Next-generation Wi-Fi for ever more demanding applications

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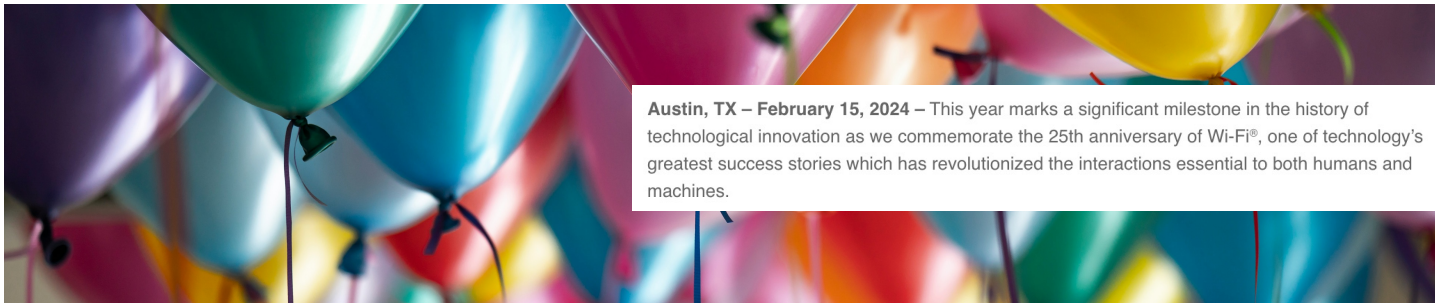

Austin, TX – February 15, 2024 – This year marks a significant milestone in the history of technological innovation as we commemorate the 25th anniversary of Wi-Fi®, one of technology's greatest success stories which has revolutionized the interactions essential to both humans and machines.

25 YEARS

Wi Fi ALLIANCE

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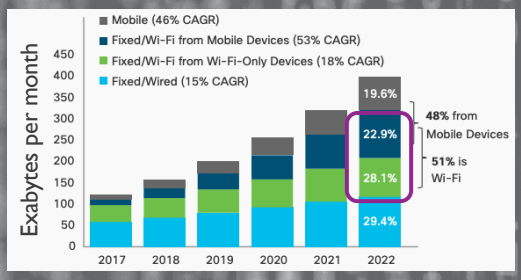
Local networking

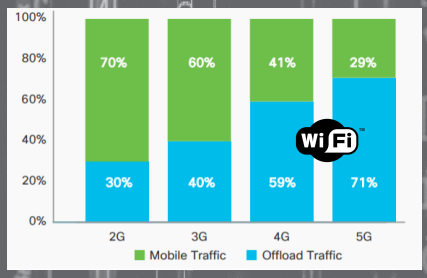
Connectivity for homes and enterprises

Unlicensed spectrum

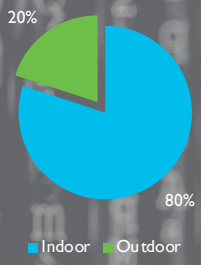
> 21.000.000.000 devices in use today
4.000.000.000 new devices in 2023



1) IP traffic by access technology



2) Mobile and offload traffic from mobile connected devices



3) Data origin

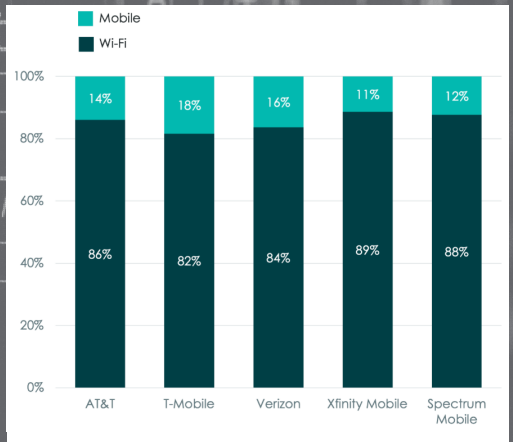
Source 1) & 2): Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2017–2022
Source 3) Chttps://www.abiresearch.com/press/abi-research-anticipates-building-mobile-data-traf/

Bombshell report: Mobile data consumption over Wi-Fi closes in on 90% in the US

November 1, 2024 | BREAKING NEWS | by Claus Hetting, Wi-Fi NOW CEO & Chairman

By Claus Hetting, WiFi NOW CEO & Chairman

We've known for more than a decade that Wi-Fi carries by far the lion's share of smartphone traffic nearly everywhere across the globe – but now finally we have fresh numbers at least for the US: Wi-Fi's proportion of data traffic on smartphones is now closing in on a staggering 90% overall and even exceeds (in nearly all cases) 80% away from home. We suspected as much but OpenSignal's report just released confirms it.

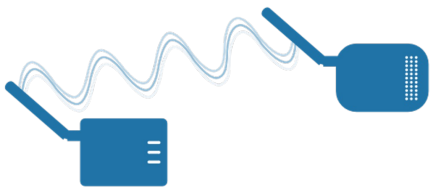


Source: https://www.opensignal.com/2024/10/31/wi-fi-drives-smartphone-data-consumption-in-the-us-but-trends-vary-across-operators?_ga=2.215940887.1692113672.1733736898-1673882283.1733736898

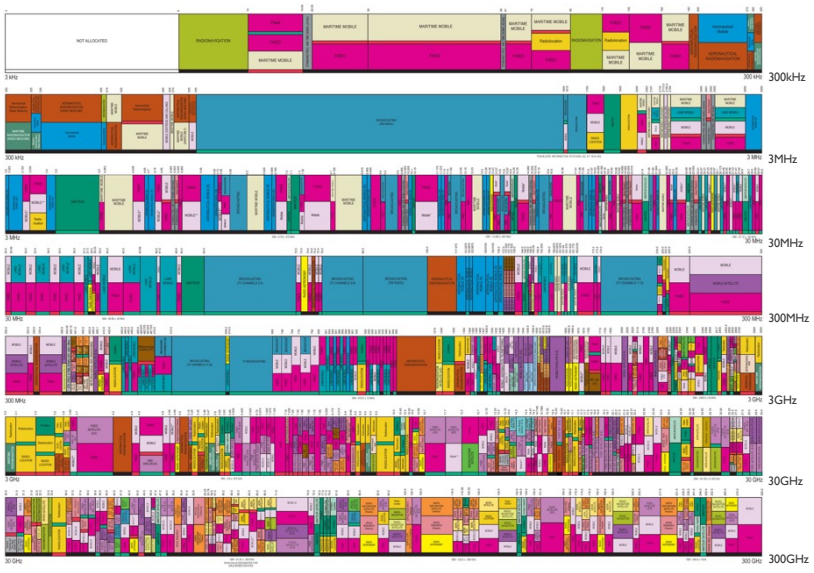
Wireless communication basics

Wireless signal

Electromagnetic wave at certain frequency



- Licensed
  - Paid
- Unlicensed
  - Free to use
  - Rules to ensure coexistence
  - E.g. 2.4GHz, 5GHz, etc.



