How Threatening is Wi-Fi 6E for IoT Systems based on UWB Technology?

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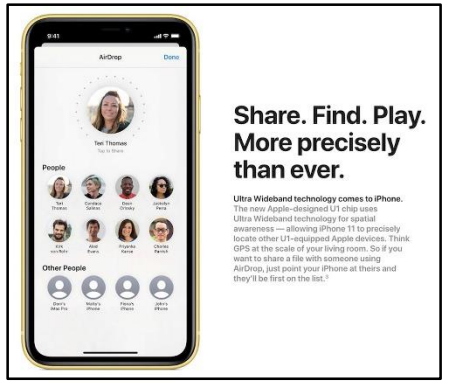
Ultra-Wideband Technology (UWB)

- The popularity of UWB technology is soaring
  - Several hundred millions device shipments in 2021 (source: ABI research)
  - UWB market expected to hit 2.7 billion $ by 2025 (source: MarketsAndMarkets)
  - Major investments by key players
    - Apple, Samsung, and Xiaomi have integrated UWB chips into their high-end smartphones
    - Tesla, Volkswagen, and BMW have embedded UWB-based keyless entry systems in their vehicles
  - A plethora of UWB system providers has emerged
    - Zebra Technologies, Ubisense, Kinexon, Infsoft, Sewio, ...
    - Helped fueling the adoption of UWB services

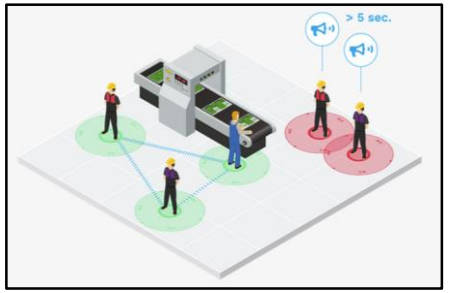
Source: Infsoft

Source: VW group



Source: Apple

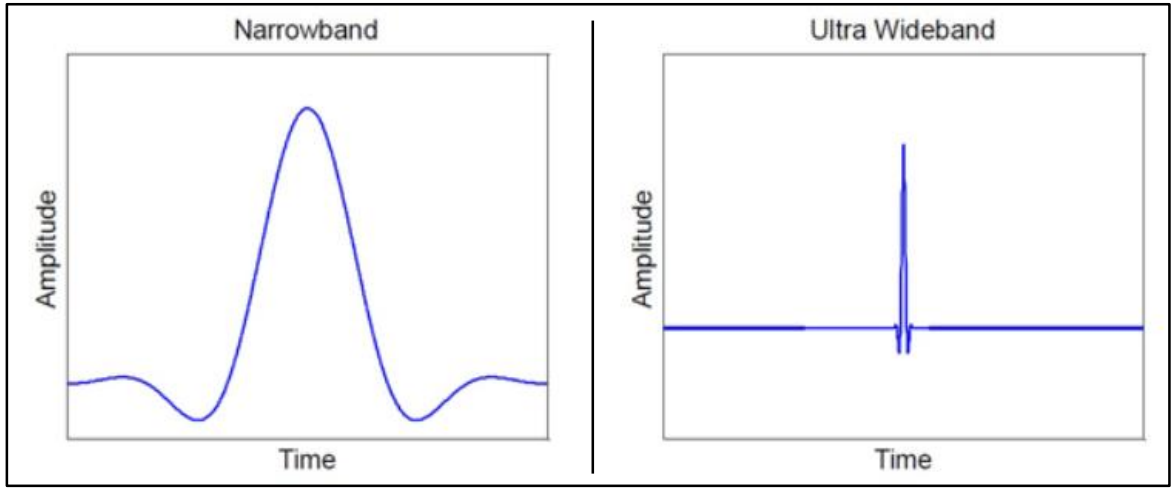
Source: Wikimedia.org



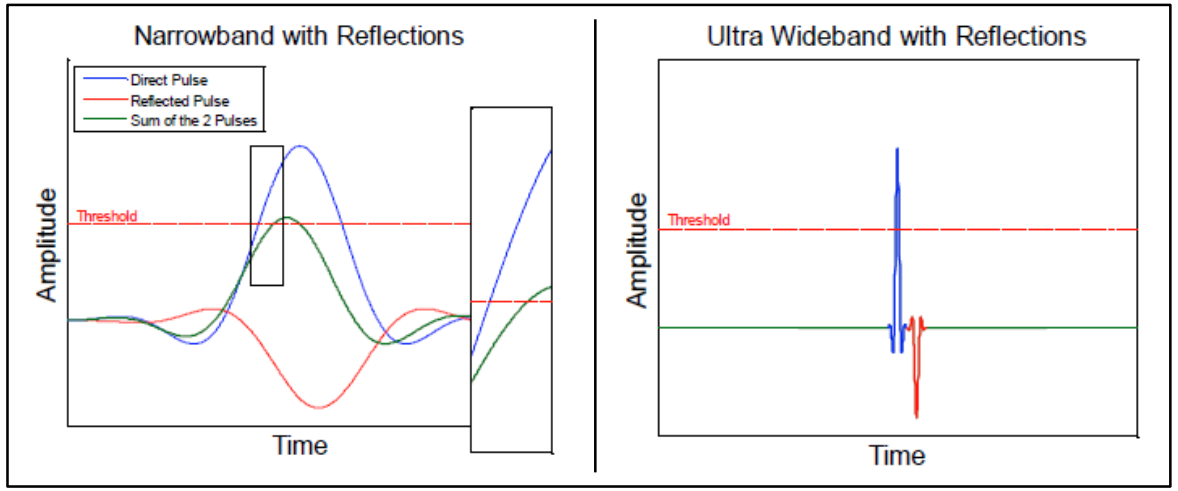
Source: Losant

Ultra-Wideband Technology (UWB)

- Why so popular?
  - Much wider bandwidth than traditional narrowband IoT technologies
    - Typically larger than 500 MHz
    - Very short pulses (~2 ns)
  - Very good time-domain resolution allowing for cm-level localization & tracking
    - High immunity to multipath fading
    - Fine estimations of the time of flight



