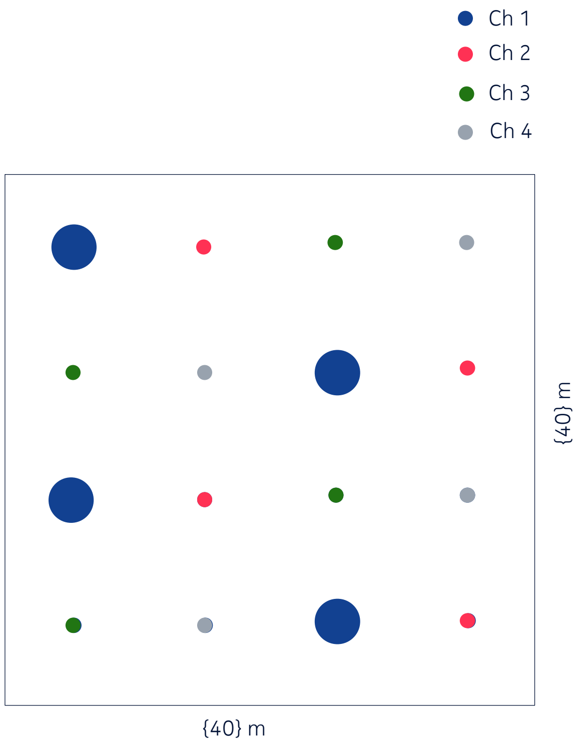
Indoor Enterprise Scenario: Access Points Deployment

- AP Ceiling-mounted at 3 meters height
- 4 channels of 80 MHz each
- 4 APs per channel
- Different AP configurations tested



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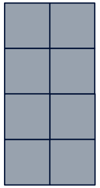
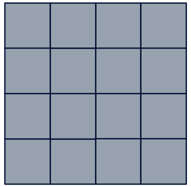
Access Point Configuration

Baseline APs

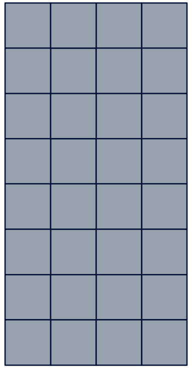


- 4x2 fully digital array
- ZF precoding
  (9 dBi max. beam gain)

EHT "friendly" mMIMO APs

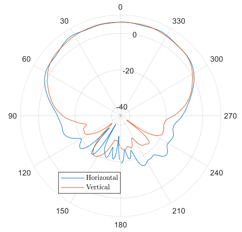


- 4x4 fully digital array
- ZF precoding (12dBi max. beam gain)



- 8x4 fully digital array
- ZF precoding (15dBi max. beam gain)

Single Element



***Opt. 1:* omnidirectional** antenna element (0 dBi),

Opt. 2: directional antenna element (7 dBi)

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Indoor Enterprise Scenario: Detailed Simulation Parameters

PHY	
Carrier frequency	5.8 GHz
System bandwidth	4 x 80 MHz
Channel bonding	80 MHz (fixed)
AP maximum EIRP	30 dBm (U-NII-2)
STA TX power	15 dBm
OFDM numerology	802.11ax
Channel estimation	Perfect channel estimation
AP digital precoding	Zero forcing
STA mobility	0 km/h
AP noise figure	7 dB
STA noise figure	9 dB
STA antenna gain	0 dBi
Thermal noise	-174 dBm/Hz

MAC	
STA association	Based on RSRP
Multiple access scheme	OFDMA
AP scheduling criterion	Round Robin
Spatial multiplexing	Downlink and uplink MU-MIMO with up to 8 STAs spatially multiplexed
Traffic model	FTP3: File size = 0.5 Mbytes, offered traffic = 25 Mbps*, uplink and downlink traffic generation with same probability

* Ultra HD video streaming type of traffic (source: Netflix)

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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 reduced number of antennas (in our case only 1)

Implications:

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

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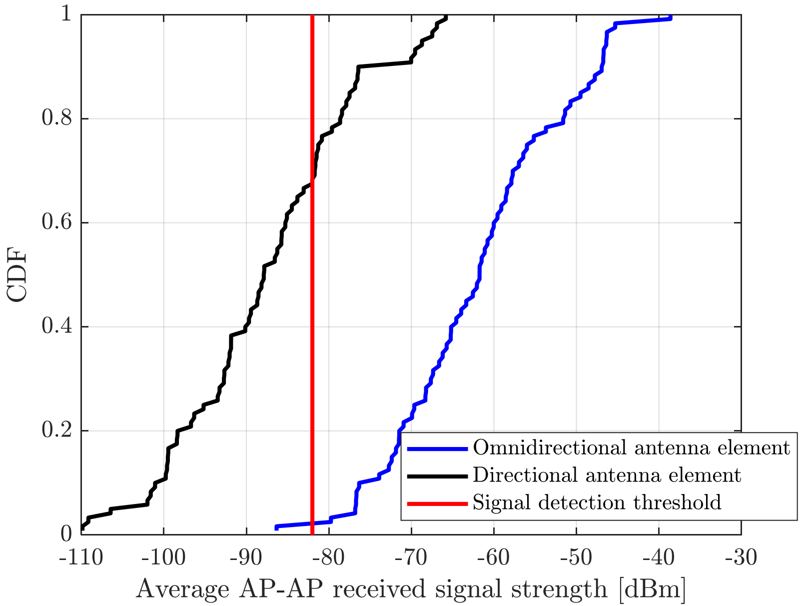
Spatial Reuse

Spatial Reuse: the effect of directive antenna elements



Observations:

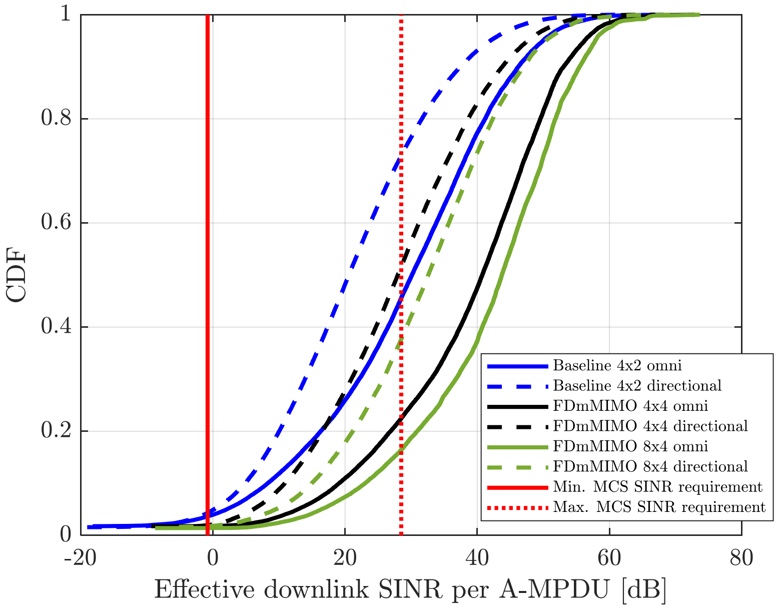
- Spatial reuse opportunities are decided during the LBT phase (single antenna measurement).

- Omnidirectional antenna element:
  - Almost certainly all APs listen to each other, thus they have to access the channel alternatively.

- Directional antenna element:
  - More than 60% of the time APs do not listen to each other, thus leading to an increase of the spatial reuse, but potentially to higher interference.

Beamforming and Multiplexing

DL SINR: the effect of spatial reuse



When the PLCP header is not decoded, by convention, we set the A-MPDU SINR to –Inf.

- Increased spatial reuse introduced by directive antenna elements leads to higher interference, thus resulting in lower SINR.
- EIRP limitation in DL reduces the potential beamforming gain introduced by large antenna arrays.
- Large antenna arrays mainly introduce benefits in terms of spatial resolution (nearby STAs can be better separated).
- Large antenna arrays help when many users are multiplexed (precoder/decoder are better dimensioned).

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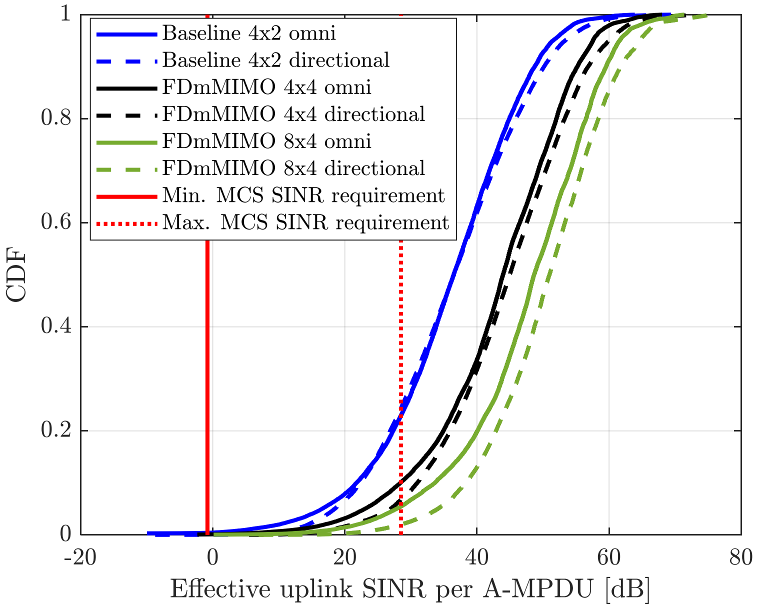
UL SINR: the effect of beamforming



When the PLCP header is not decoded, by convention, we set the A-MPDU SINR to –Inf.

