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Wireless Networks Lab

KHARKEVICH INSTITUTE FOR INFORMATION TRANSMISSION PROBLEMS
OF THE RUSSIAN ACADEMY OF SCIENCES

Challenges and Open Issues in Wi-Fi 6 and Wi-Fi 7

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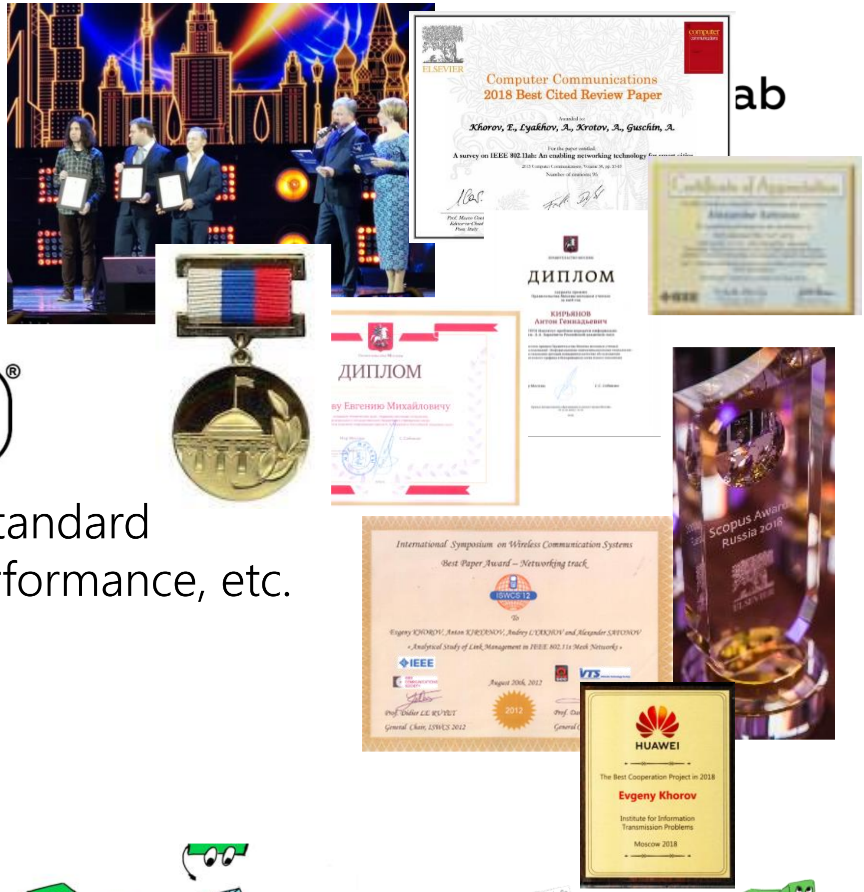
Kharkevich Institute for Information Transmission Problems
of the Russian Academy of Sciences

https://wireless.iitp.ru/

Main Directions

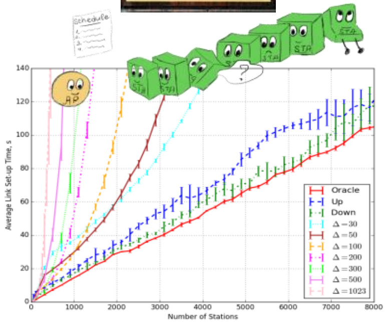


Technological Consulting, Research & Development in Wireless Networks

World-known experts in Wi-Fi
Membership in IEEE 802.11, dozens of contributions to the standard
Numerous mathematical models, algorithms to improve performance, etc.

Resource allocation & Cross-layer optimization
xStream, ARBAT, MUST and other solutions for manifold gains in QoE for 5G systems

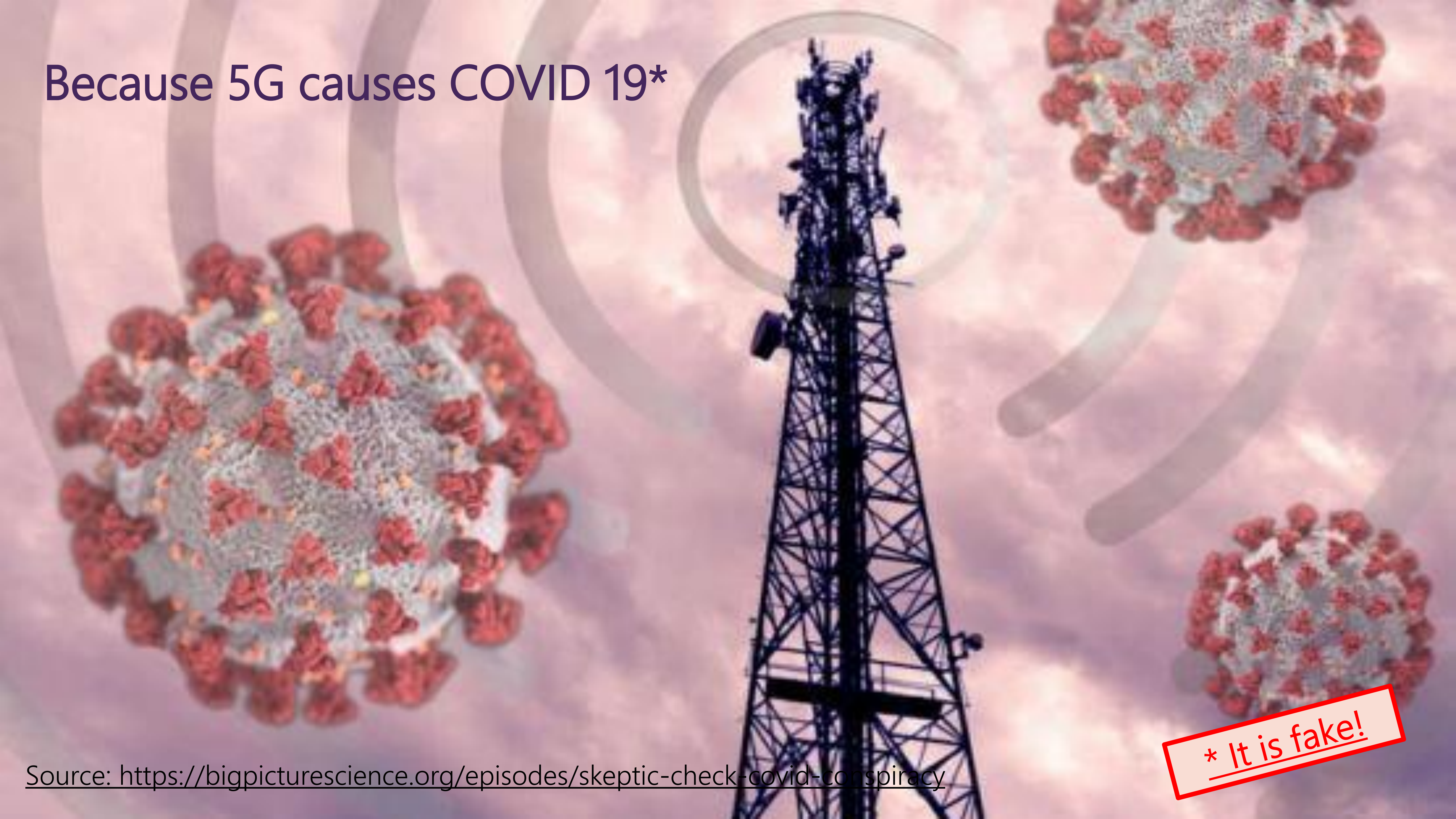
Numerous algorithms to master chaos in Wireless IoT networks
Modifications for the LoRaWAN standard



Multiple keynotes/tutorials @top conferences, Best paper awards @ top conferences/journals
Members of various expert boards

Why Wi-Fi?

Because 5G causes COVID 19*



* It is fake!

Source: https://bigpicturescience.org/episodes/skeptic-check-covid-conspiracy

IP Traffic by Access Technology

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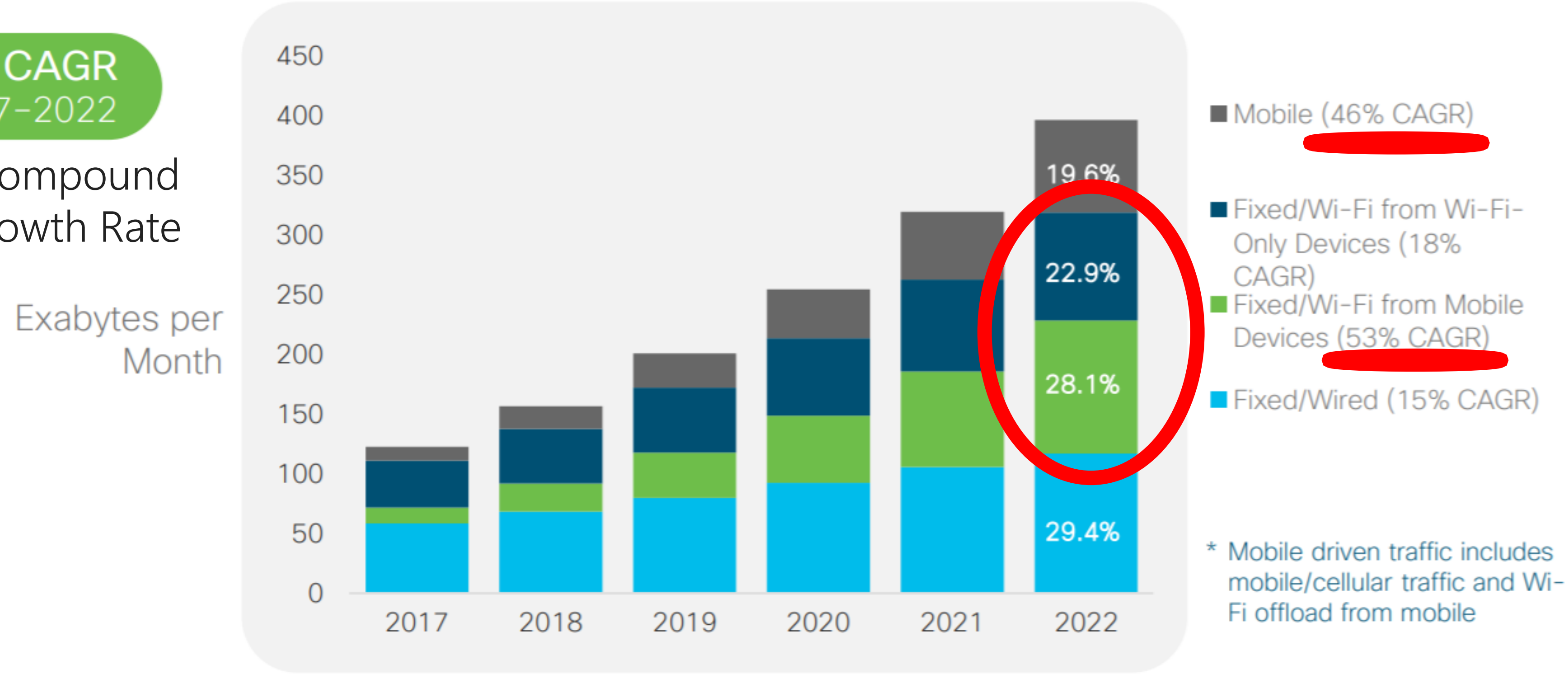
Global IP Traffic by Local Access Technology