Source: Electronic design



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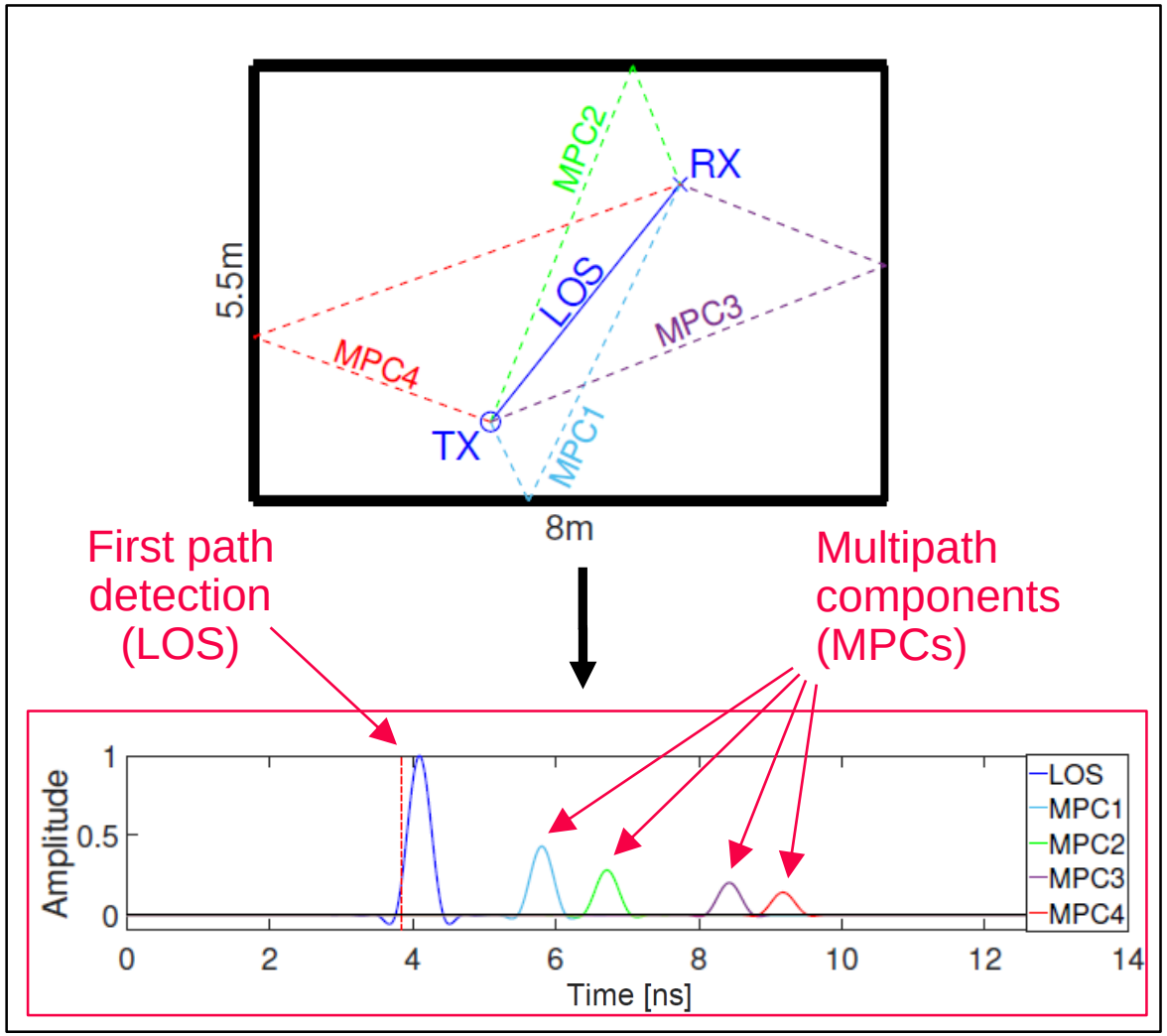

Source: Großwindhager et al.

Ultra-Wideband Technology (UWB)

- Why so popular?
  - Much wider bandwidth than traditional narrowband IoT technologies
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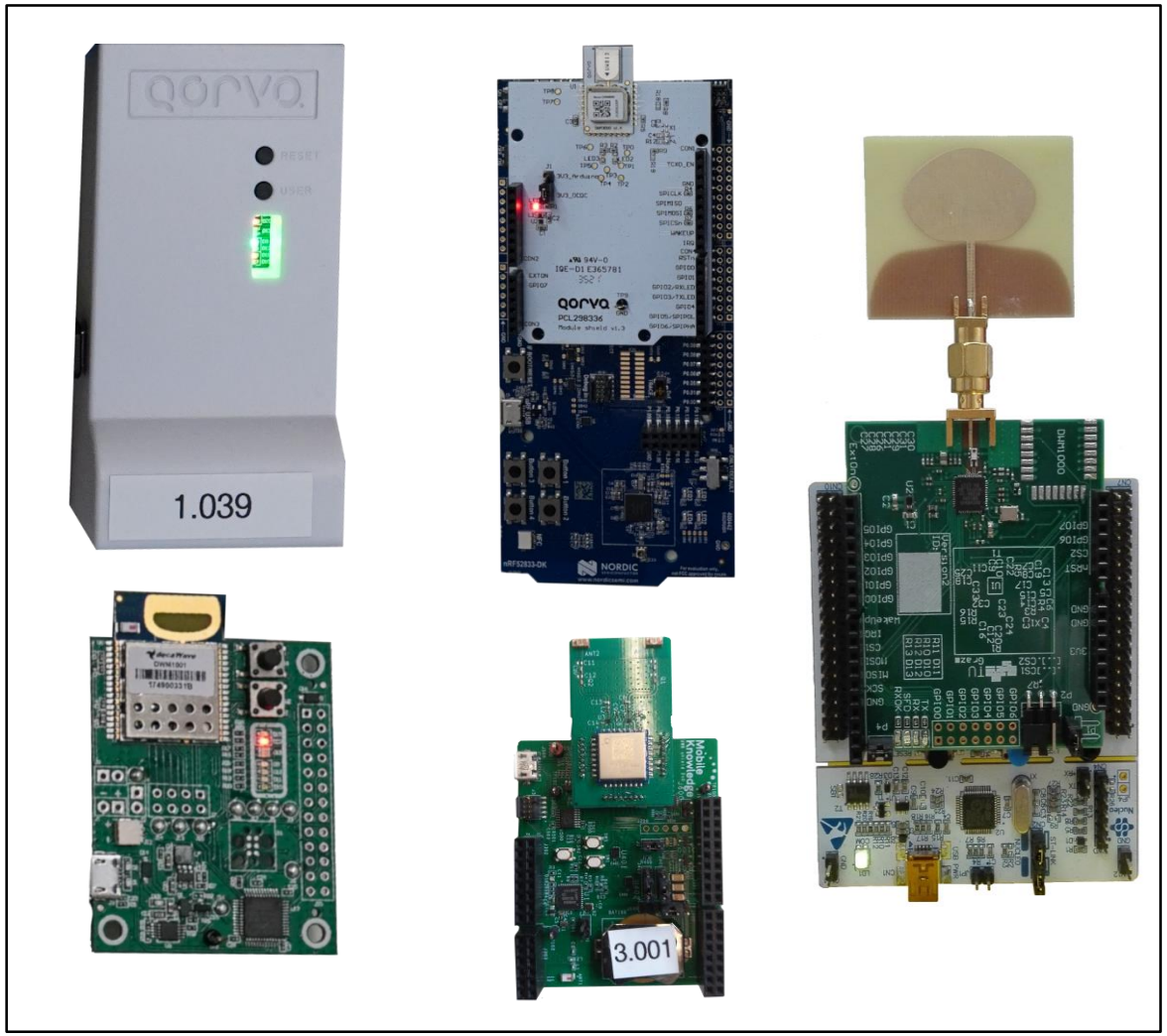
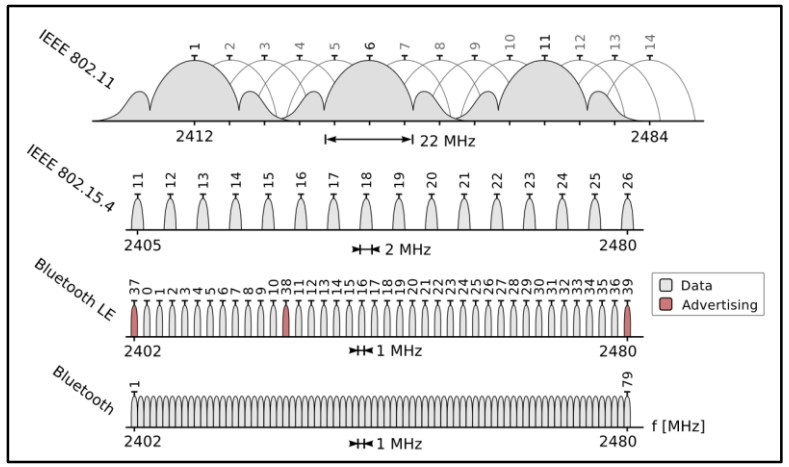
  - Very good time-domain resolution allowing for cm-level localization & tracking
    - High immunity to multipath fading
    - Fine estimations of the time of flight
  - Off-the-shelf low-power radio transceivers enabling short-range communication
    - Qorvo DW3000: ~40/70 mA TX/RX
    - Support for cheap & mobile tags