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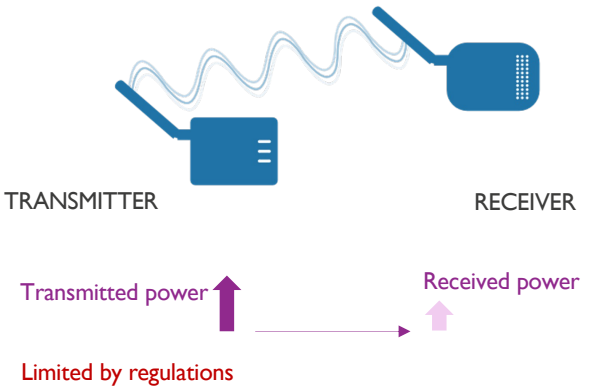
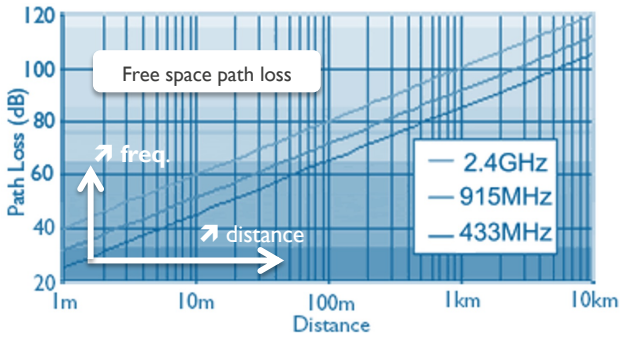
Frequency affects range

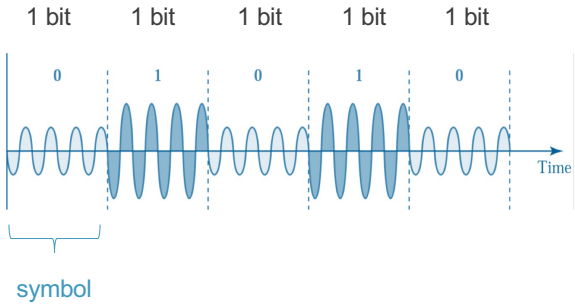
But also Tx power, antenna, receiver sensitivity, *modulation*, obstacles, etc.



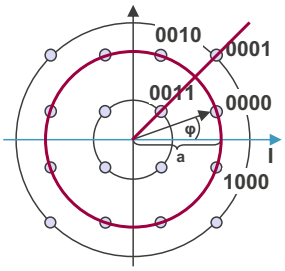


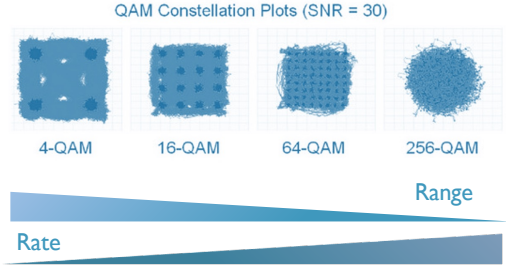
Modulation

Is required to encode information



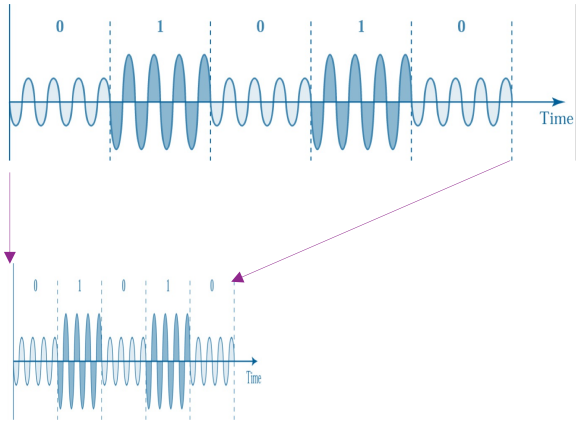
E.g. 16-QAM





Increase rate by sending symbols faster

But this requires more bandwidth



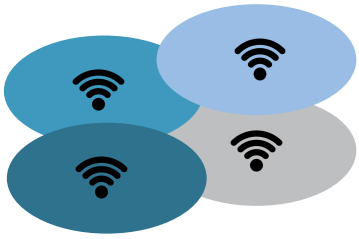
BAND	AVAILABLE BANDWIDTH
868MHz	7 MHz
2.45 GHz	150 MHz
5.80 GHz	Up to 750 MHz
60 GHz	Up to 4000 MHz

Channel capacity $C = B \log_2\left(1 + \frac{S}{N}\right)$

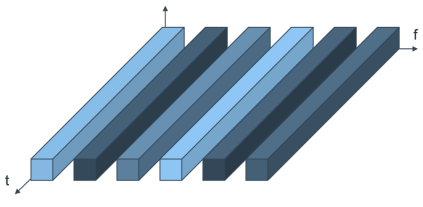
- Upper bound on rate at which information can be reliably transmitted
- Requires intelligent coding/modulation techniques

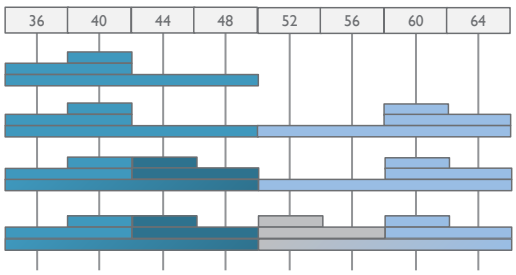
Available bandwidth needs to be shared

Across systems



Divide available bandwidth in channels

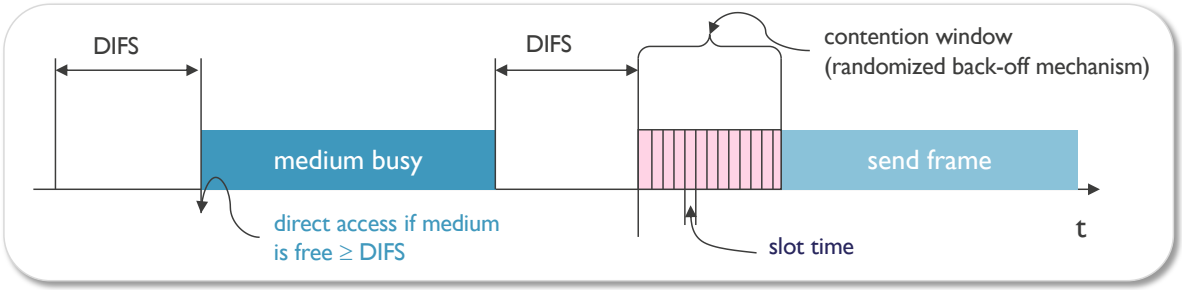




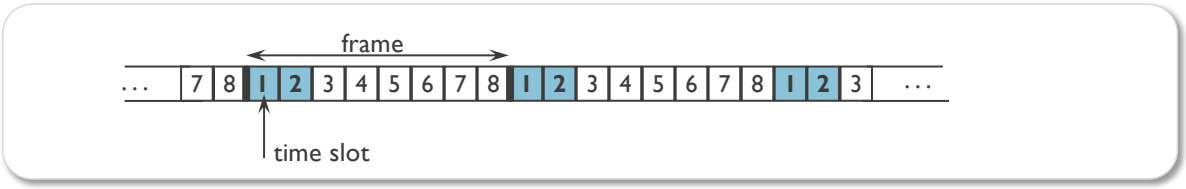
Available bandwidth needs to be shared

Within system

CSMA/CA



TDMA



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Evolution of Wi-Fi from 1999 until 2013 (Wi-Fi 5 or IEEE 802.11ac)