- With no EIRP limitations, large antenna arrays are free to bring-in their higher beamforming gain.
- Directive antenna elements increase spatial reuse, leading to higher interference. At the same time, they further boost the beamforming gain, especially when the precoder/decoder is well dimensioned as with larger antenna arrays.

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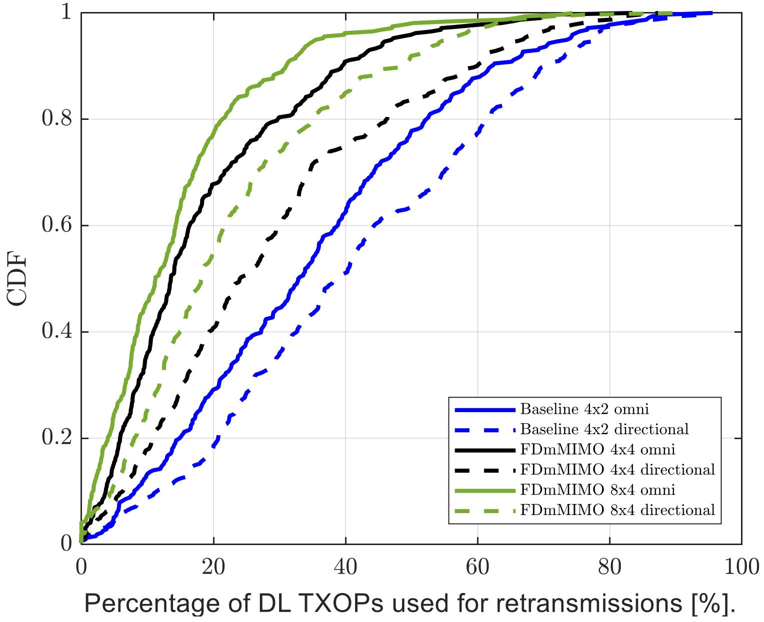
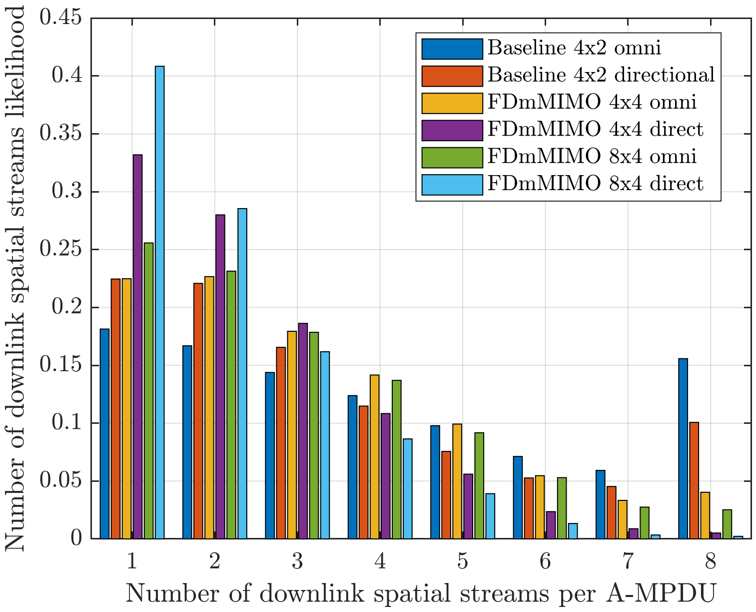
DL retransmissions



- The large number of retransmissions is a result of the high traffic demand (25 Mbps per STA).
- Many retransmissions force the system to schedule more STAs within the same TXOP.
- Higher spatial reuse supported by directional antenna elements generates more retransmissions compared to the omnidirectional case.
- Larger arrays are more suitable to deal with the high traffic, due to their better spatial multiplexing capabilities.