Source: Großwindhager et al.

Coexistence Threats on the Horizon

- UWB systems have so far enjoyed a relatively noiseless RF spectrum
  - Commercial UWB devices operate between 3 and 10 GHz, mainly in the 6 – 8.5 GHz range
- Away from the crowded 2.4 GHz ISM band where ubiquitous wireless devices operate
  - Devices employing Wi-Fi, Bluetooth classic / LE, IEEE 802.15.4 / ZigBee, OpenThread, …
  - Home appliances such as microwave ovens
- No overlap with the frequencies used by Wi-Fi
  - IEEE 802.11b/g → 2.4 GHz only
  - IEEE 802.11n/ac → 2.4 GHz + 5 GHz

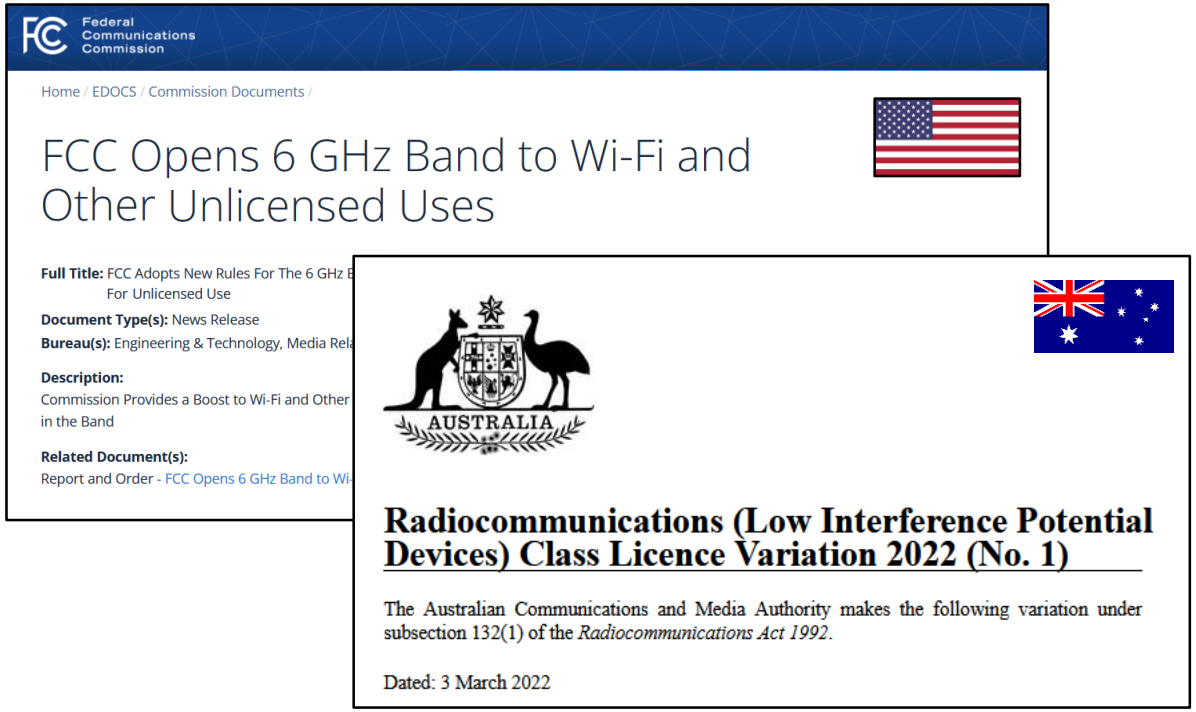


Source: Wetzker et al.

At least until today...

Coexistence Threats on the Horizon

- Regulatory bodies around the world have started to open the 6 GHz unlicensed band for Wi-Fi use, in connection to the release of the Wi-Fi 6E standard


Federal Communications Commission

Home / EDOCS / Commission Documents /

FCC Opens 6 GHz Band to Wi-Fi and Other Unlicensed Uses

Full Title: FCC Adopts New Rules For The 6 GHz B For Unlicensed Use

Document Type(s): News Release

Bureau(s): Engineering & Technology, Media Rela

Description:
Commission Provides a Boost to Wi-Fi and Other in the Band

Related Document(s):
Report and Order - FCC Opens 6 GHz Band to Wi-

AUSTRALIA

Radiocommunications (Low Interference Potential Devices) Class Licence Variation 2022 (No. 1)

The Australian Communications and Media Authority makes the following variation under subsection 132(1) of the *Radiocommunications Act 1992*.