Focus on speed

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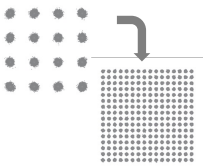
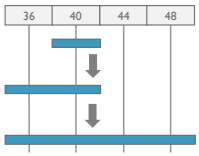
Evolution of Wi-Fi from 1999 until 2013 (Wi-Fi 5)

Focus on speed

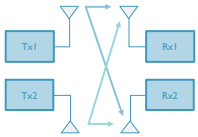
1. Modulation and coding



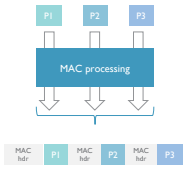
2. Bandwidth



3. Spatial Streams



4. Aggregation



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Evolution of Wi-Fi from 1999 until 2013 (Wi-Fi 5)

Focus on speed

Year	Amendment	RF / Modulation	Channel width	2.4 | 5 | 6 GHz	Max. streams	Data rate
1997	802.11 legacy	DSSS, FHSS	20 MHz	✓ | X | X	1 (SISO)	1-2 Mbps
1999	802.11b	HR-DSSS	20 MHz	✓ | X | X	1 (SISO)	1-11Mbps
1999	802.11a	OFDM 64-QAM	20 MHz	X | ✓ | X	1 (SISO)	6-54 Mbps
2003	802.11g	OFDM 64-QAM	20 MHz	✓ | X | X	1 (SISO)	6-54 Mbps
2009	802.11n	OFDM 64-QAM	20/40 MHz	✓ | ✓ | X	4 (SU-MIMO)	Up to 600 Mbps
2013	802.11ac	OFDM 256-QAM	20/40/80/ 160MHz or 80+80MHz	X | ✓ | X	8 (*DL* MU-MIMO)	Up to 6.93 Gbps

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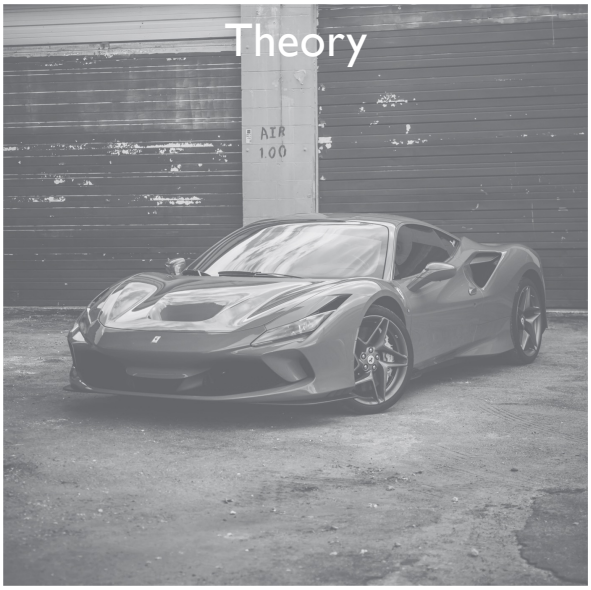
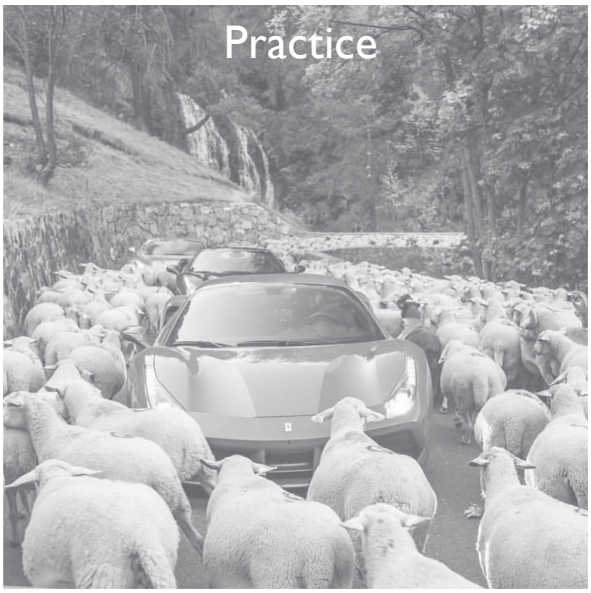
Wi-Fi 6(E) (802.11ax) and beyond

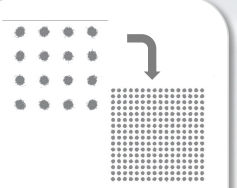
More speed?

Year	Amendment	RF / Modulation	Channel width	2.4 | 5 | 6 GHz	Max. streams	Data rate
1997	802.11 legacy	DSSS, FHSS	20 MHz	✓ | X | X	1 (SISO)	1-2 Mbps
1999	802.11b	HR-DSSS	20 MHz	✓ | X | X	1 (SISO)	1-11Mbps
1999	802.11a	OFDM 64-QAM	20 MHz	X | ✓ | X	1 (SISO)	6-54 Mbps
2003	802.11g	OFDM 64-QAM	20 MHz	✓ | X | X	1 (SISO)	6-54 Mbps
2009	802.11n	OFDM 64-QAM	20/40 MHz	✓ | ✓ | X	4 (SU-MIMO)	Up to 600 Mbps
2013	802.11ac	OFDM 256-QAM	20/40/80/ 160MHz or 80+80MHz	X | ✓ | X	8 (*DL* MU-MIMO)	Up to 6.93 Gbps
2019	802.11ax	OFDM(*A*) 1024-QAM	20/40/80/160 80+80	✓ | ✓ | ✓	8 (*UL/DL* MU-MIMO)	Up to 9.60 Gbps
2024 2028	802.11be 802.11bn	OFDM(*A*) 4096-QAM	Up to 320MHz	✓ | ✓ | ✓	8 (*UL/DL* MU-MIMO) 16 (*UL/DL* MU-MIMO)	Up to 23 Gbps Up to 46 Gbps

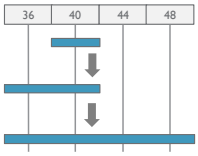
Speed



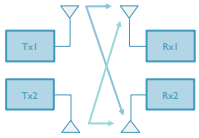




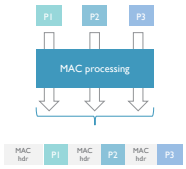
- Only in optimal conditions
- Not everything sent at highest speed



- Availability?
- Densely deployed APs?
- Constrained devices?



- Small form factor devices with limited number of antennas



- Not suitable for all traffic types

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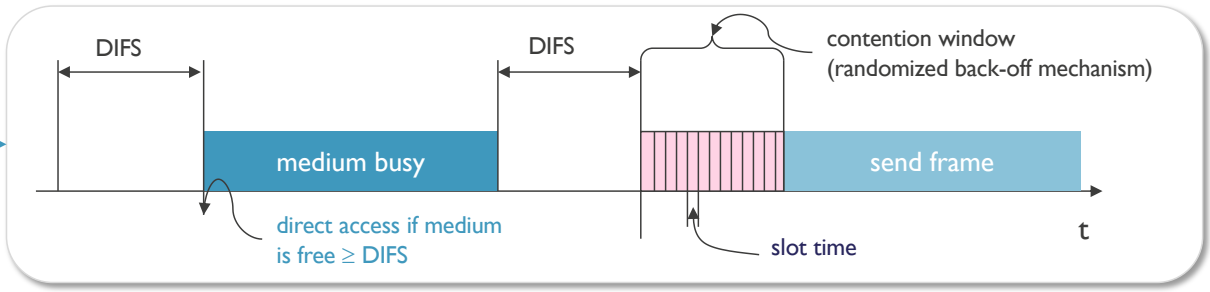
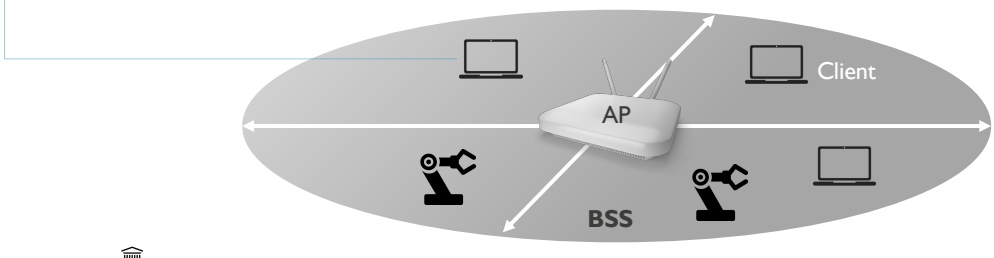
Main showstopper = contention!