Half of traffic is generated by Wi-Fi devices

26% CAGR
2017–2022

CAGR = Compound Annual Growth Rate



Source: Cisco VNI Global Mobile Data Traffic Forecast, 2017–2022

https://www.cisco.com/c/dam/m/en_us/network-intelligence/service-provider/digital-transformation/knowledge-network-webinars/pdfs/190320-mobility-ckn.pdf

Evolution of Wi-Fi

Evolution of Wi-Fi

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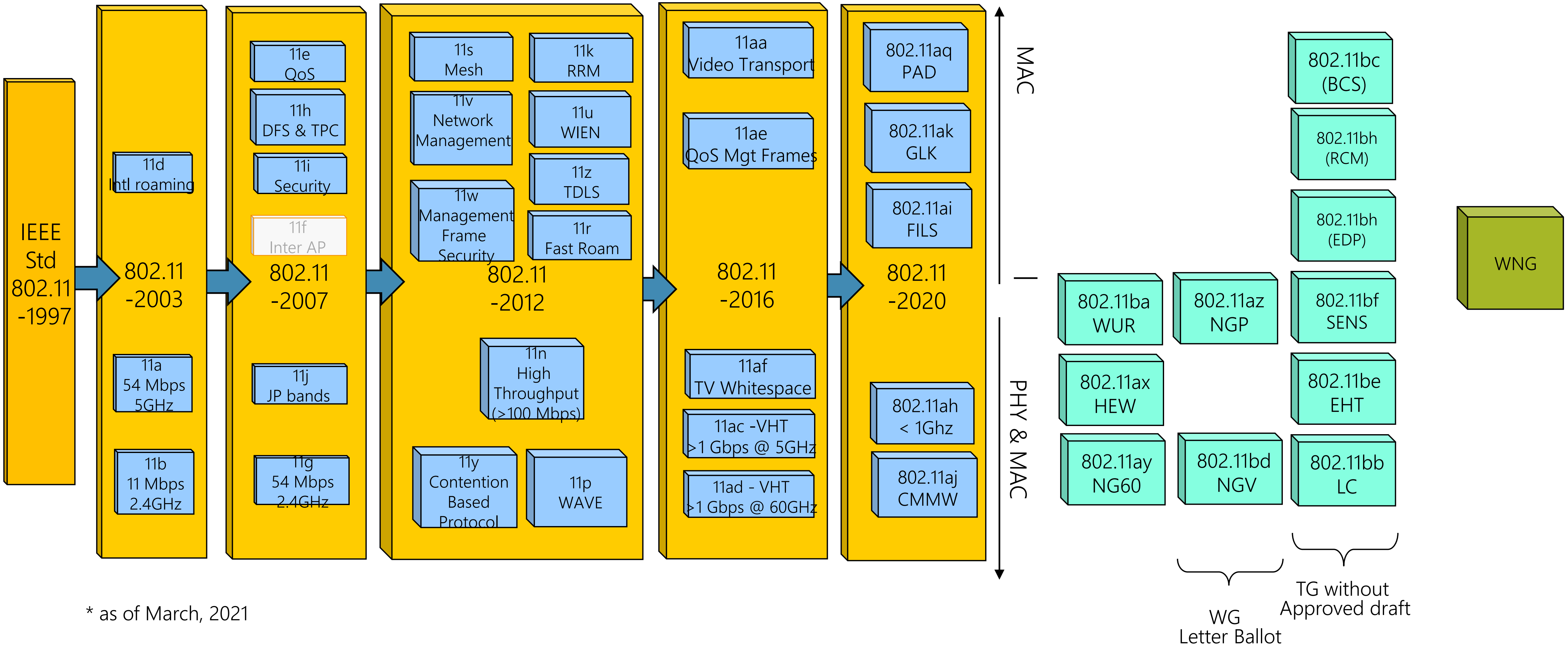
The work has started in September 1990



* as of March, 2021

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History of Wi-Fi Rates

The beginning	802.11	802.11a 802.11b	802.11g	802.11n	802.11ad	802.11ac (Wi-Fi 5)	802.11ah	802.11ax (Wi-Fi 6)	802.11ay	802.11be (Wi-Fi 7)	802.11bb
1990	1997	1999	2003	2009	2012	2013	2016	2020	2021	2024	2022?
Data rate, bps	2M	54M 11M	54M	600M	~8000M	~7000M	346M	~10G	>250G	>>40G	
Freq. band, GHz	2.4	5 2.4	2.4	2.4/5	60	5	<1	2.4/5/6	60	2.4/5/6	Light
Max channel Bandwidth, MHz	22	20 22	20	40	2160	160	16	160	8640	320 Many links	
MIMO	-	-		4x4 (th)		8x8 DL-MU	4x4	8x8 DL/UL MU	8x8	16x16 OFDMA	

Changing the paradigm

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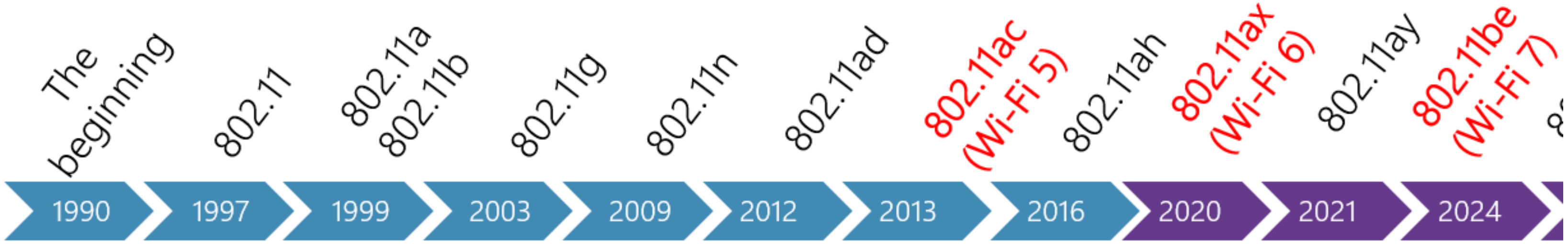
Before Wi-Fi 6 every new "version" of Wi-Fi provided ~10x increase in the nominal data rates

Wi-Fi 6 is an exception: it focuses on efficiency (user goodput), not the nominal rates

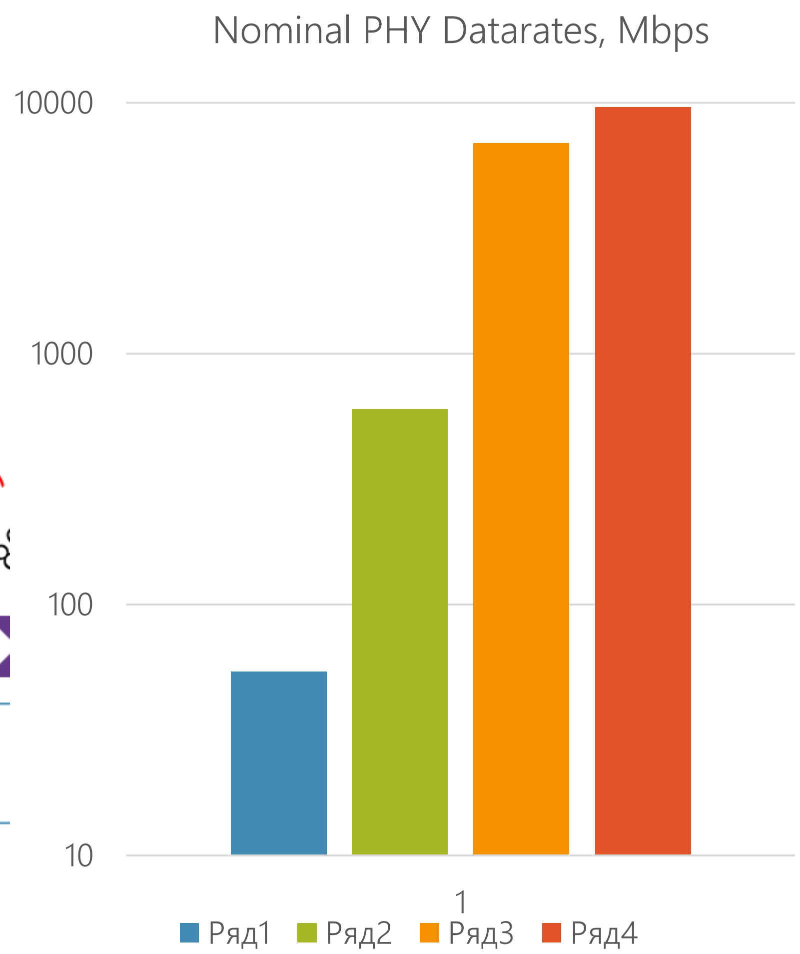
Wi-Fi 7 both increases rates and improves efficiency in terms of delays

Interestingly, the Internet Architecture Board also switches from throughput to network quality

https://www.iab.org/activities/workshops/network-quality/



Data rate, bps	2M	54M 11M	54M	600M	~8000M	~7000M	346M	~10G	>250G	~40G



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Wi-Fi 6

E. Khorov, A. Kiryanov, A. Lyakhov and G. Bianchi, "A Tutorial on IEEE 802.11ax High Efficiency WLANs," in *IEEE Communications Surveys & Tutorials*, vol. 21, no. 1, pp. 197-216, Firstquarter 2019, doi: 10.1109/COMST.2018.2871099.