Dated: 3 March 2022

Government of Canada Gouvernement du Canada

MENU

Canada.ca > Business and industry > Permits, licences and regulations > Federally regulated industry sectors > Broadcasting and telecommunications regulation > Spectrum management and telecommunications > Spectrum allocation

Decision o Framewo 6 GHz Ba

May 2021

Gazette Notice

Official Journal of the European Union L 232

English edition Legislation Volume 64 30 June 2021

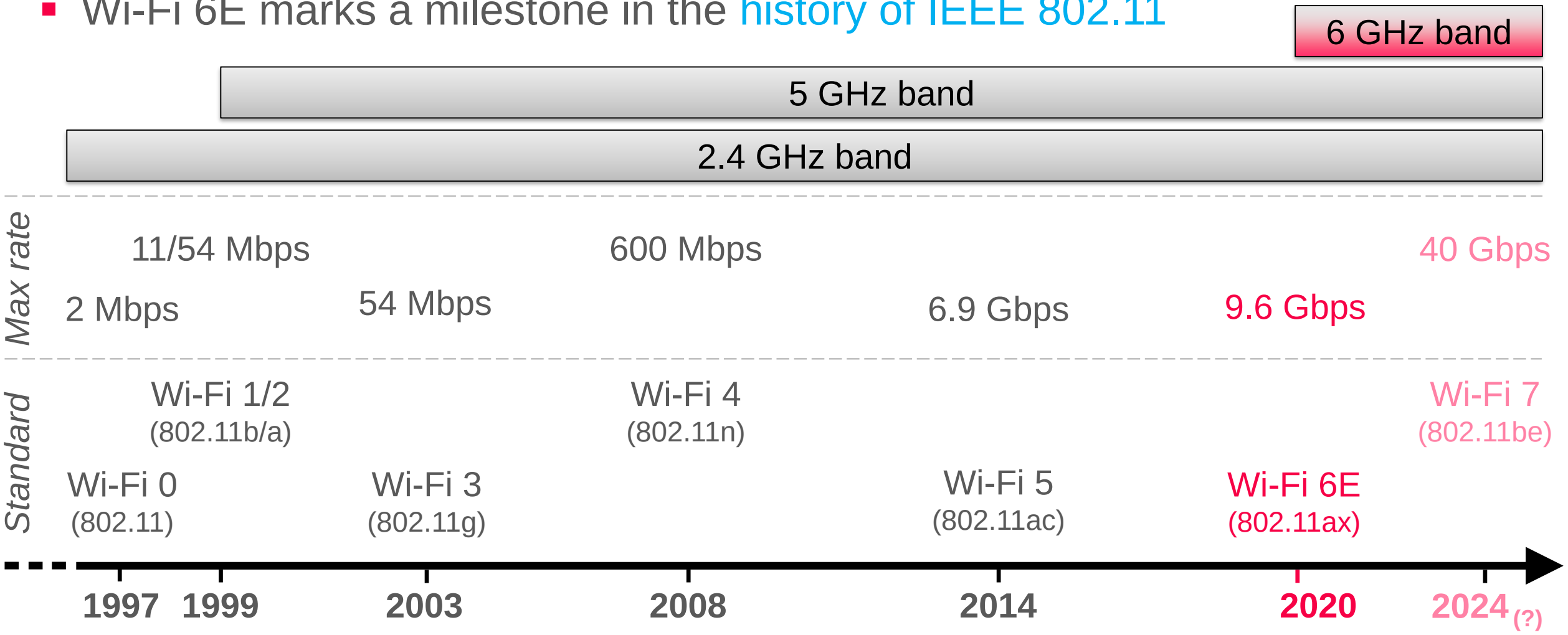
DECISIONS

★ Commission Implementing Decision (EU) 2021/1067 of 17 June 2021 on the harmonised use of radio spectrum in the 5 945-6 425 MHz frequency band for the implementation of wireless access systems including radio local area networks (WAS/RLANs) *(notified under document C(2021) 4240)* [1] 1

Image sources: wikimedia.org, europa.eu, fcc.gov, gov.au, and gc.ca

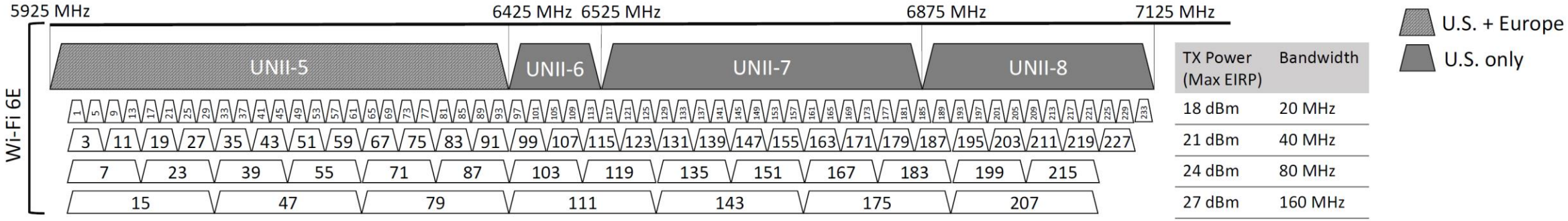
Coexistence Threats on the Horizon

- Wi-Fi 6E marks a milestone in the history of IEEE 802.11



Coexistence Threats on the Horizon

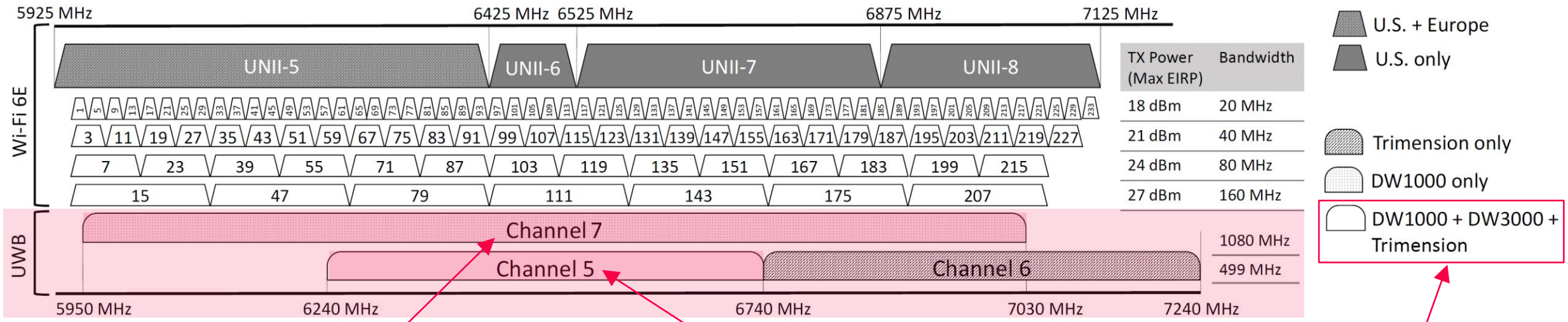
- Wi-Fi 6E marks a milestone in the history of IEEE 802.11
  - Additional contiguous spectrum of up to 1200 MHz (5925 – 7125 MHz)
  - Support for channel bandwidths of 20, 40, 80, or 160 MHz
  - Allows high-throughput and low-latency communication in yet uncongested bands