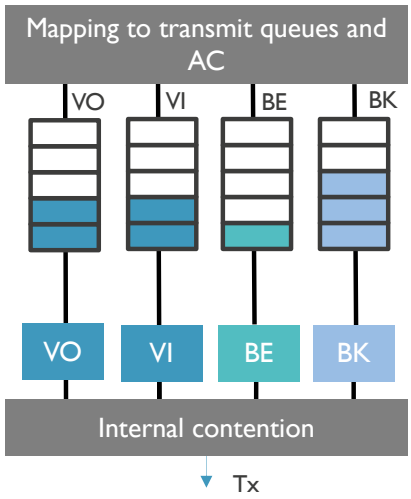
Among nodes | *within node* | across overlapping BSS





QoS support

Enhanced Distributed Channel Access (EDCA) (IEEE 802.11e)



AC	CWmin	CWmax	AIFSN	Max TXOP
Background (AC_BK)	15	1023	7	0
Best Effort (AC_BE)	15	1023	3	0
Video (AC_VI)	7	15	2	3.008ms
Voice (AC_VO)	3	7	2	1.504ms

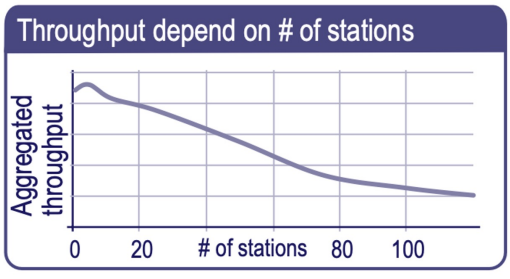
IEEE 802.11aa: AC_VO and AC_VI are enhanced with an additional queue to support intra-AC prioritization.

Reality

Single device with queue always filled

No. aggr. pkts	Pkt size (bytes)	Data rate (Mbps)	Application throughput (Mbps)
1	150	12	3.78
1	150	36	5.62
1	1500	36	23.37
10	150	36	23.37
10	1500	36	34.15

Single AP with many stations



Source: Rohde & Schwarz, "Realizing extreme high throughput with Wi-Fi 7"

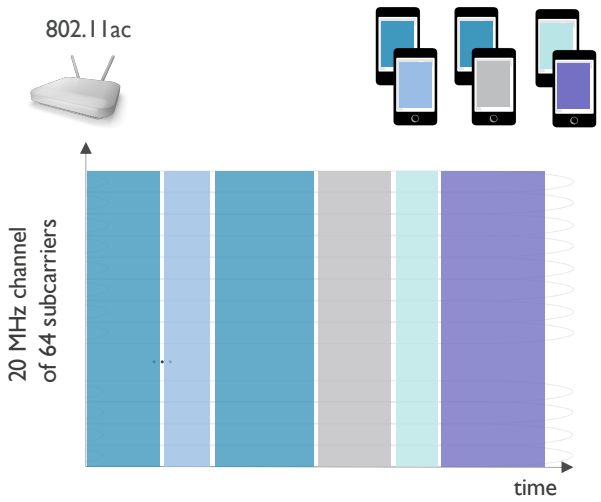
Wi-Fi 6 (802.11ax)

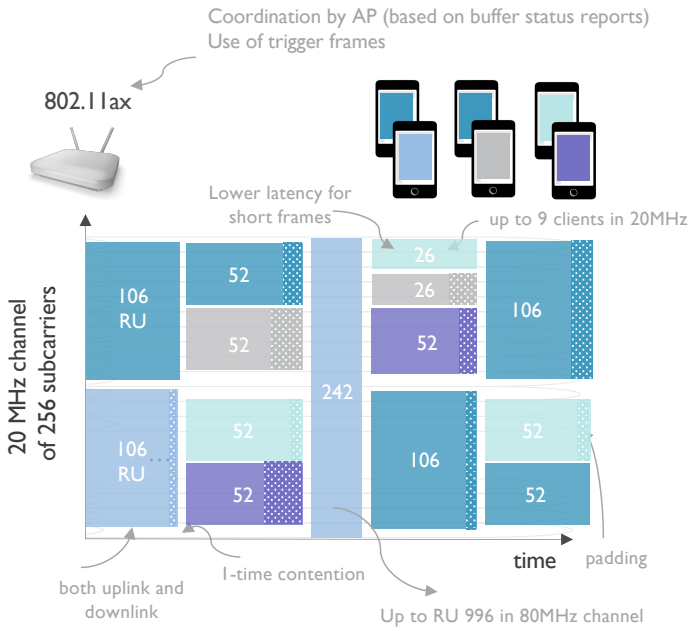
Paradigm shift: more than just speed

Amendment that defines
modifications to the
PHY and MAC sublayer for
high efficiency operations
in frequency bands between
1 GHz and 6 GHz