Popular Articles	Latest Published Articles

Internet Of Things: A Survey On Enabling Technologies, Protocols, And Applications
Ala Al-Fuqaha; Mohsen Guizani; Mehdi Mohammadi; Mohammed Aledhari; Moussa Ayyash

A Survey On The Internet Of Things (IoT) Forensics: Challenges, Approaches, And Open Issues
Maria Stoyanova; Yannis Nikoloudakis; Spyridon Panagiotakis; Evangelos Pallis; Evangelos K. Markakis

A Survey Of Data Mining And Machine Learning Methods For Cyber Security Intrusion Detection
Anna L. Buczak; Erhan Guven

A Tutorial On IEEE 802.11ax High Efficiency WLANs
Evgeny Khorov; Anton Kiryanov; Andrey Lyakhov; Giuseppe Bianchi

A Survey On Mobile Edge Computing: The Communication Perspective
Yuyi Mao; Changsheng You; Jun Zhang; Kaibin Huang; Khaled B. Letaief

802.11ax has attracted many researchers

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Google Scholar

802.11ax

Articles

About 3,860 results (**0.02** sec)

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A tutorial on IEEE **802.11 ax** high efficiency WLANs

E Khorov, A Kiryanov, A Lyakhov… - … Surveys & Tutorials, 2018 - ieeexplore.ieee.org

While celebrating the 21st year since the very first IEEE 802.11 "legacy" 2 Mbit/s wireless local area network standard, the latest Wi-Fi newborn is today reaching the finish line, topping the remarkable speed of 10 Gbit/s. IEEE **802.11 ax** was launched in May 2014 with …

Cited by 246 Related articles All 5 versions

IEEE **802.11 ax**: High-efficiency WLANs

B Bellalta - IEEE Wireless Communications, 2016 - ieeexplore.ieee.org

IEEE **802.11 ax**-2019 will replace both IEEE 802.11 n-2009 and IEEE 802.11 ac-2013 as the next high-throughput WLAN amendment. In this article, we review the expected future WLAN scenarios and use cases that justify the push for a new PHY/MAC IEEE 802.11 amendment …

Cited by 357 Related articles All 11 versions

IEEE **802.11 ax**: Next generation wireless local area networks

DJ Deng, KC Chen, RS Cheng - 10Th international conference …, 2014 - ieeexplore.ieee.org

Recently, IEEE 802 started a task group to investigate and deliver next generation WLAN technologies for the scenarios of dense networks with a large number of stations and access point. The proposal is specified as the IEEE **802.11 ax** amendment. Due to the significant …

Cited by 140 Related articles All 3 versions

Implementation

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Available chips:

- Quantenna (Oct'16)
- Qualcomm (Feb'17)
- Broadcom (Aug'17)

Available APs:

- ASUS (Aug'17)
- HUAWEI (Sep'17)

New Features of 802.11ax

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BSR
Color
DCM
RU
UL MU-MIMO
OFDMA
Microsleep
OPS
UORA
QTP
OBSS PD
DSC
2 NAVs
1024 QAM
Trigger Frame
TWT

IEEE 802.11ax OFDMA Fundamentals

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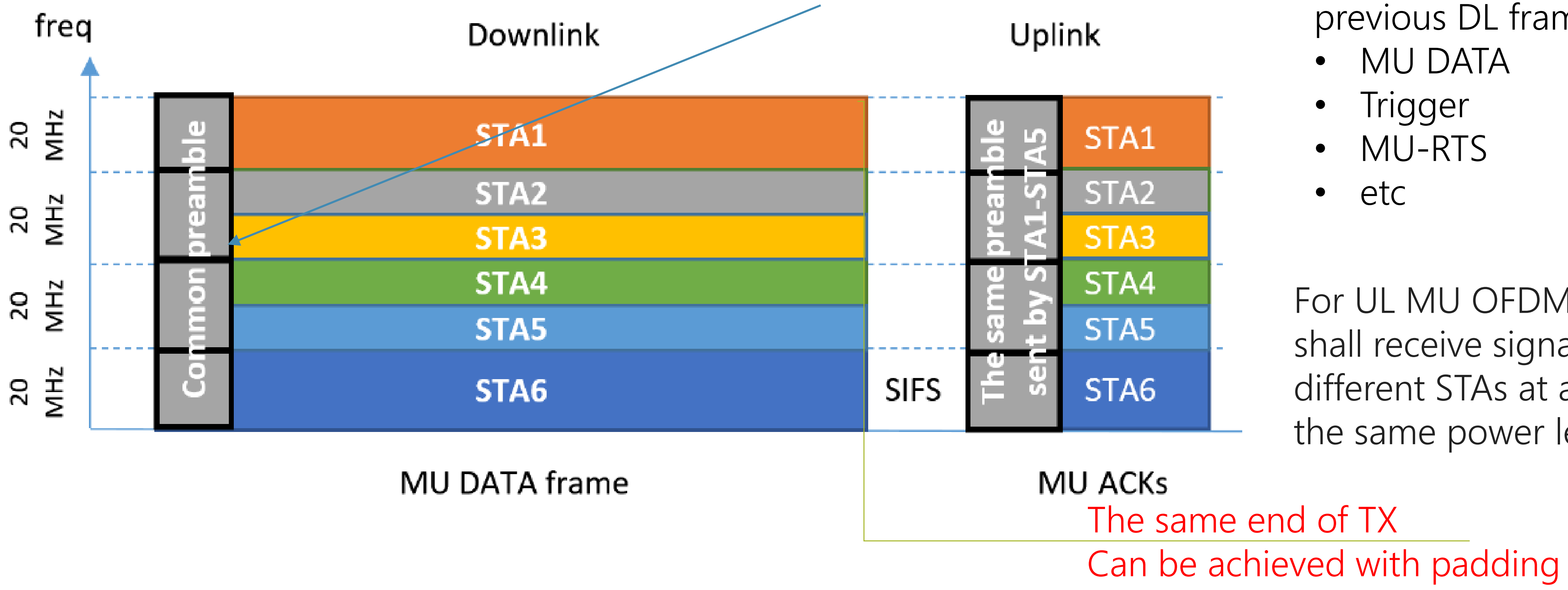
In contrast to LTE and 5G with its rigid OFDMA structure, in 802.11ax OFDMA is used at the per-packet basis and works upon legacy CSMA/CA

RU allocation map (incl. MCS and number of spatial streams) of the DL OFDMA frame is included in the packet PHY header

RU allocation map (incl. MCS and number of spatial streams) of the UL OFDMA frame is described in the previous DL frame:

- MU DATA
- Trigger
- MU-RTS
- etc



For UL MU OFDMA, the AP shall receive signals from different STAs at almost the same power level.

RU Structure

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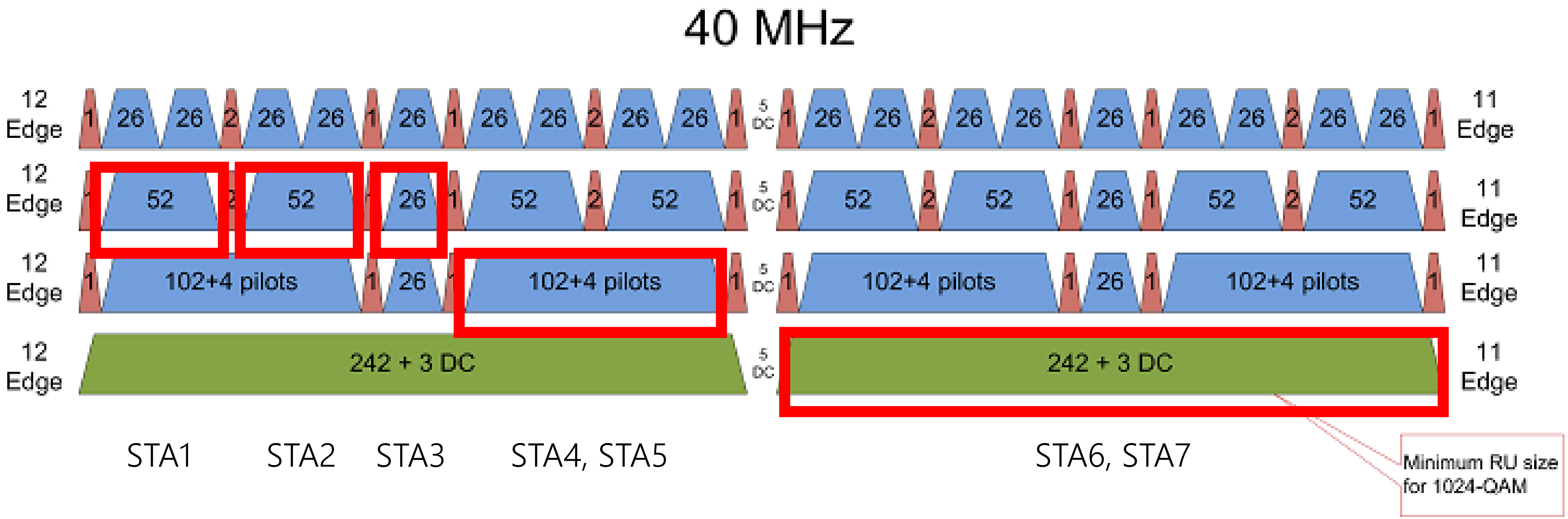