TX Power (Max EIRP)	Bandwidth
18 dBm	20 MHz
21 dBm	40 MHz
24 dBm	80 MHz
27 dBm	160 MHz

Coexistence Threats on the Horizon

- The frequencies used by most UWB devices overlap with those of Wi-Fi 6E
  - Commercial UWB devices are allowed to operate between 3 and 10 GHz
  - Existing radios mainly operate on the 6 – 8.5 GHz range, and use channels with a bandwidth of ~500 or 1000 MHz



Channel 7 overlaps with the entire band

Only channel 5 supported by the main UWB chips

Coexistence Threats on the Horizon

- The frequencies used by most UWB devices overlap with those of Wi-Fi 6E
  - UWB devices typically offer few channels, some of them spanning > 1 GHz
    (e.g., Qorvo DW3000 only offers channel 5 and 9)

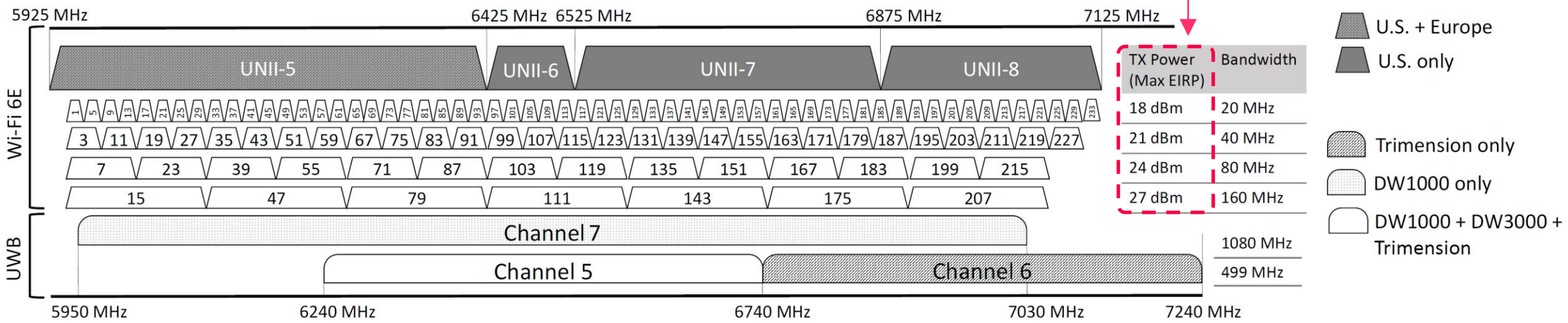
UWB channels			Supported by		
#	Freq. (MHz)	BW (MHz)	DW1000	DW3000	NXP Trimension
1	3494.4	499.2	X		
2	3993.6	499.2	X		
3	4492.8	499.2	X		
4	3993.6	1331.2	X		
5	6489.6	499.2	X	X	X
6	6988.8	499.2			X
7	6489.6	1081.6	X		
8	7488.0	499.2			X
9	7987.2	499.2		X	X

→ Very few options for UWB devices to proactively avoid Wi-Fi 6E interference
(especially when enforcing interoperability)

Coexistence Threats on the Horizon

- The frequencies used by most UWB devices overlap with those of Wi-Fi 6E
  - UWB is likely to suffer the most from the overlap, due to the much lower transmission power

UWB devices should have a maximum equivalent isotropically radiated power of -41.3 dBm/MHz << Transmission power of Wi-Fi 6E access points can be up to 27 dBm



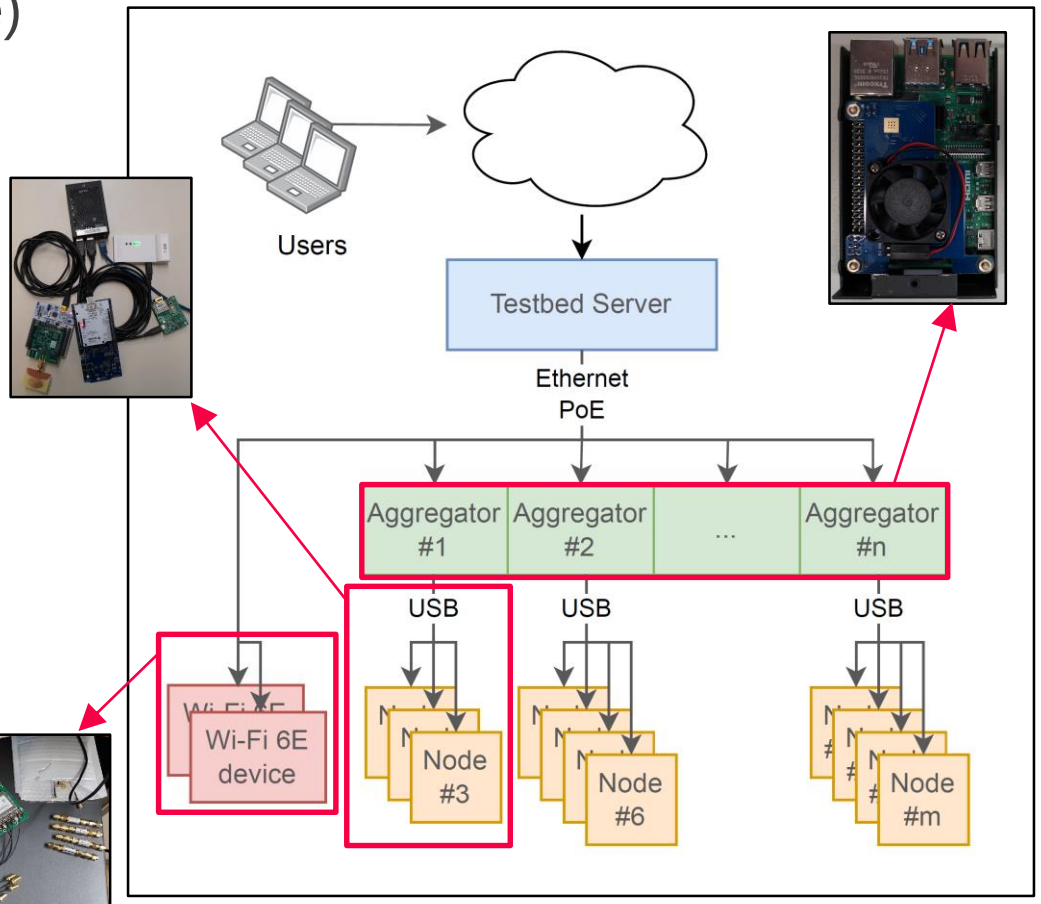
The UWB alliance raised concerns and requested Wi-Fi devices to reduce interference by using directional antennas, dynamic transmit power control, and minimizing duty cycle [link]