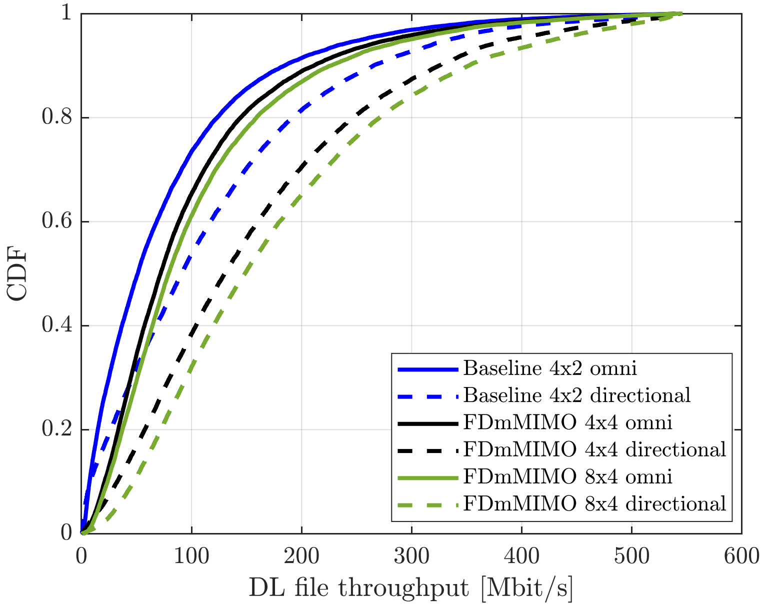
DL spatial streams: the effect of multiplexing



- Baseline 4x2 AP with omnidirectional antenna elements transmits 15% of the time with 8 spatial streams.
- Massive MIMO 8x4 configuration with directional antenna elements transmits 40% of the time with only 1 spatial stream.

Throughput

DL file throughput



- 8x4 vs 4x2 array configuration:
  - Around 54% gain at the median with omni antenna elements.
  - Around 63% gain at the median with directive antenna elements.

- In massive MIMO 8x4 configuration:
  - Around 87% gain at the median introduced by directive antenna elements compared to omni antenna elements.

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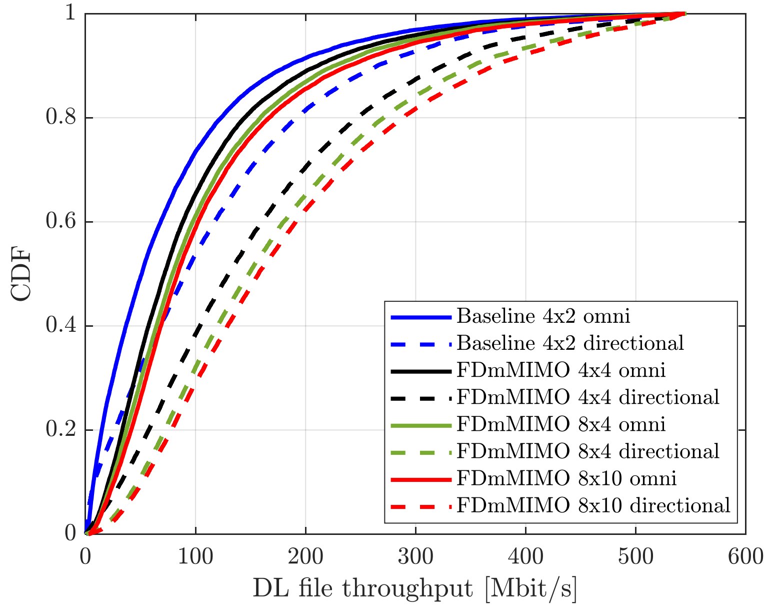
DL file throughput



- 8x4 vs 4x2 array configuration:
  - Around 54% gain at the median with omni antenna elements.
  - Around 63% gain at the median with directive antenna elements.
- In massive MIMO 8x4 configuration:
  - Around 87% gain at the median introduced by directive antenna elements compared to omni antenna elements.
- Further increasing the array size (8x10) does not introduce significant gains:
  - In line with the number of DL spatial streams statistic.
  - Higher traffic demands or lower AP density may impact the conclusion.

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Conclusions

Conclusions

1. Directional antenna elements help to isolate APs from each other, increasing the spatial reuse at the expense of higher interference (and more retransmissions).

2. Increasing antenna array size improves SINR and reduces retransmissions:
   - Higher spatial resolution and multiplexing gain.
   - Beamforming in DL is limited by EIRP regulations, but fully exploited in UL.

3. Large antenna arrays reduce the need of multiplexing many STAs in the same TXOP:
   - Higher traffic demands will trigger increasing spatial multiplexing needs.
   - In line with EHT, some of the degrees of freedom can be used for nulling, instead for multiplexing.

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Abu Dhabi, UAE

12 December 2018

Q&A