RUs of 106 tones and wider can be used for MU MIMO

Forbidden RU Allocation

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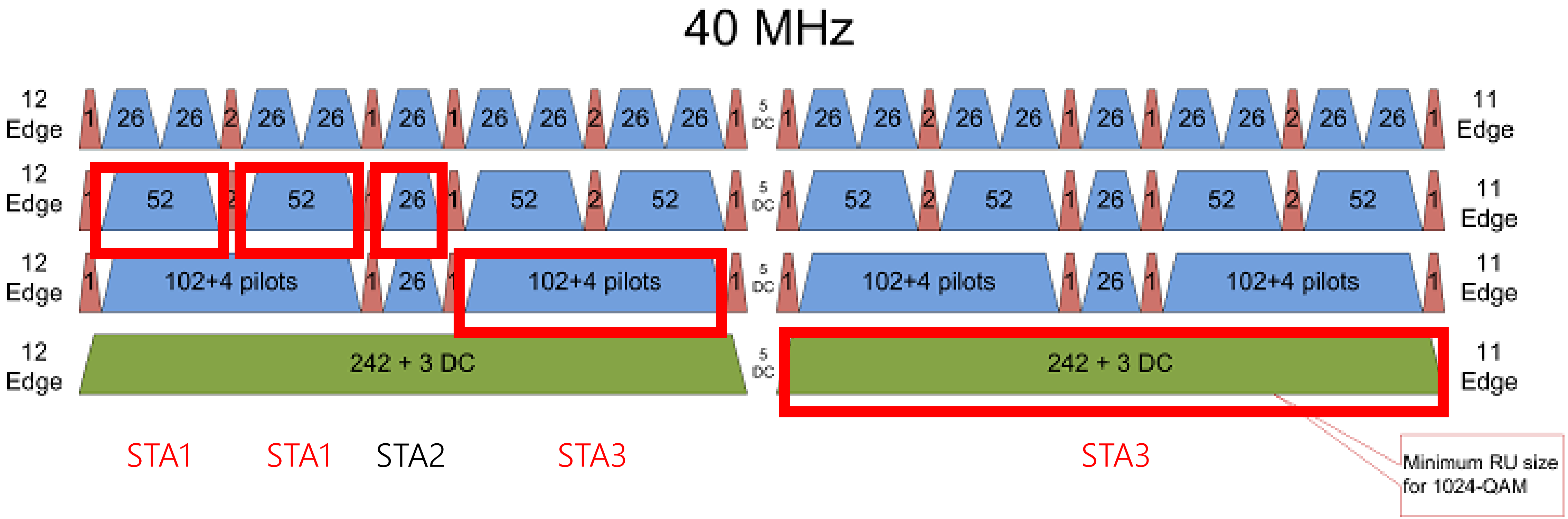
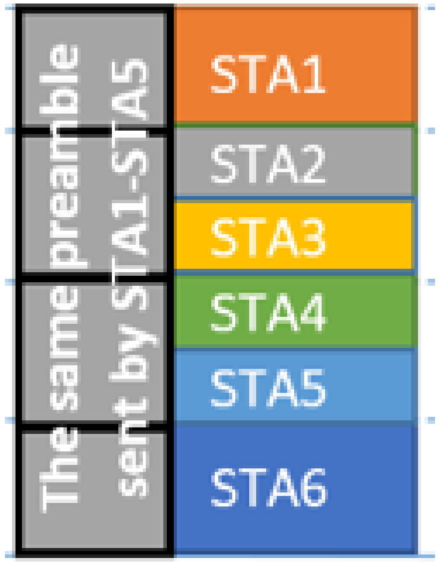
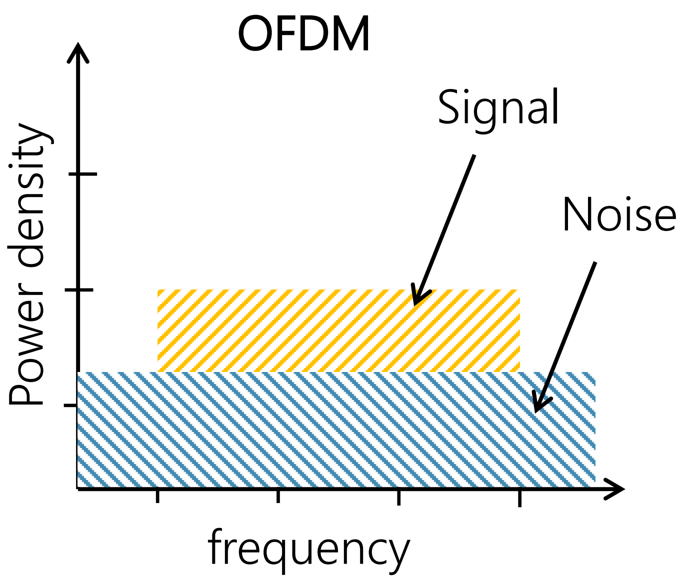


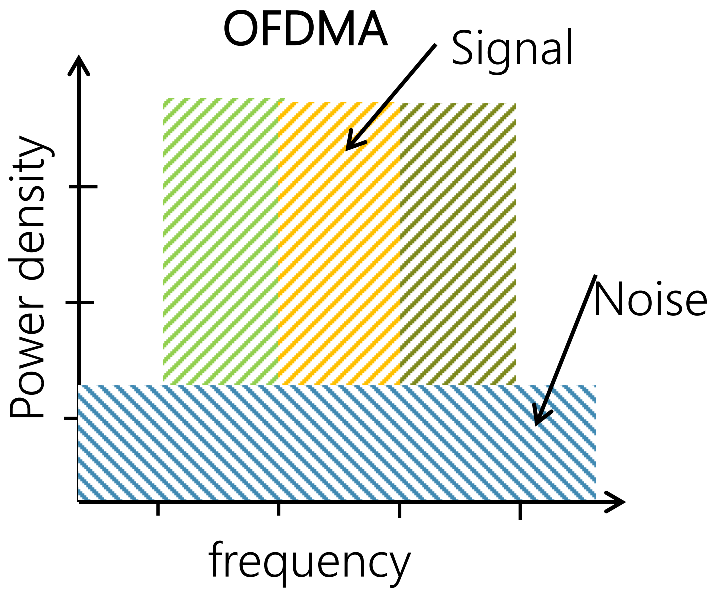
Every STA can obtain not more than ONE RU, which complicates the scheduling problem

Increasing UL Power Spectral Density

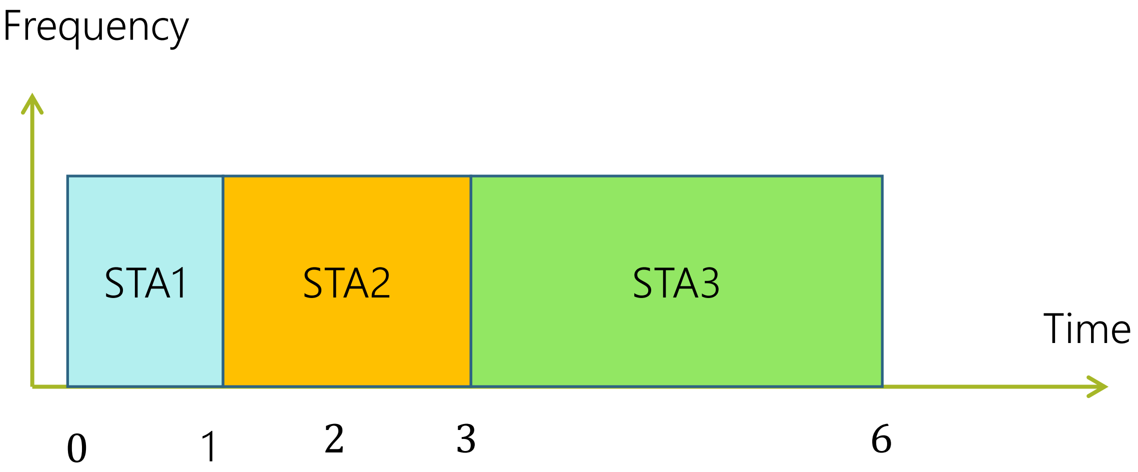


6x higher power

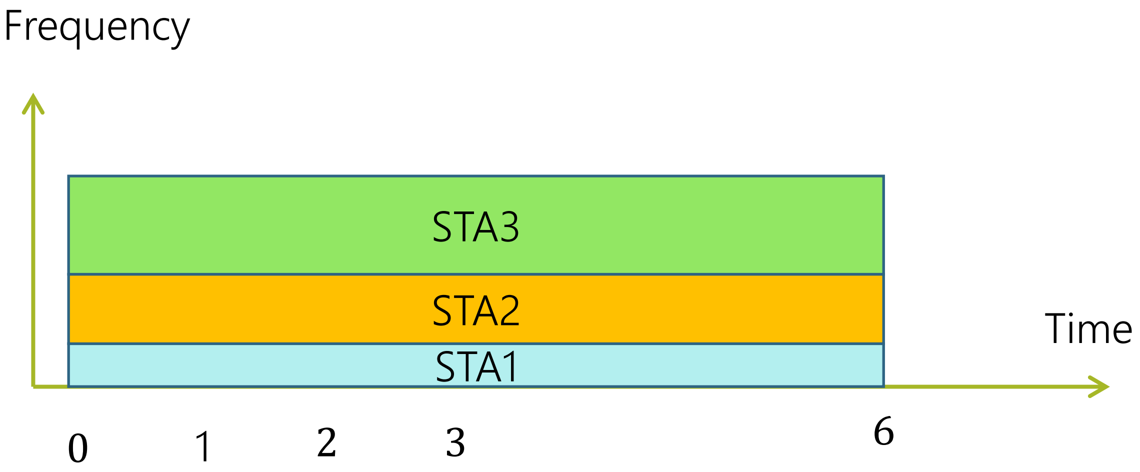




Scheduling problem: minimization of delivery time



T=(1+3+6)/3=3,3



T=(6+6+6)/3=6

Shortest Remaining Time First: Sort STAs by their remaining processing time in the ascending order

Scheduling problem: minimization of delivery time in case of 802.11ax

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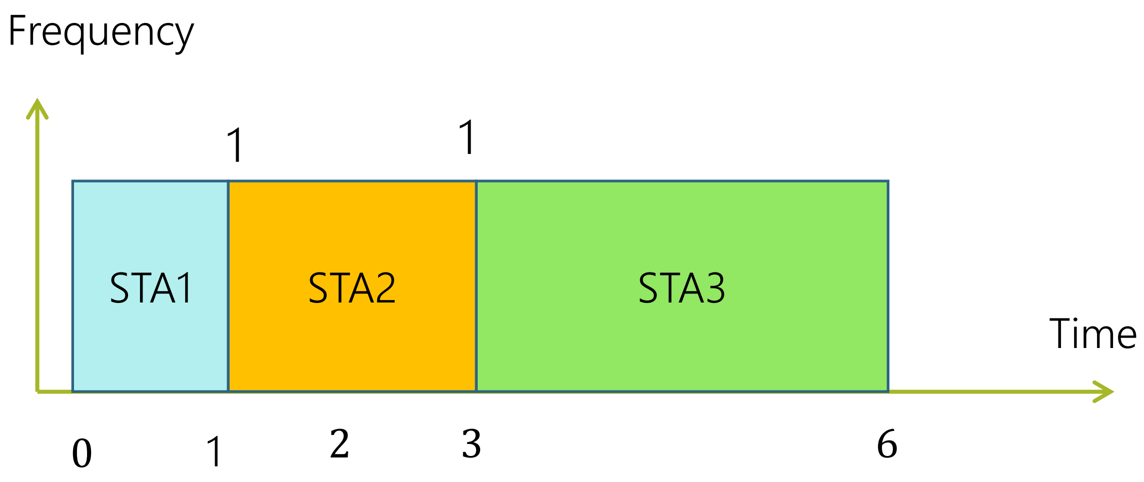