Outline

- Introduction
  - Proliferation of UWB and Wi-Fi 6E systems
  - Coexistence threats at the horizon
- How does Wi-Fi 6E traffic affect UWB systems?
  - Impact on UWB communication
  - Impact on UWB ranging and localization
  - Anatomy of the Wi-Fi 6E impact on UWB systems
- Mitigating the impact of Wi-Fi 6E traffic on UWB systems
- Open questions & next steps

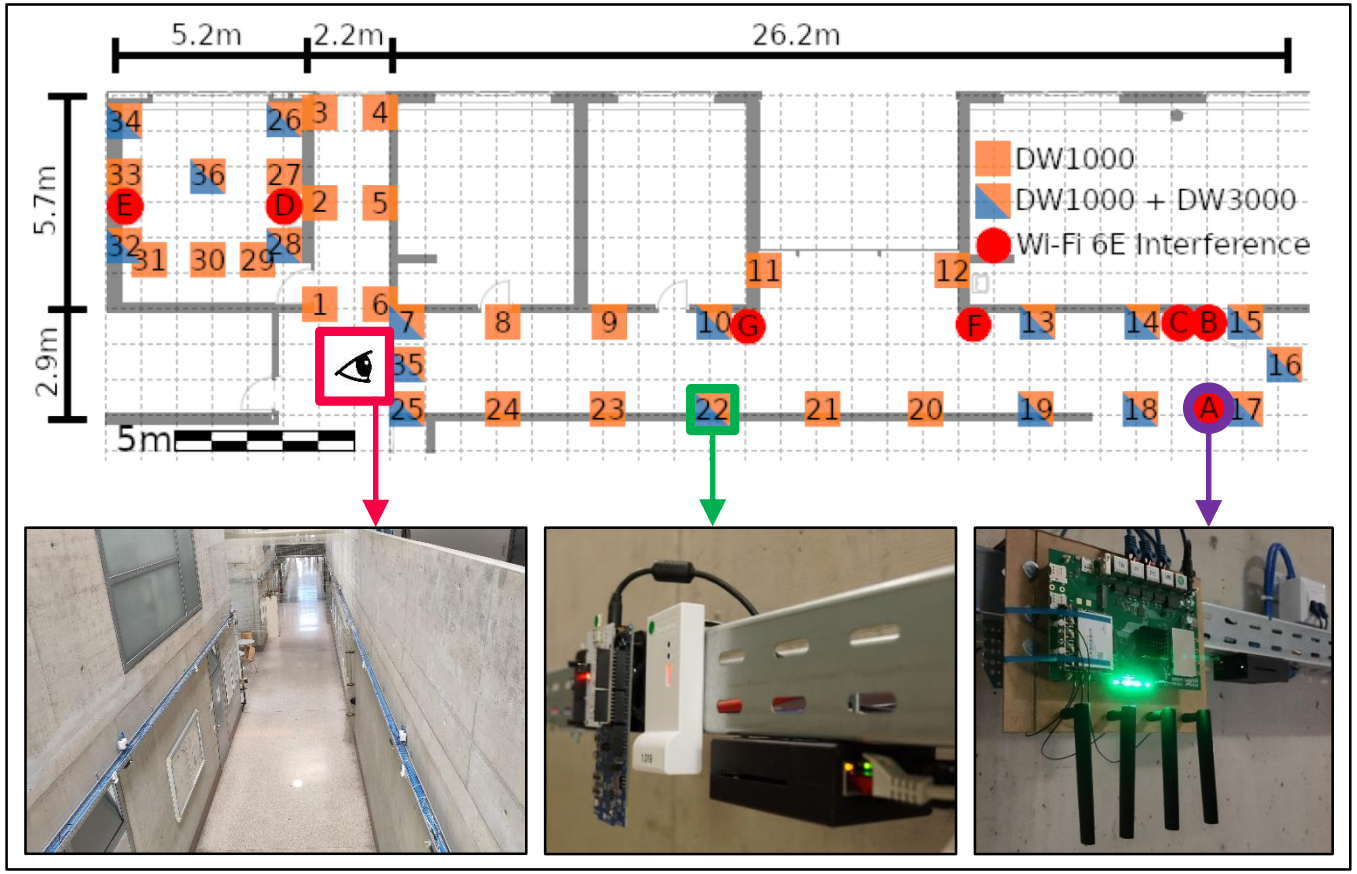
Experimental Setup

- We set up a testbed to study coexistence issues experimentally
  - Ethernet backbone infrastructure (same as D-Cube)
    - PoE for supplying power and power-cycling
    - Fiber connection between PoE switch and server
  - Observer (aggregator) devices
    - Raspberry Pi 4B, 8 GB RAM
    - Up to four target UWB nodes
  - Wi-Fi 6E devices
    - Based on Qualcomm QCN9074 / Intel AX210 modules
  - Towards a full-fledged benchmark
    - Testbed functionality increasing over time
    - Planned: energy profiling, reproducible jamming, and support for more UWB nodes



Experimental Setup

- We set up a testbed to study coexistence issues experimentally
  - Across a large hallway (130 m²) and inside an office room (30 m²)
  - 36 “old-generation” UWB nodes
    - Decawave MDEK1001 boards (nRF52832 + DW1000 radio)
    - Compliant to IEEE 802.15.4a
    - Relatively high density
  - 17 “new-generation” UWB nodes
    - Custom boards (nRF52833 + DW3000 radio)
    - Compliant to IEEE 802.15.4z (revision supporting secure ranging)
  - 7 Wi-Fi 6E devices