OFDMA

Concept: partitioning of frequency space

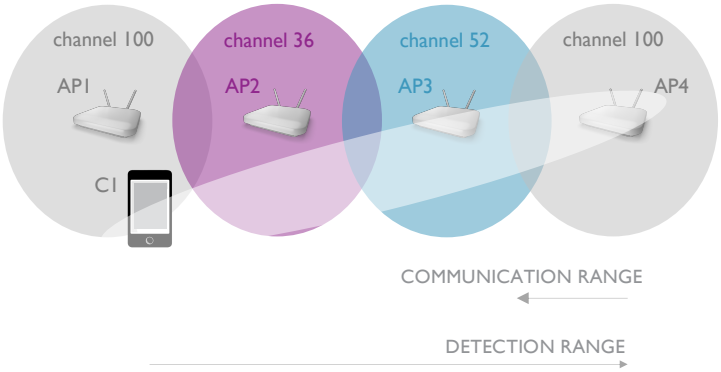


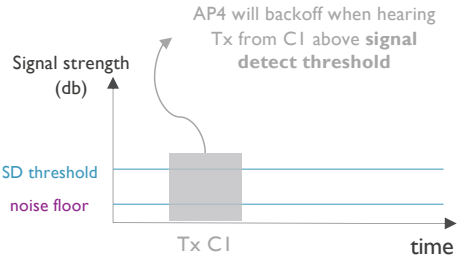


BSS coloring and spatial reuse

Problem

Overlapping BSS → contention, consuming valuable airtime

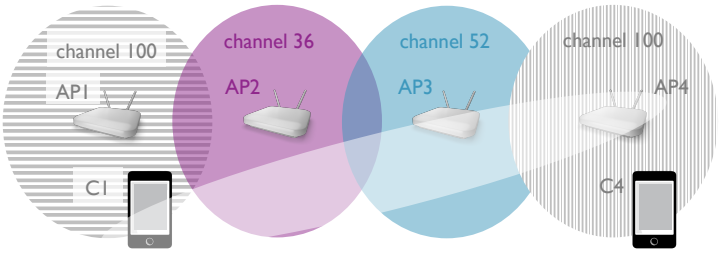




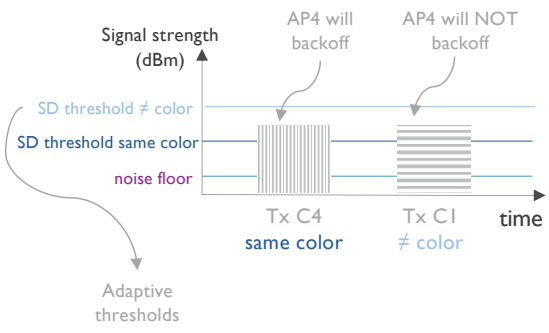
BSS coloring and spatial reuse

Solution

Use of BSS coloring: 6-bit identifier of BSS → **Color dependent channel access (CCA)**



color information is communicated at both the PHY layer and the MAC sublayer

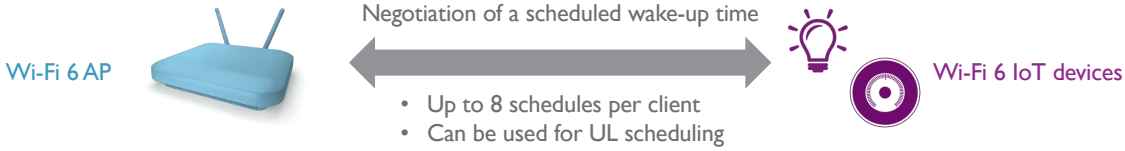


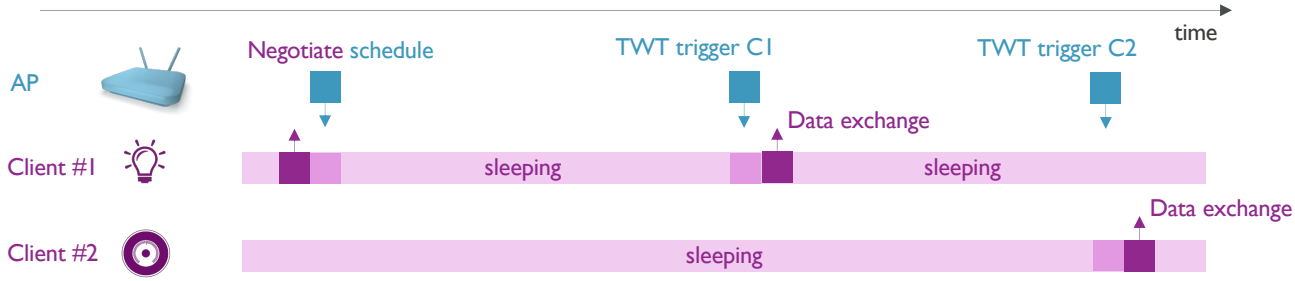
Target Wake Time (TWT)

Power-saving mechanism

Negotiation of a scheduled wake-up time

Individual TWT





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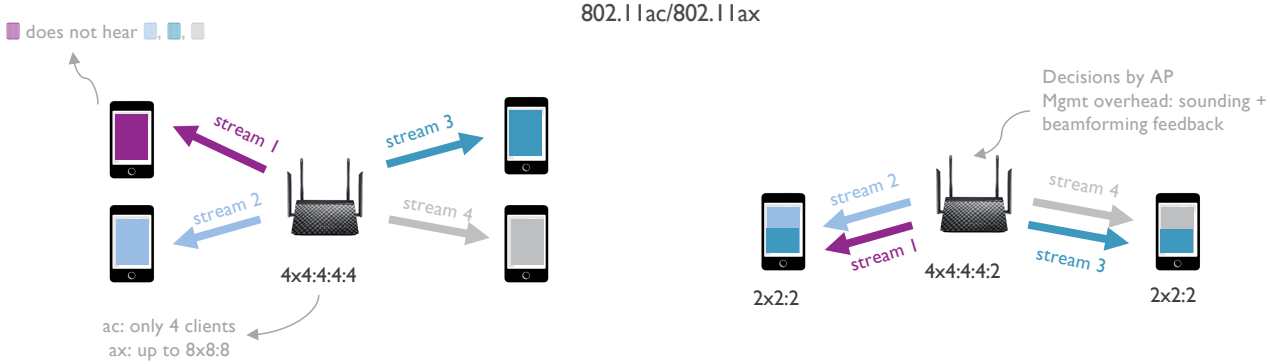
Broadcast TWT: AP provides sleep period for group of devices

MU-MIMO

Concept: use of spatial diversity to send multiple streams at same time

Downlink MU-MIMO

802.11ac/802.11ax



Uplink MU-MIMO

802.11ax

MU-MIMO + OFDMA (RU ≥106)

802.11ax

only in Wave 2

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Additional enhancements

Other

1.

Longer symbol time (12.8us instead of 3.2us)

3 different guard intervals

Longer guard intervals for high multipath indoor environments or for more robust outdoor communication

2.

20MHz only mode for clients

- Can take part in OFDMA, but only primary RU
- For small form factor devices with limited processing capability and lower power requirements

3.

Multi-Traffic Identifier AMPDU

- Aggregation of frames from multiple QoS access categories and TIDs
- More efficient aggregation, increasing efficiency and throughput

4.

WPA3

- Latest security standard
- More robust authentication and increased cryptographic strength

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Wi-Fi 6E

New deployment options

2.4GHz spectrum

5GHz spectrum

It's official: EU releases 480 MHz of 6 GHz spectrum to Wi-Fi – finally

June 30, 2021 | Breaking News | by Claus Hetting, Wi-Fi NOW CEO & Chairman

By Claus Hetting, Wi-Fi NOW CEO & Chairman

Europeans should be celebrating today – and not (at least not yet) because of the football: The European Commission today formally released the lower 6 GHz band to Wi-Fi. The decision was formally announced in the Official Journal of the European Union and is now binding for EU member states. At the global level the EU is still far behind the Americas, the Middle East, and parts of Asia in allocating 6 GHz spectrum.

The European Commission today formally released 480 MHz of (low) 6 GHz spectrum to Wi-Fi. The announcement came in the form of publication of the new rules in the Official Journal of the European Union here. The decision is binding for all EU member states. This in practice means that every EU member state must update their national frequency allocation plans to reflect the 6 GHz decision before December 1, 2021, sources say.