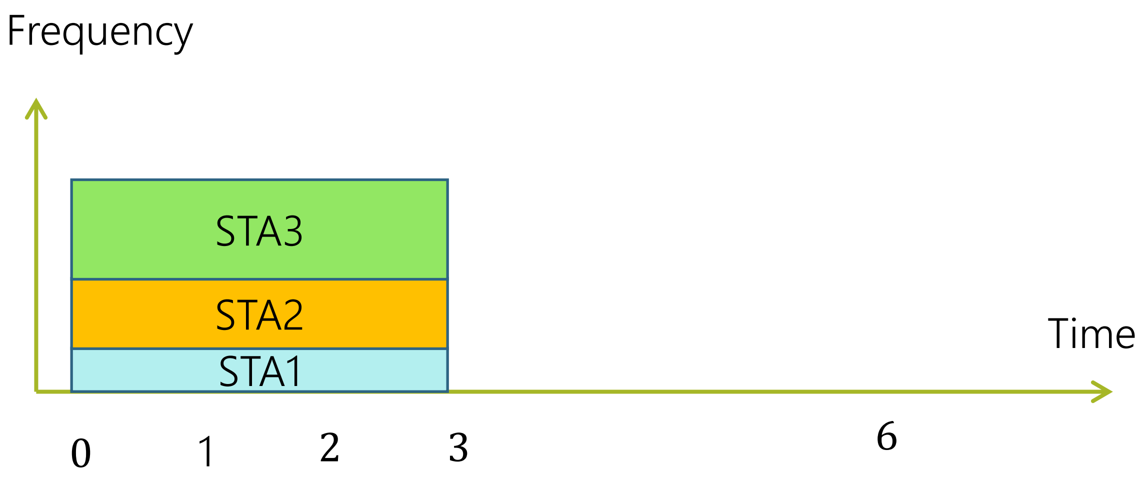

T=(1+3+6)/3=3,3

T=(3+3+3)/3=3

Shortest Remaining Time First: Sort STAs by their remaining processing time in the ascending order

Scheduling in 11ax: Solution

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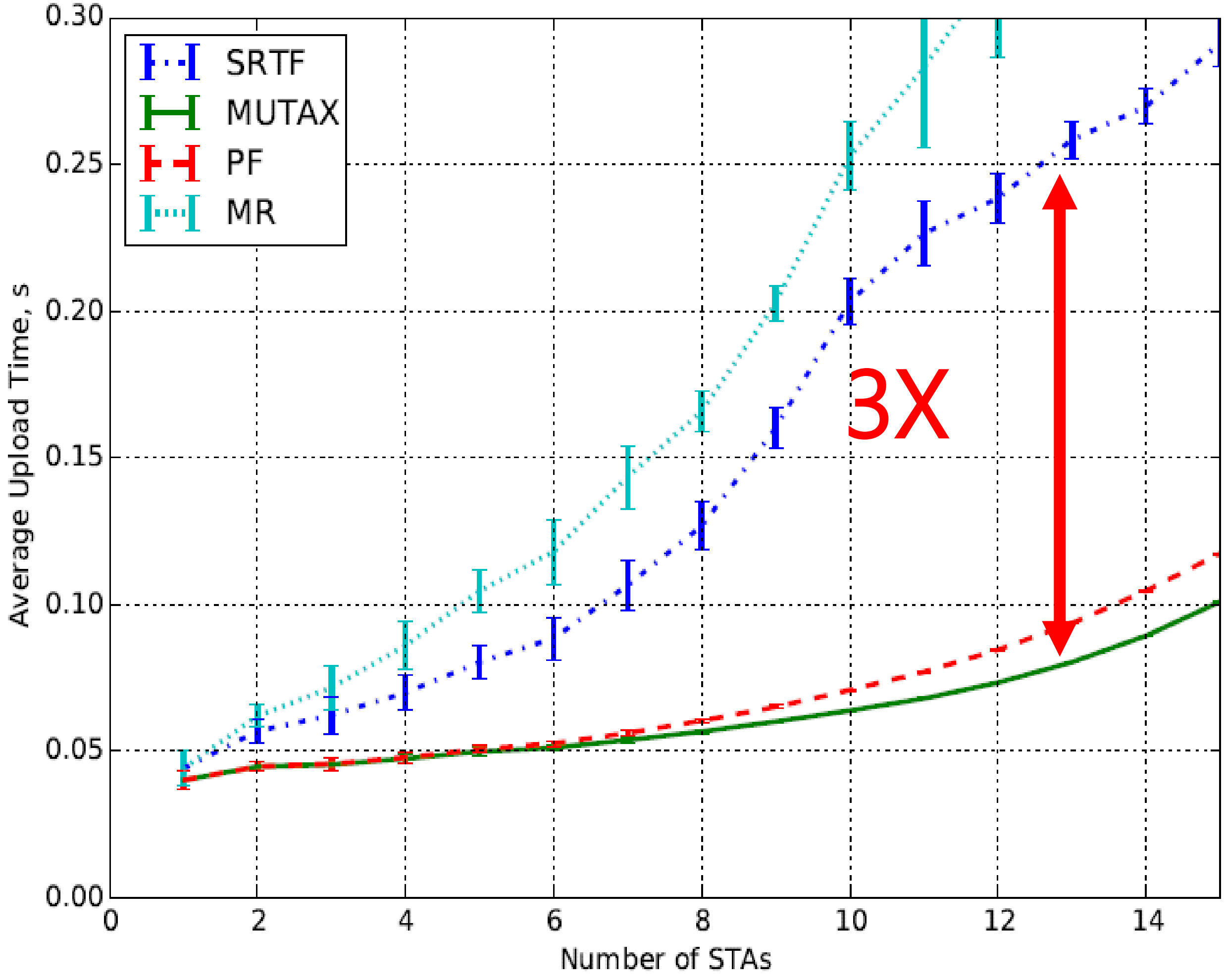

Results from: D. Bankov, A. Didenko, E. Khorov, V. Loginov, A. Lyakhov.
IEEE 802.11ax Uplink Scheduler to Minimize Delay: a Classic Problem with New Constraints.

What happens when multiple APs operate in the same area?

How channel fluctuations affect the results?

Our recent research supported by the Russian Science Foundation (Grant No 20-19-00788) confirms that it is possible to obtain high gain even in complex scenarios.

E. Khorov et al. IEEE 802.11ax OFDMA Resource Allocation with Frequency Selective Fading (under review)

UL OFDMA Random Access

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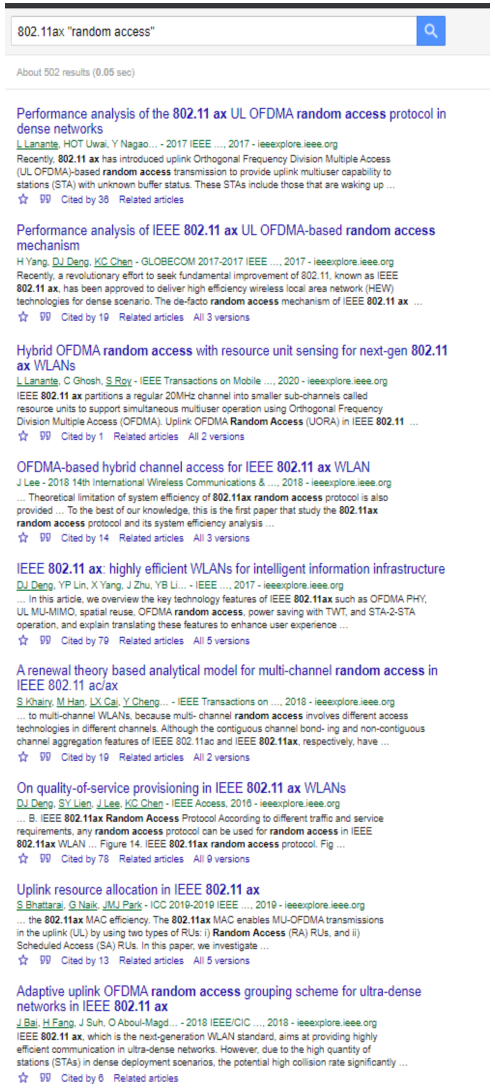
- IEEE 802.11ax introduces UL OFDMA Random Access (UORA) procedure
- Trigger frame can describe Resource Units (RUs) which are not assigned to any particular STA, but are used for random access
- Following a special procedure a STA can transmit its data in an RU for random access
  - Binary exponential backoff

UORA performs similar to multichannel Aloha



UL OFDMA Random Access

- Many papers try to improve throughput of UORA

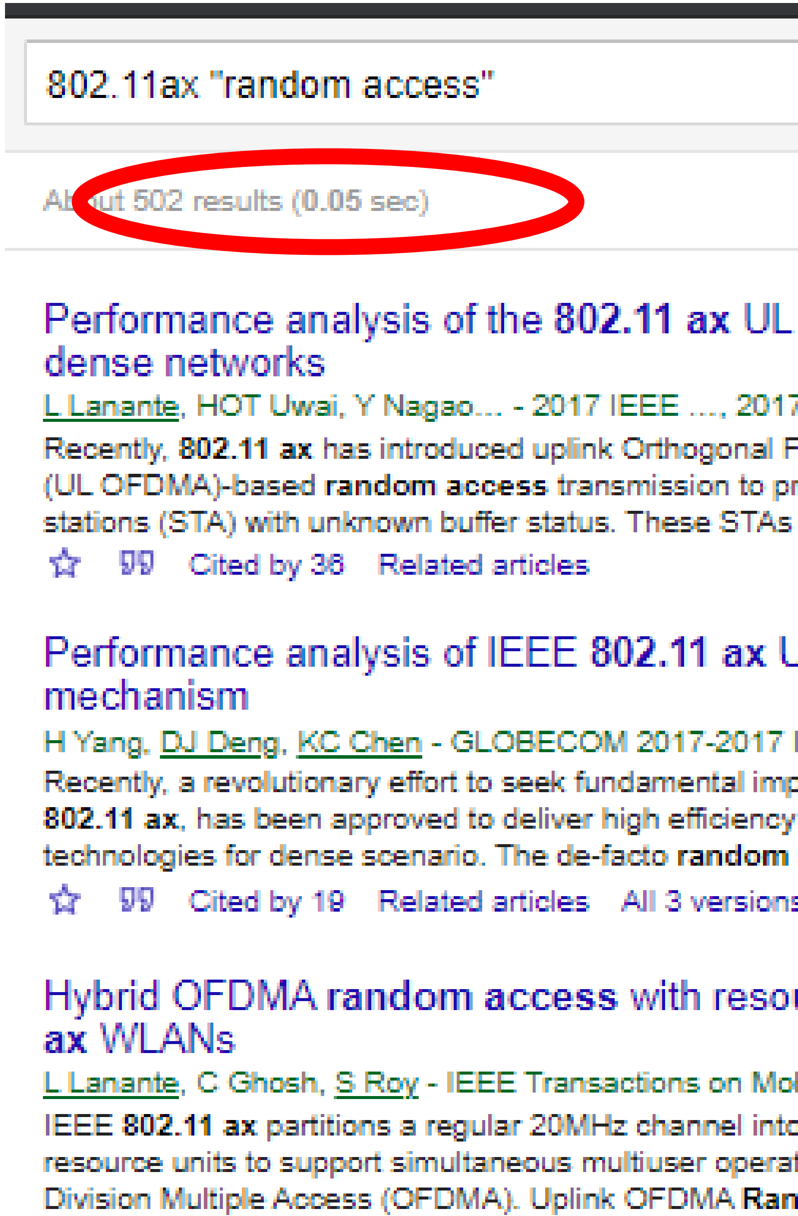
What is the best solutions?