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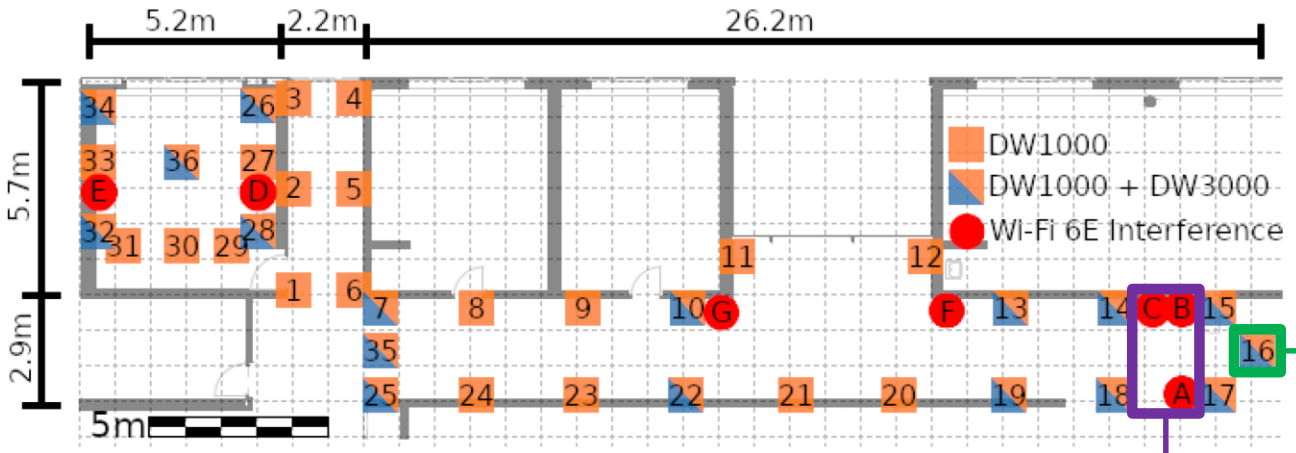
Experimental Findings

- #1: Does Wi-Fi 6E traffic affect (at all) UWB communications?
  - We let a DW1000 UWB node broadcast packets, while all others measure the PRR



UWB transmissions

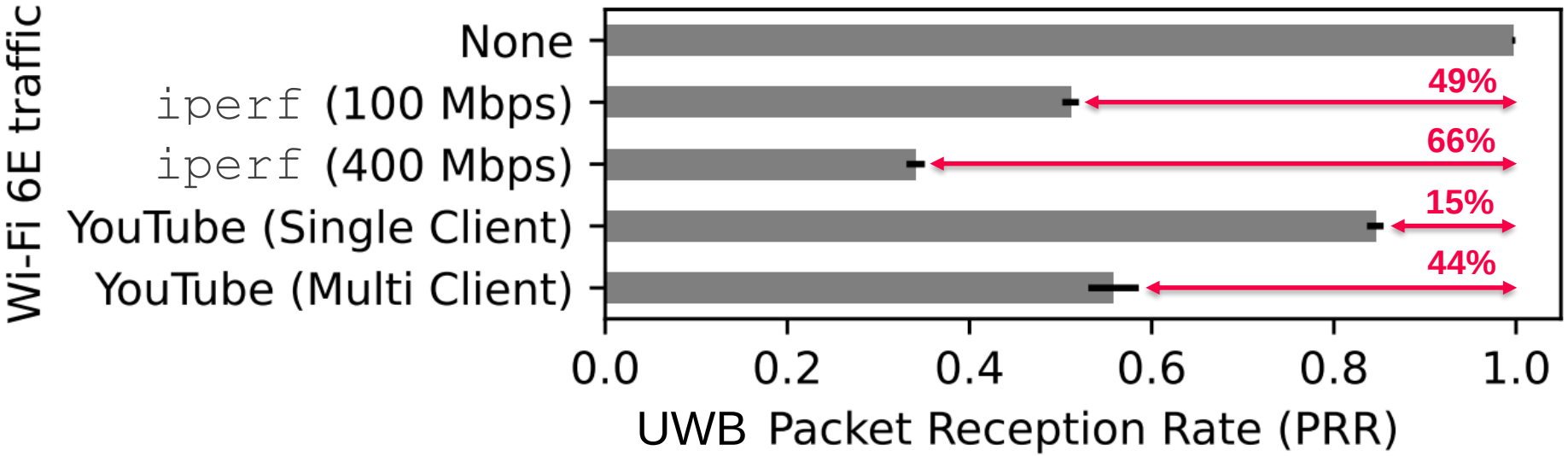
- Channel 5
  - 6.495 GHz center frequency, 500 MHz bandwidth
- Default PHY settings
  - PRF = 64 MHz, PSR = 1024, DR = 6.8M, Payload = 16B

Wi-Fi 6E traffic

- Channel 111
  - 6.495 GHz center frequency, 160 MHz bandwidth
- Different traffic patterns
  - UDP stream at fixed bitrate (`iperf`) from device B to A
  - YouTube traffic, single-client (A = access point, B = client)
  - YouTube traffic, multi-client (both B and C as clients)

Experimental Findings

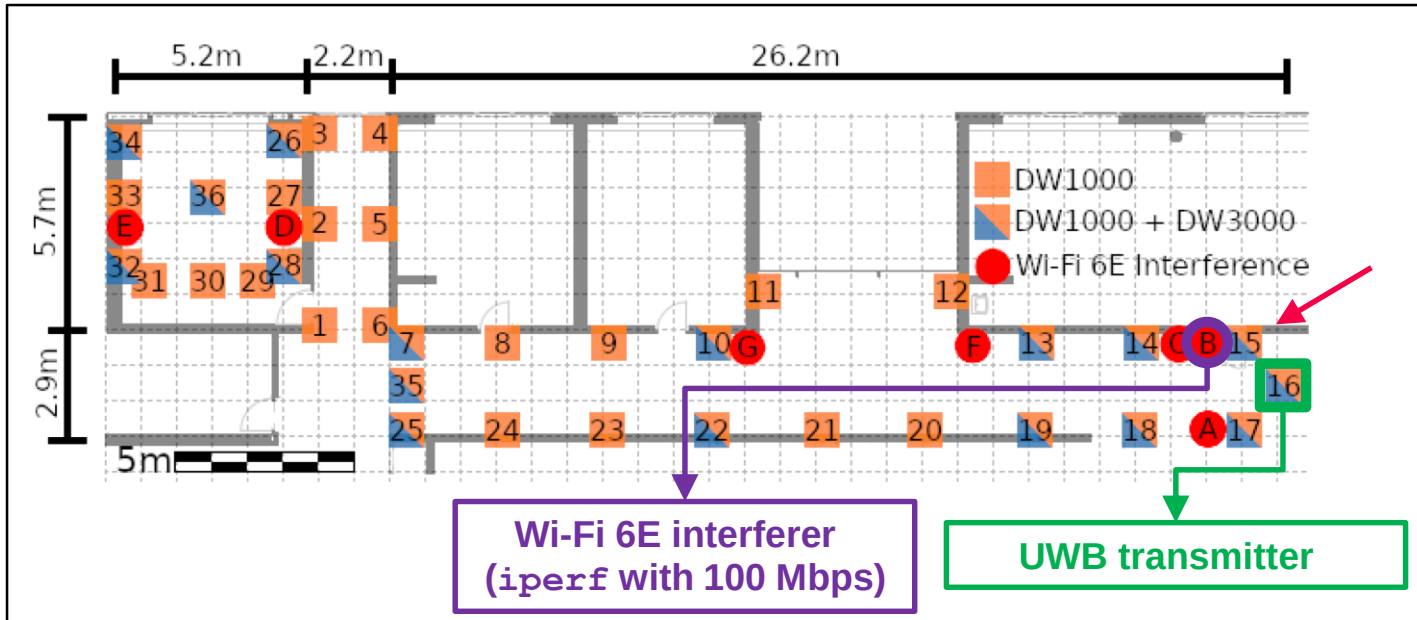
- #1: Does Wi-Fi 6E traffic affect (at all) UWB communications?
  - Yes: the average PRR across all testbed nodes drops significantly