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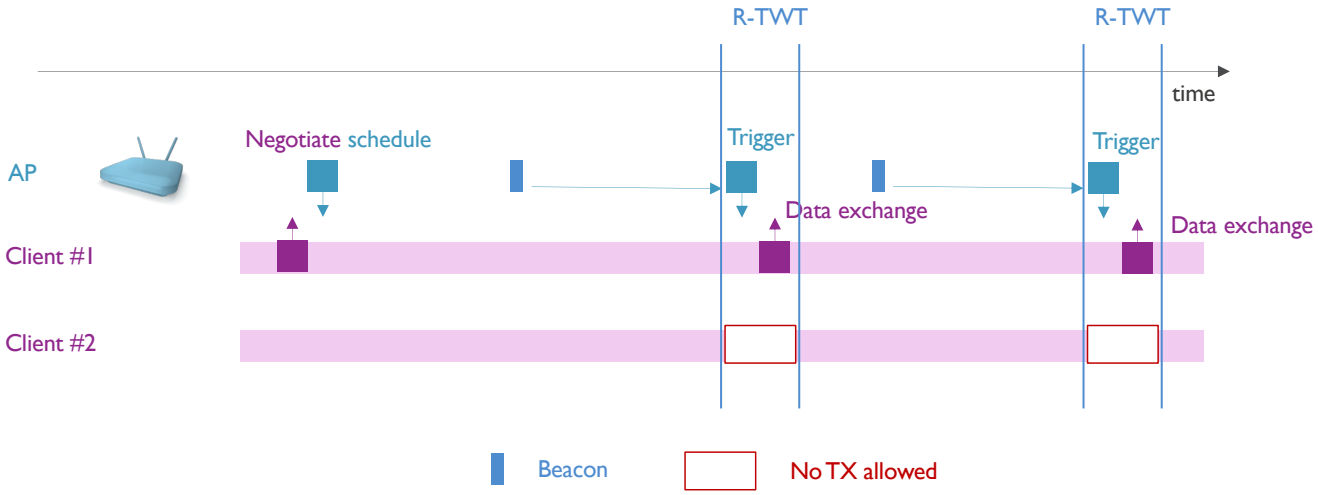
Wi-Fi 7 (IEEE 802.11be)

Enhancements for Extremely High Throughput (EHT)

	Wi-Fi 6	Wi-Fi 7
Max. BW (MHz)	160	320
Bands (GHz)	2.4, 5 and 6	2.4, 5 and 6
Max. PHY rate	Up to 9.6 Gbps	Up to 23 Gbps
Modulation	1024 QAM	4096 QAM
Spatial streams	8	8
MU-MIMO	UL & DL	UL & DL
Target Wait Time	Individual, broadcast	Restricted
OFDMA (#RU/STA)	Yes (single)	Yes (*multiple*)
Multi-link operation		Yes
Other		Preamble puncturing, *triggered UL access optim., AP-triggered P2P,*

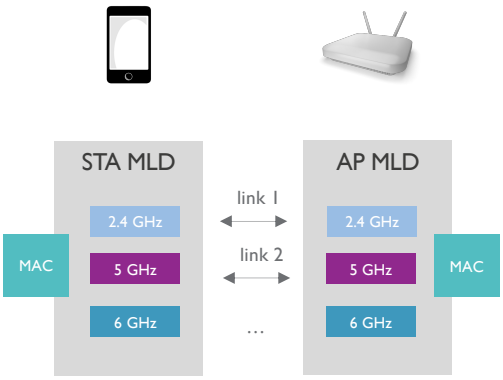
Restricted Target Wake Time (R-TWT)

Reserved time intervals without contention

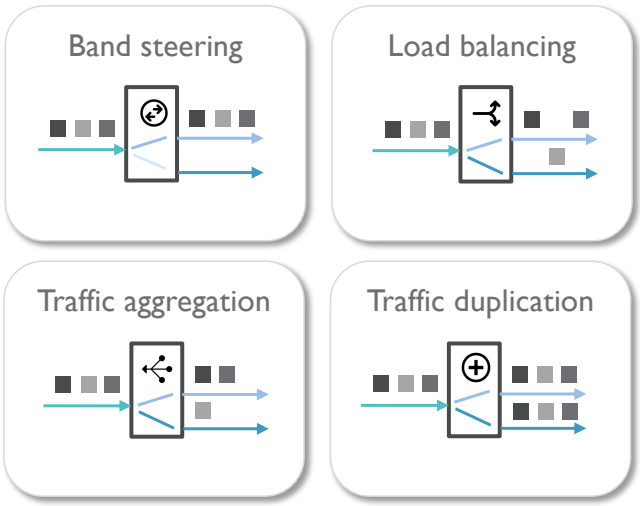


Multi-link operation

Combining 2 or more Wi-Fi bands into a single Wi-Fi link

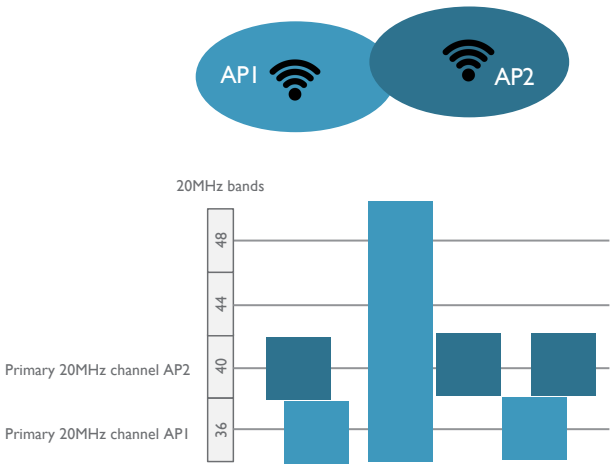


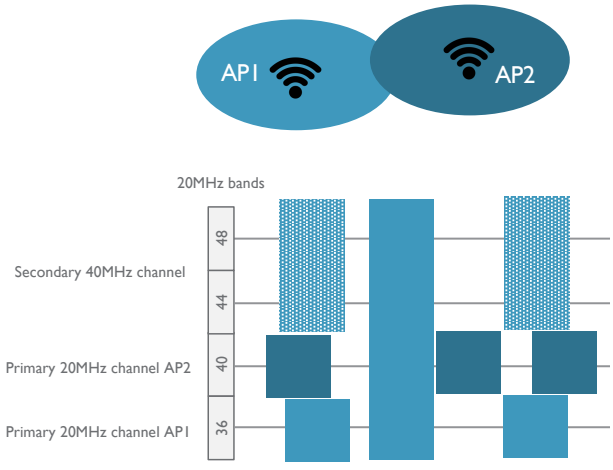
Non-simultaneous vs. simultaneous Tx/Rx



Preamble puncturing

Overcoming difficulty to find clear contiguous channels of 80MHz and larger





Wi-Fi 8 (IEEE 802.11bn)

Ultra-high reliability (UHR)

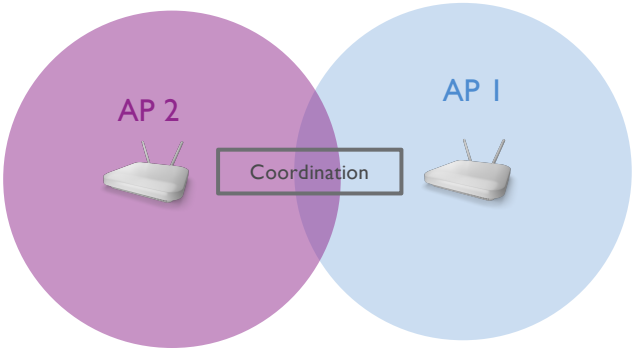
Expectations

	Wi-Fi 6	Wi-Fi 7	Wi-Fi 8
Max. BW (MHz)	160	320	320
Bands (GHz)	2.4, 5 and 6	2.4, 5 and 6	2.4, 5 and 6
Max. PHY rate	Up to 9.6 Gbps	Up to 23 Gbps	Up to 46 Gbps
Modulation	1024 QAM	4096 QAM	4096 QAM
Spatial streams	8	8	16
MU-MIMO	UL & DL	UL & DL	UL & DL
Target Wait Time	Individual, broadcast	Restricted	Coordinated
OFDMA (#RU/STA)	Yes (single)	Yes (multiple)	Yes (multiple)
Multi-link operation		Yes	Yes (distributed)
Multi-AP coordination			Yes
Other		Puncturing, *AP-triggered P2P, triggered UL access optim.*	*+ HARQ, AP power saving, dRU, NPCA*