Note: Aloha shows lower throughput than CSMA

Avoid OURA for data transmission

- use UORA just to send Buffer Status Report or some mgnt frames

What about delays?



Research Challenges in OFDMA

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- When does DL OFDMA provide gains?

OFDMA

  - Reduces overhead for short packets
    - How many short-packet users are simultaneously active?
  - Benefits from frequency-selective fading.
    - Requires accurate channel quality information
    - High gains are observed only for very narrow Rus

- How to design a low-complexity scheduler
  - No regular timing
  - Some decisions shall be done within TXOP
  - Many constraints
  - Many dimensions

Adjustment of Sensitivity Threshold and Transmit Power (OBSS PD)

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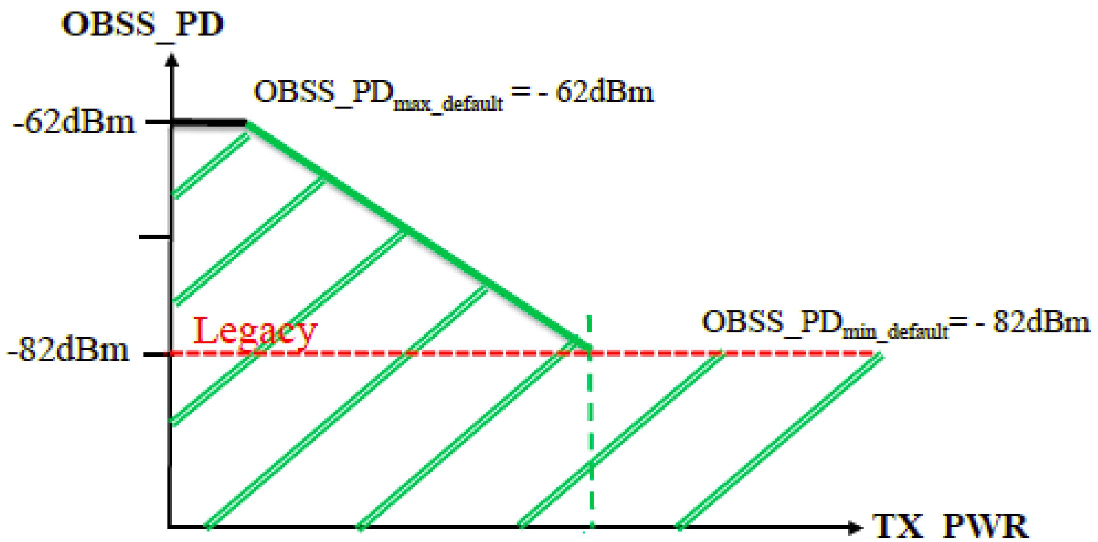
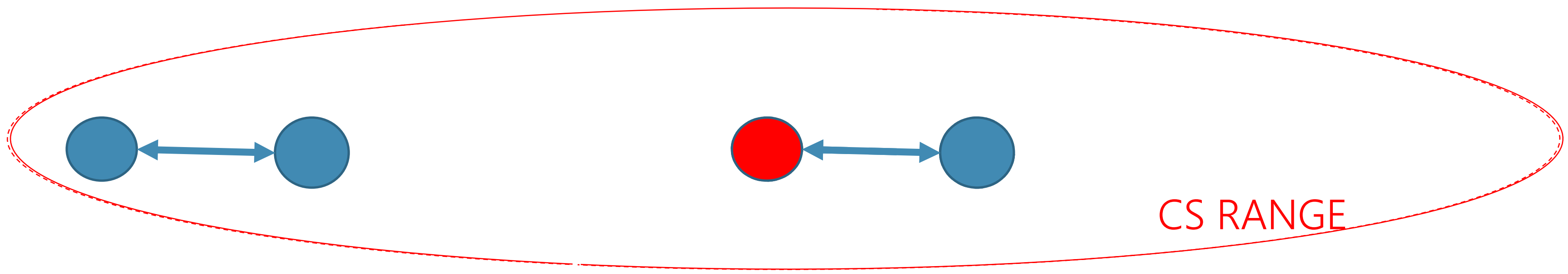


With Color, Wi-Fi devices can distinguish between the transmissions in its own BSS and an alien one

Sensitivity threshold can be increased only if the TX power is decreased by the same value



A. Krotov, A. Kiryanov, E.Khorov. Rate Control with Spatial Reuse for Wi-Fi 6 Dense Deployments //IEEE Access, 2020

Adjustment of Sensitivity Threshold and Transmit Power

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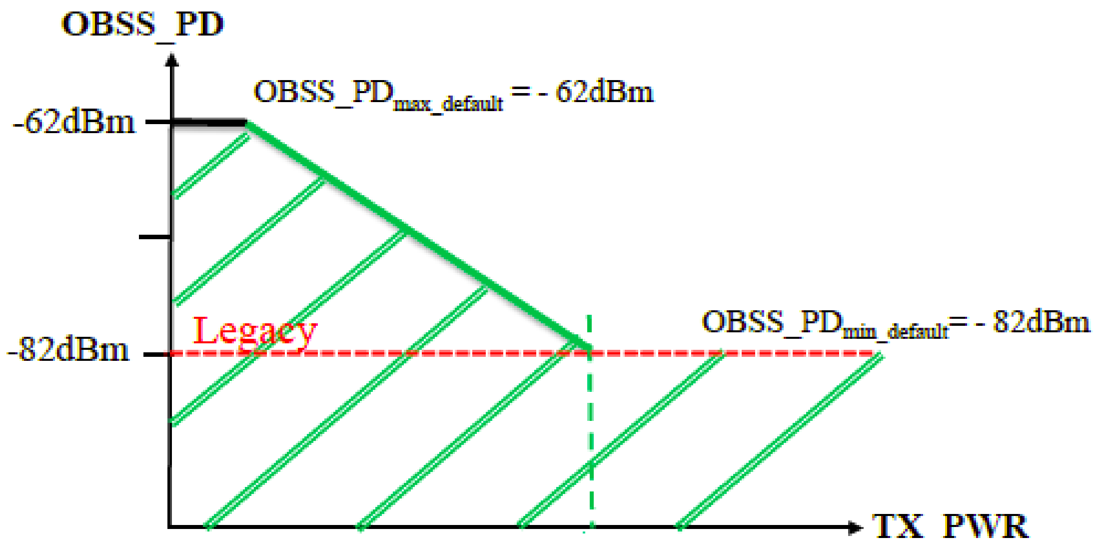
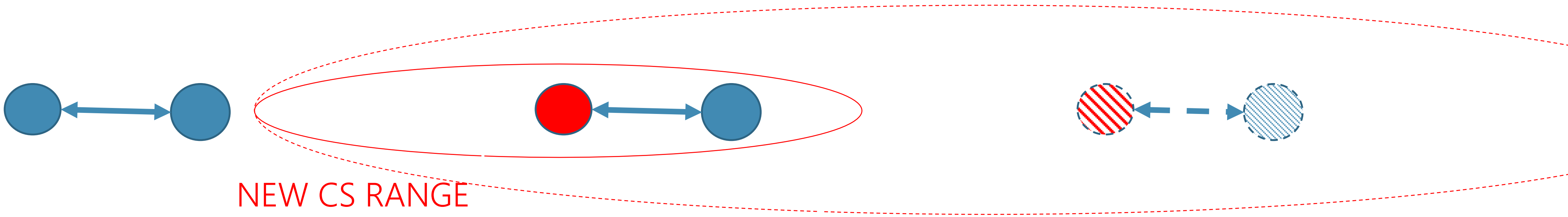


Sensitivity threshold can be increased only if the TX power is decreased by the same value



A. Krotov, A. Kiryanov, E.Khorov. Rate Control with Spatial Reuse for Wi-Fi 6 Dense Deployments //IEEE Access, 2020

Spatial Reuse is not Well-Studied and Understood

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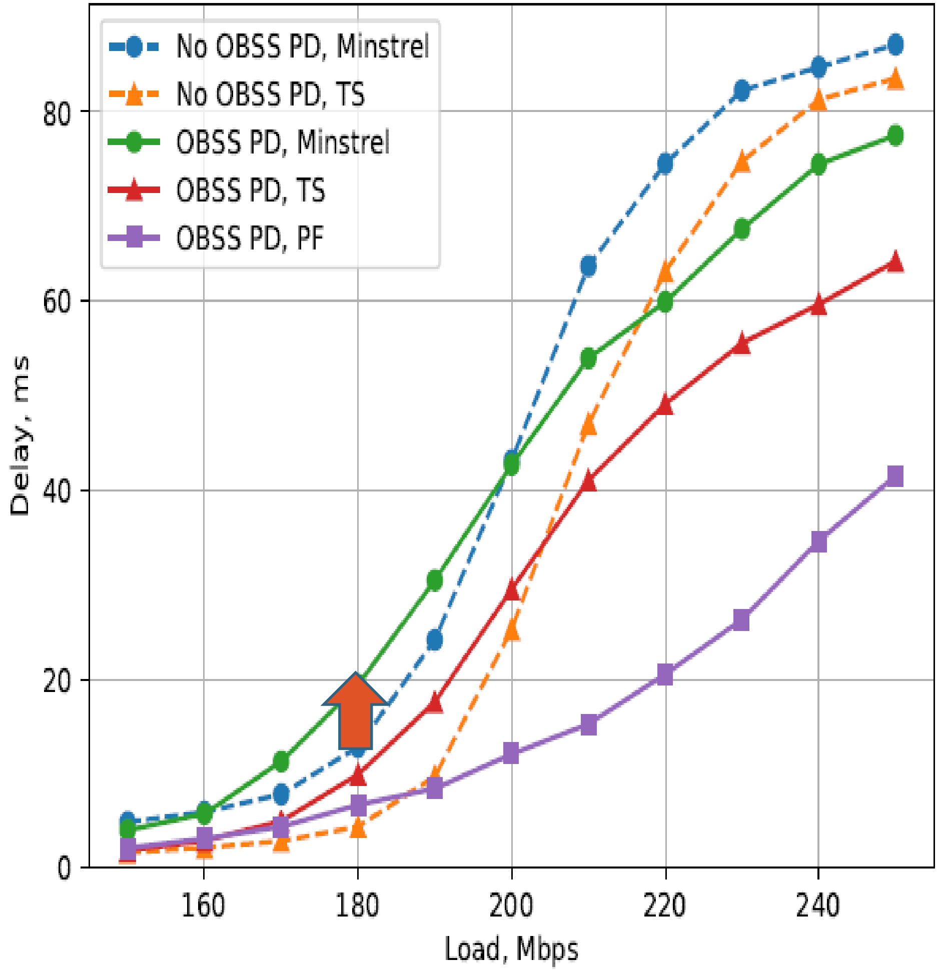
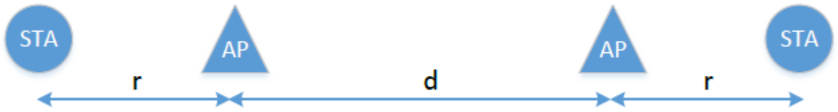




In the study on 11ax spatial reuse, we SHALL take into account rate control behavior

Unfortunately, many papers ignore this fact and obtain wrong results.

The reality is much complex, as shown in the paper below. If we do not take into account all effects, the performance will even degrade

A. Krotov, A. Kiryanov, E.Khorov. Rate Control with Spatial Reuse for Wi-Fi 6 Dense Deployments //IEEE Access, 2020

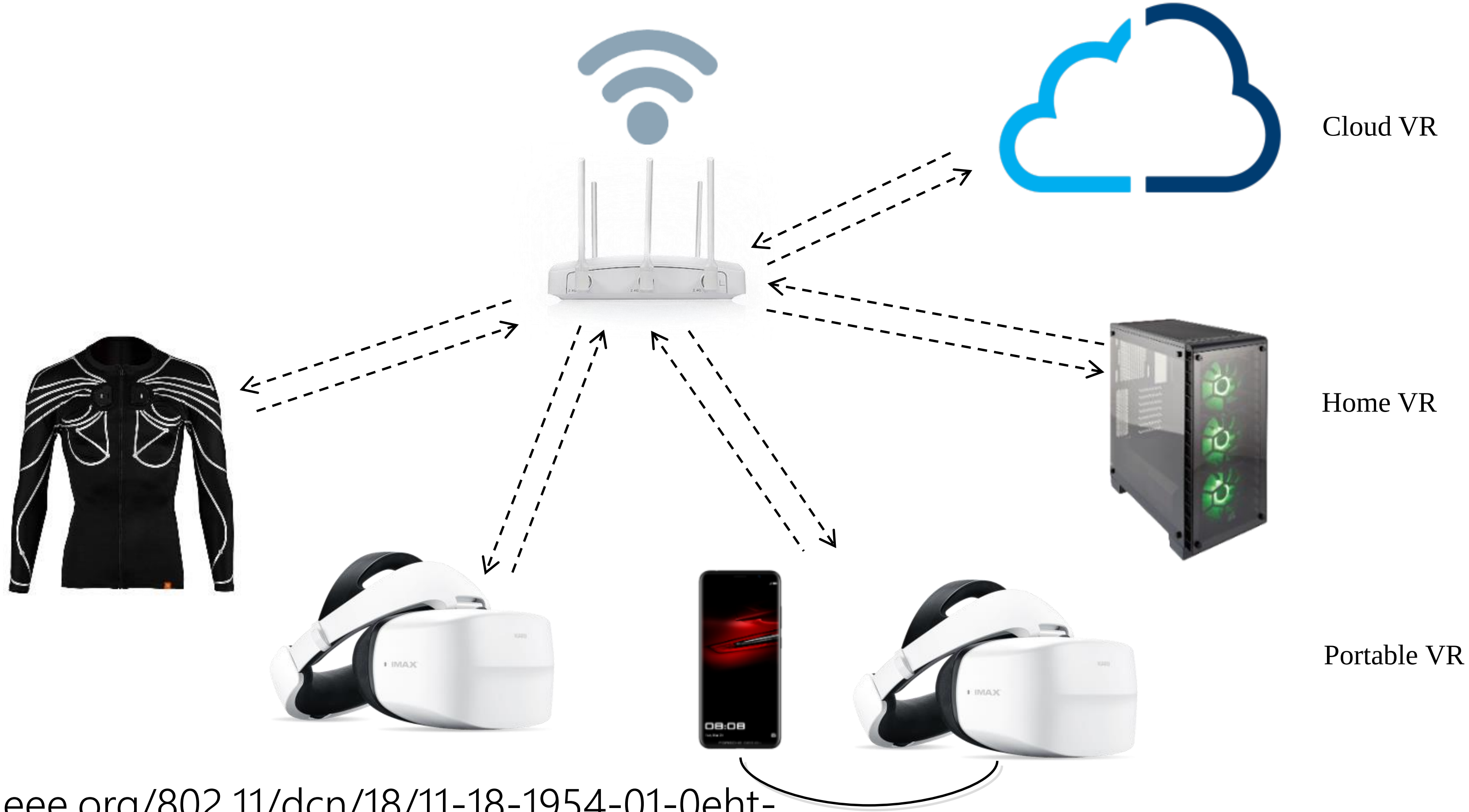
IEEE 802.11be:

E. Khorov, I. Levitsky, I. F. Akyildiz.

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

IEEE Access, 2020

Virtual Reality



https://mentor.ieee.org/802.11/dcn/18/11-18-1954-01-0eht-eht-use-case-discussion-vr-requirement-follow-up.pptx

Main Targets for Future Wi-Fi

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- High Throughputs (Dozens of Gbps)
- Low delays (Several ms)
- Low energy consumption (the energy shall be consumed only during and for transmission or reception of the data)
- Stable performance in congested dense environments

Increasing Throughput

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- 4K-QAM (+20%)
- MU-MIMO 16x16 (x2)
- Bandwidth up to 320 MHz (x2)
- Multi-band (multi-link) operation (x N)

$$N*(9.6 * 2 * 2 * 1.2) \approx (43.2 * N)\text{Gbps}$$

Main Directions & Issues

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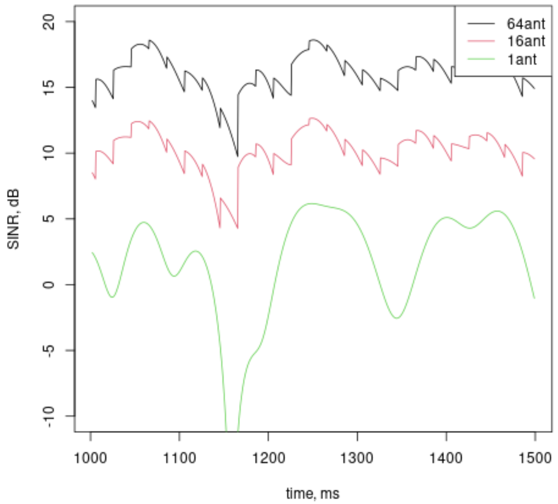
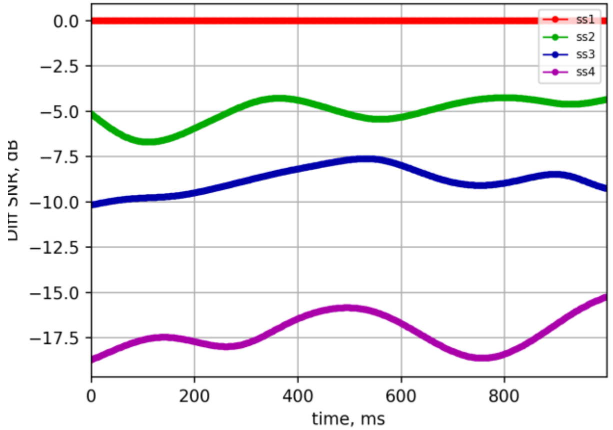
- Higher order of MU-MIMO
  - Streams non-orthogonality
  - Small throughput gain of additional streams for the same user
  - Precoder Aging Effect
  - Explicit Sounding is too heavy
  - No good simulation platform to evaluate performance of the joint usage of MIMO and OFDMA and other techniques in close-to-reality scenarios
- Higher bandwidth
  - 160/240/360 MHz are hard to efficiently utilize in dense environment because of frequency selective interference
  - Fixed nominal performance indices limit competition between vendors
  - Available spectrum differs in various countries
  - The flexible usage of multilink operation is a promising solution





*Grant No 20-19-00788 of the Russian Science Foundation

Studies on MIMO mainly focus on PHY

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- have different assumptions
- obtain contradictive results
- typically focus on throughput optimization

Existing simulation tools do not allow accurate cross-layer optimization

They do not allow taking into account both peculiarities of traffic, and PHY effects such as precoding aging effect.

Our lab is developing such a tool

Multi Link operation

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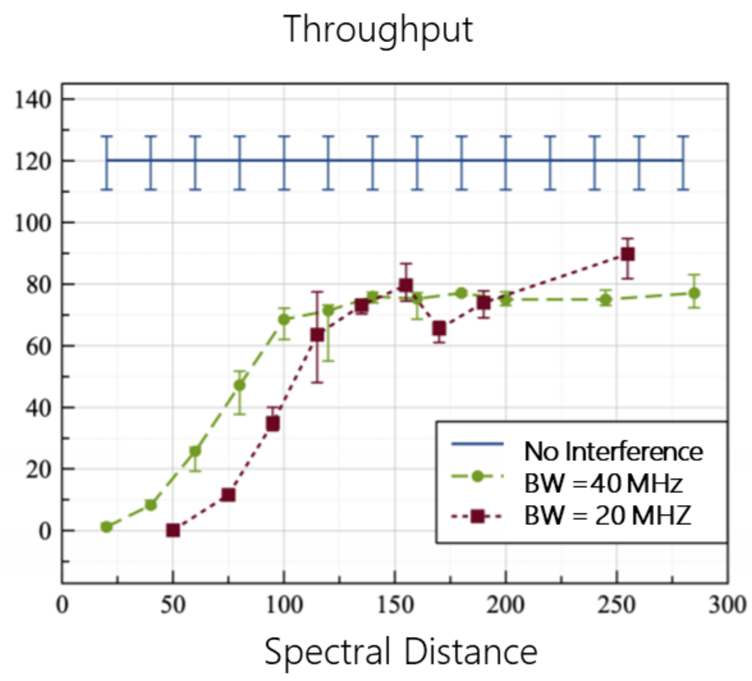
- From the standard point of view, ML is quite simple unless we deal with the devices that cannot simultaneously transmit and receive (non-STR)
- From implementation point of view, ML is quite difficult, if we want to use ML in an optimal way (i.e., to reduce delays and increase perceived throughputs)

Open issues of ML:

- Power efficiency
  - How to reduce the energy consumption without loss of ML benefits?
  - How to reduce the energy consumption of APs?
- Transmit power
  - Shall the power limits be applied for all the STAs affiliated with an MLD?
- Different TX range
- Backward compatibility and coexistence with legacy devices
- What to do in the non-STR case



*I.Levitsky, Y.Okatyev, Study of STR in Wi-Fi 7, Tech. rep. Grant No 20-19-00788 of the Russian Science Foundation