High-criticality use cases

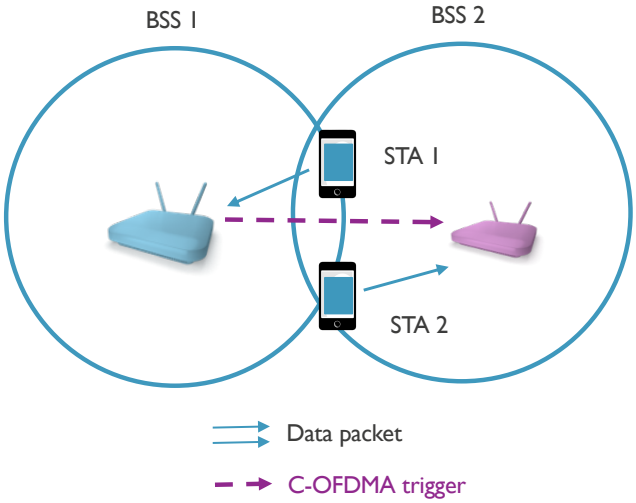
AP coordination

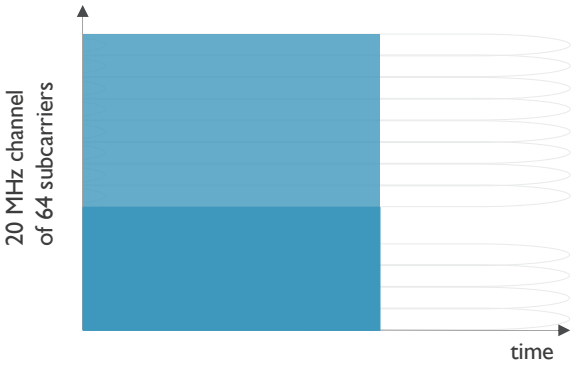
Over-the-air, via trigger frames



AP coordination

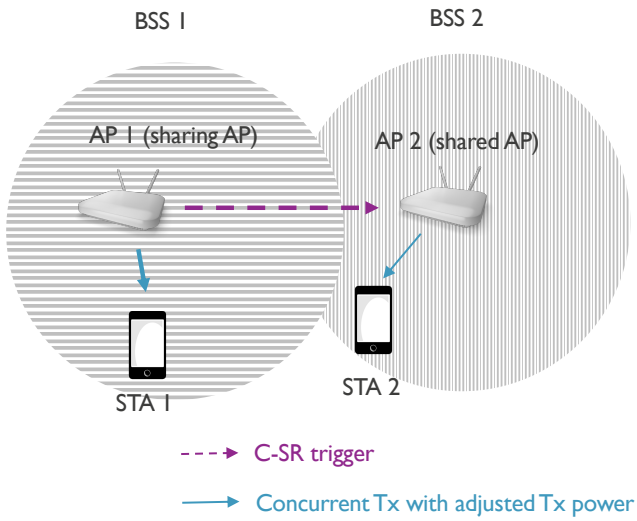
Example 1: Coordination UL OFDMA



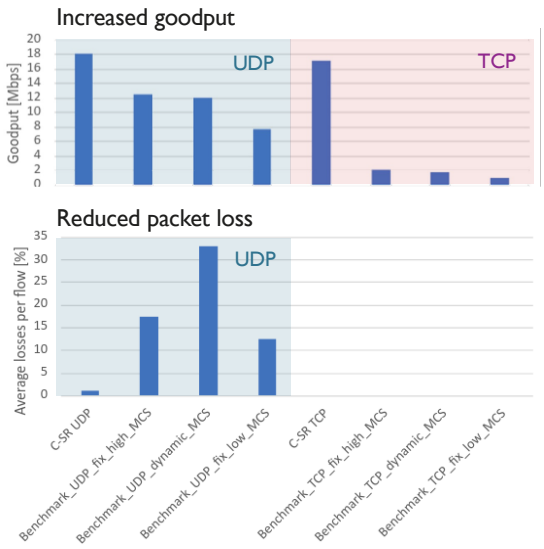


AP coordination

Example 2: Coordinated Spatial Reuse (C-SR)



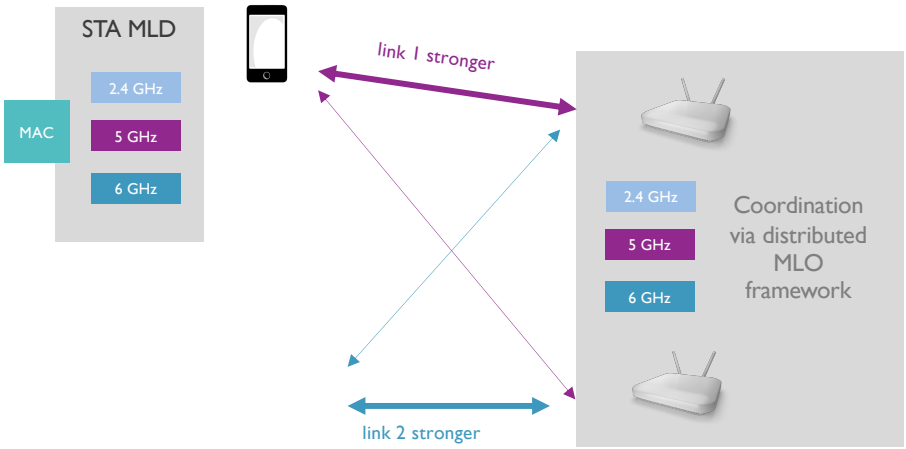
Up to 50% increase in goodput



J. Haxhibeqiri *et al.*, "Coordinated spatial reuse for WiFi networks : a centralized approach," WFCS 2024
J. Haxhibeqiri et al., "Coordinated SR and Restricted TWT for Time Sensitive Applications in WiFi 7 Networks," IEEE Communications Magazine, vol. 62, no. 8, pp. 118-124, August 2024

Distributed MLO

Overcome unreliability due to device roaming



Markets

Industrial automation
Ultra-reliable, low-latency (20µs-10 ms) M2M communication

Energy & power
Smooth functioning of energy production/distribution systems

Oil & gas
Timely communication for process and control networks

Tactile Internet
Human-machine interaction: E2E latency < 5ms

Audio & video
Real-time, low-latency professional multimedia

Holographic-type communications
E2E latencies < 20ms, Gbps rates

Social roboverse /Collaborative robotics
Multi-sensory input to remote decision-making < 10-100ms

Transportation
Continuous train and trackside communication

Automotive
Safety-critical and real-time in-vehicle systems

Aerospace
Precise time-stamped data acquisition and real-time traffic

Mission-critical communication
Reliable & secure MCX services, ad-hoc tactile bubbles

High-Performance Computing (HPC)
High-speed data plane, Low-latency & reliable P2MP control plane

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Time-sensitive networking (TSN)

Time synchronization
All devices in the network have the same sense of time with sub-microsecond accuracy

Resource management
Configuration and management of resources to meet the requirements of TS streams

Bounded low latency
TS traffic streams are delivered within a specified time via scheduling and shaping

Ultra reliability
TS traffic is protected against bandwidth violations and redundancy is provided

Set of IEEE 802.1 standards for deterministic transmission over Ethernet

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Problems

Time synchronization

Understanding Precision Time Protocol in Today's Wi-Fi Networks: A Measurement Study

Paizhuo Chen and Zhice Yang, *ShanghaiTech University*

https://www.usenix.org/conference/atc21/presentation/chen

This paper is included in the Proceedings of the 2021 USENIX Annual Technical Conference.