Coordinated Operation

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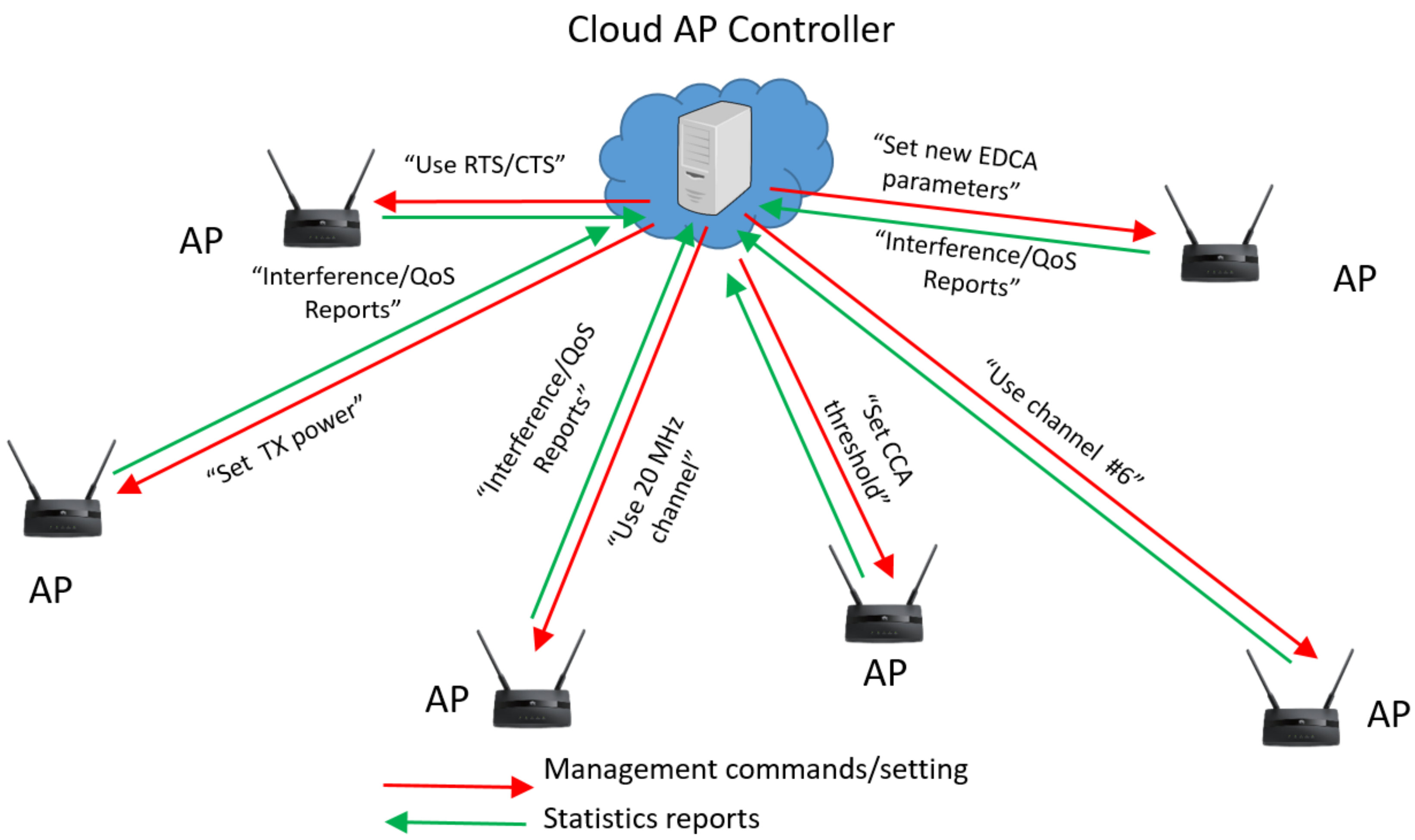

Better Coordination Gives Higher Gains

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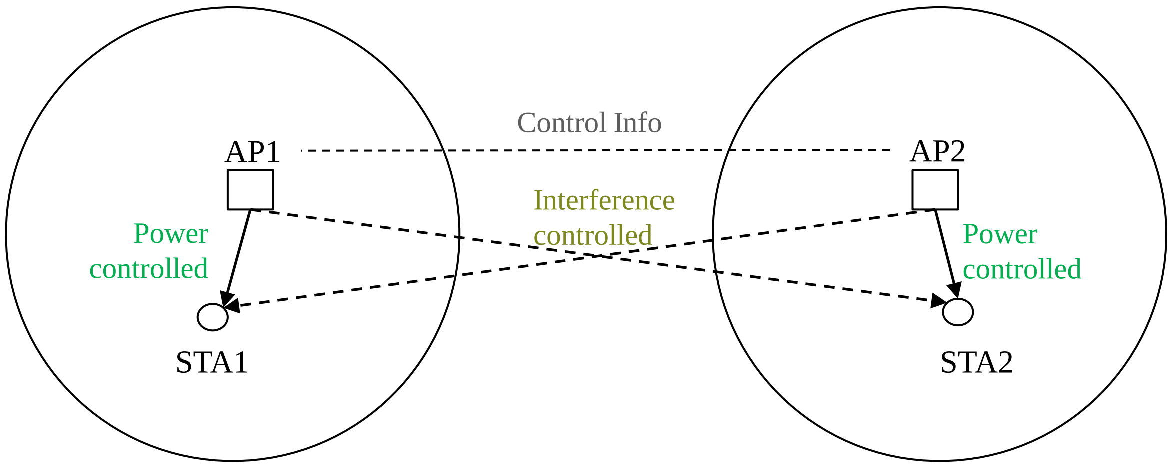

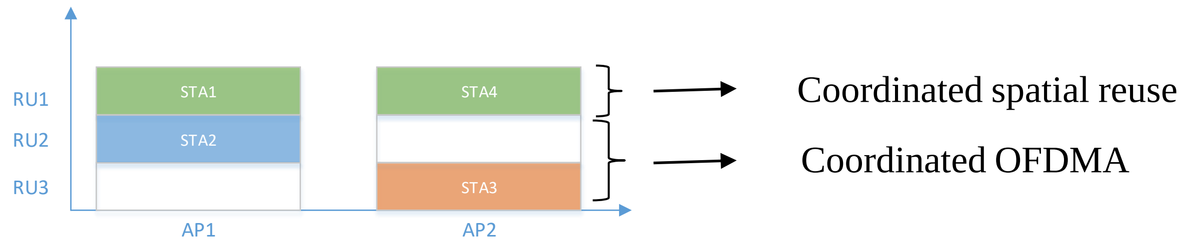

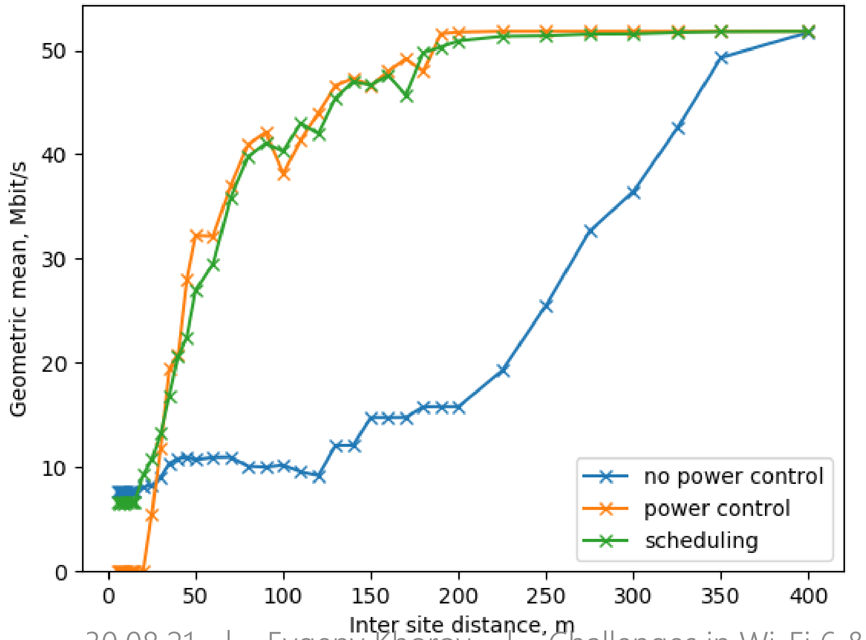

Issues:
- How to coordinate APs?
- How to manage sensitivity efficiently?
- How to combine it with power control and rate control?

Evgeny Khorov, Anton Kiryanov, Alexander Krotov. Joint Power Control and Time Division to Improve Spectral Efficiency in Dense Wi-Fi Networks // In proc. of IEEE BlackSeaCom 2018

Real-Time Applications in Wi-Fi

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Scenarios

Requirements

- Packet delivery time up to 1–10 ms
- PLR up to 10^{-8}–10^{-5}

RTA TIG created to propose RTA solutions in Wi-Fi

Proposed in 2017 -> RTA TIG -> a part of 11be

https://mentor.ieee.org/802.11/dcn/17/11-17-1734-01-0wng-wtsn.pptx

D. Bankov, E. Khorov, A. Lyakhov, M. Sandal. **Enabling Real-Time Applications in Wi-Fi Networks**. International Journal of Distributed Sensor Networks, May 2019
E. Avdotin, D.Bankov, E.Khorov, A. Lyakhov. **Enabling Massive Real-Time Applications in IEEE 802.11be Networks** //In Proc. of IEEE PIMRC 2019 (**Best Paper Award**)

Thoughts on RTA

- Wi-Fi is based on CSMA/CA
  - Even modern OFDMA works upon CSMA/CA (OFDMA transmission/TF can be sent only if the AP accesses the channel according to EDCA)
- Wi-Fi is full of legacy devices
  - A user may upgrade all his/her APs, but it is hardly possible to quickly upgrade all the devices connected to these AP
  - 802.11be may include new channel access methods, but a typical 802.11 network consists of devices of various generation, including those not supporting new features. We need to satisfy RTA requirements in the presence of legacy devices transmitting heavy delay-tolerant flows.
- Ways to support RTA
  - Tuning channel access parameters
  - Channel reservations
    - Periodic channel reservations
    - Preliminary channel access

Conclusion

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- Although Wi-Fi 6 devices are present on the market, there are still many open issues that affect performance
  - OFDMA & MU-MIMO Schedulers
  - Efficient spatial reuse operation in dense deployments
  - Extremely low power delay sensitive communications
- Wi-Fi 7 will have similar challenges but with more tight constraints
- Multi AP operation in Wi-Fi 7 will bring new challenges
- Support of RTA requires controlled environment and the optimal strategies depend on particular scenarios

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