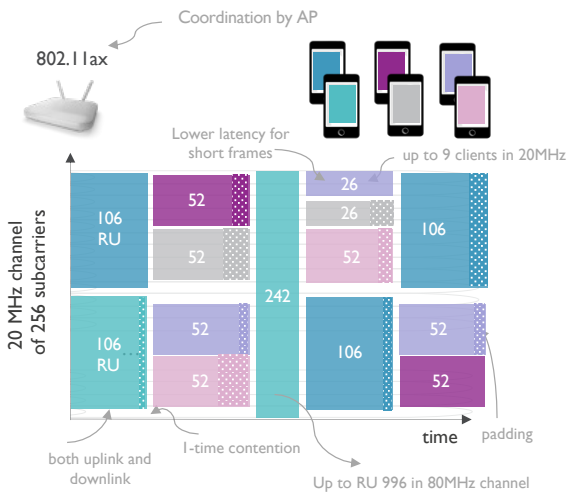
July 14–16, 2021

978-1-939133-23-6

- Software PTP
  - Reasonable accuracy with fine-tuned configurations and online calibration
  - Patching ath9k, a mature open source WNIC driver
- Hardware PTP
  - Most accurate
  - Requires PTP hardware timestamping clock not contained in Wi-Fi NICs or,
  - TSF timestamping provided there is a TSF counter reading interface

Problems

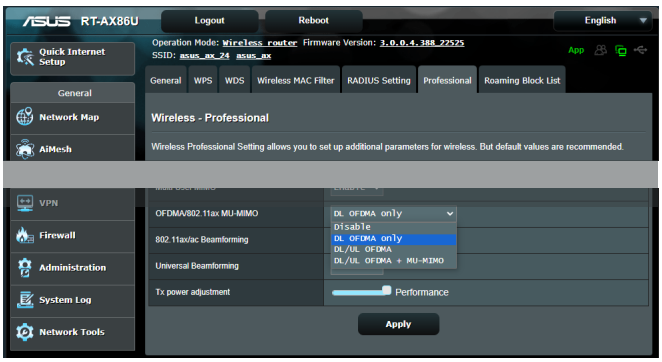
COTS chips = black box



Step 3	**dot11ax** *downlink-ofdma* **Example:** `Device(config-wlan)# dot11ax downlink-ofdma`	Enables the downlink connection that uses the OFDMA technology. Use the **no** form of the command to disable the configuration.
Step 4	**dot11ax** *uplink-ofdma* **Example:** `Device(config-wlan)# dot11ax uplink-ofdma`	Enables the uplink connection that uses the OFDMA technology .

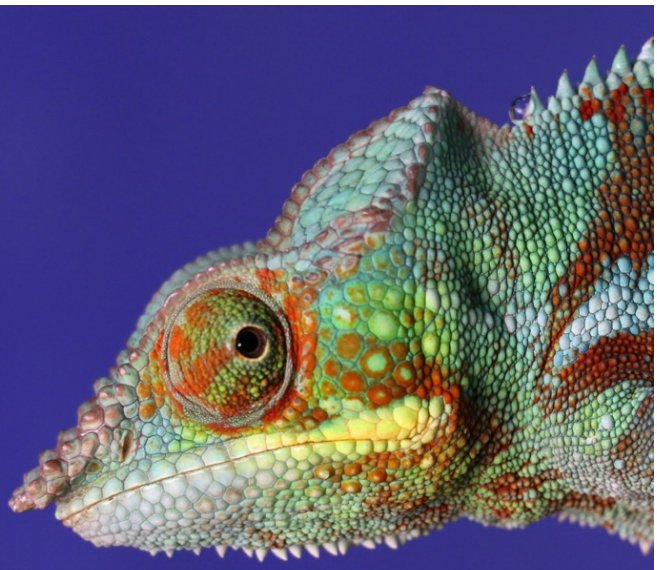
Send the below two commands to disable UL scheduler, *UL OFDMA*

```
iwpriv wlan32 he_ulofdma
wifitool wlan32 setUnitTestCmd 0x47 2 92
```



Level of control = ON/OFF

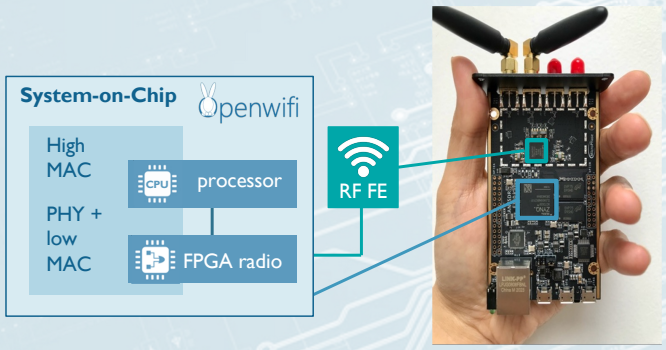
Specialized and customizable Wi-Fi innovation platform



Openwifi

Customizable Wi-Fi running on system-on-chip FPGA platforms

From digital baseband to Linux driver



Open-source AGPLv3
Dual licensing model

open source initiative®

Status Q4 2024: Wi-Fi 4
see https://github.com/open-sdr/openwifi)

Non open-source (Q4 2024)
Wi-Fi 6 features, advanced PHY, TSN features, etc.

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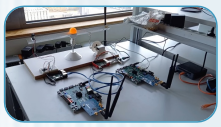
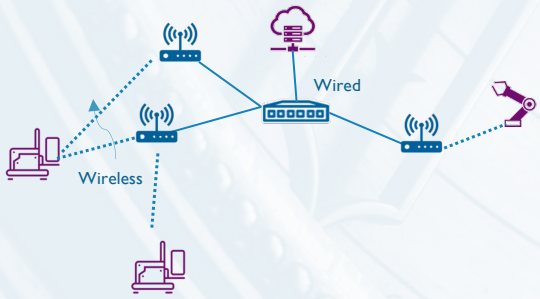
Enabling end-to-end wireless-wired TSN

Non/pre-standard

- Time synchronization with < 1.5 µs accuracy
- Flexible gating & over-the-air scheduling
- Low-level (time-aware) configurability
- Impactless bootstrapping
- Seamless mobility with determinism (<10ms handover)
- In-band telemetry
- Micro-services-based network controller (management, monitoring…)
- User interface

Technical PoC/EVK





End-to-end guarantees

Driver/SW

FPGA

openwifi

Conclusion

- Heading towards lower latency, higher reliability and more efficiency
- Ever increasing feature set, with more and more responsibilities shifting to APs

Challenges

- Complexity keeps growing + backward compatibility
- Actual performance of individual features?
- Level of control in COTS hardware?

openwifi
- Pre-standard testing/research
- Customization focusing on W-TSN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