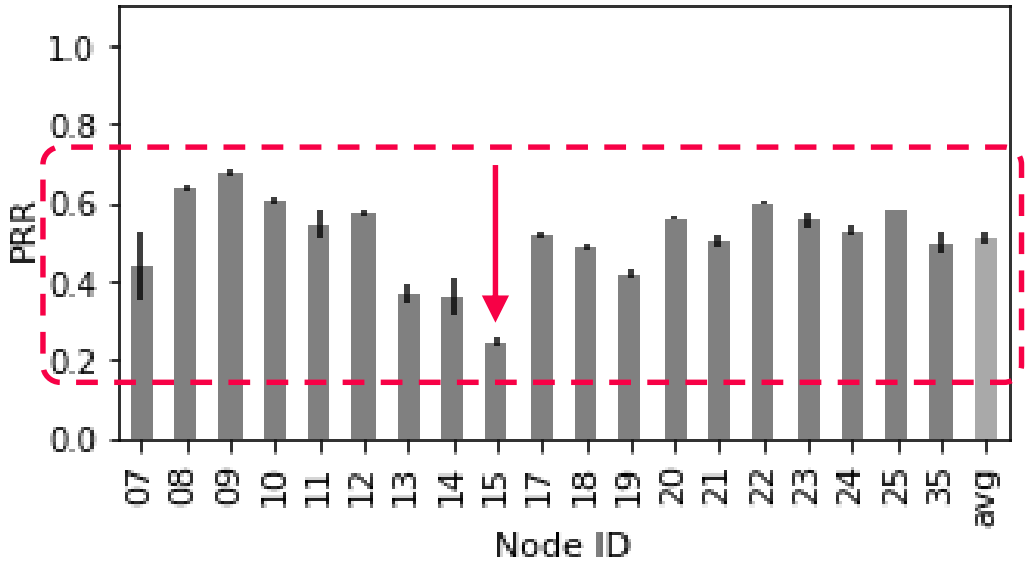


- Video streaming is often buffered → large white spaces in which UWB transmissions are successful
- Much shorter white spaces with `iperf` → higher chances for UWB packets to be hit

Experimental Findings

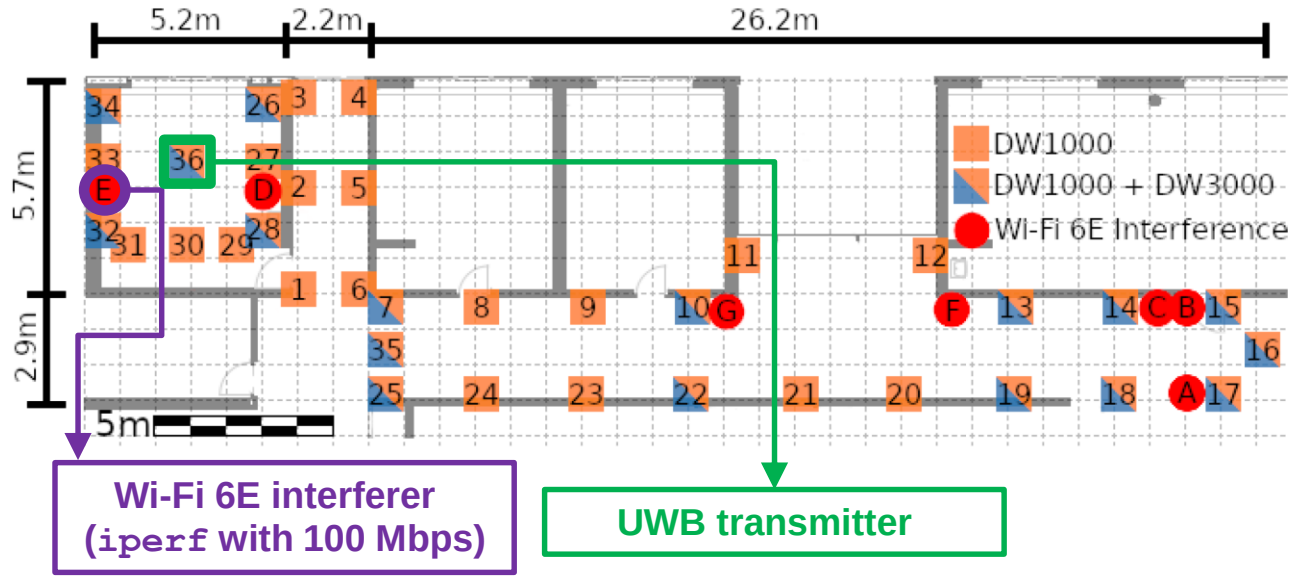
- #2: How is the packet loss spread across the testbed?
  - Hallway, node 16 as transmitter
  - The closest node (15) is the most affected
  - All nodes in the hallway (also those at >25m from the Wi-Fi 6E interferer) exhibit a low PRR

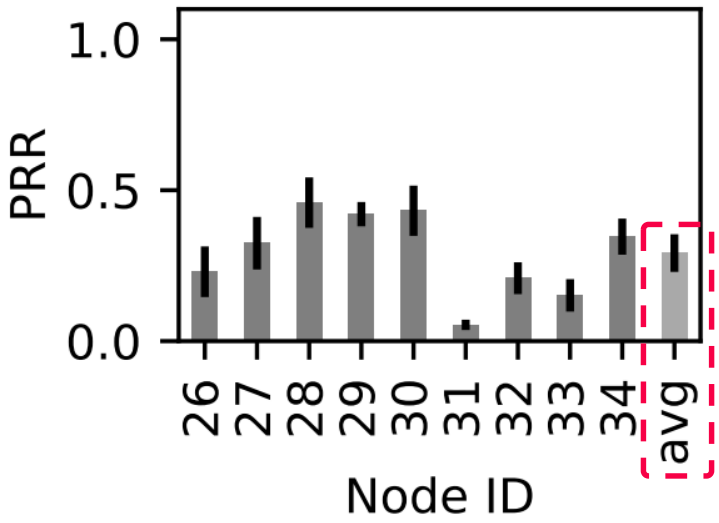




Experimental Findings

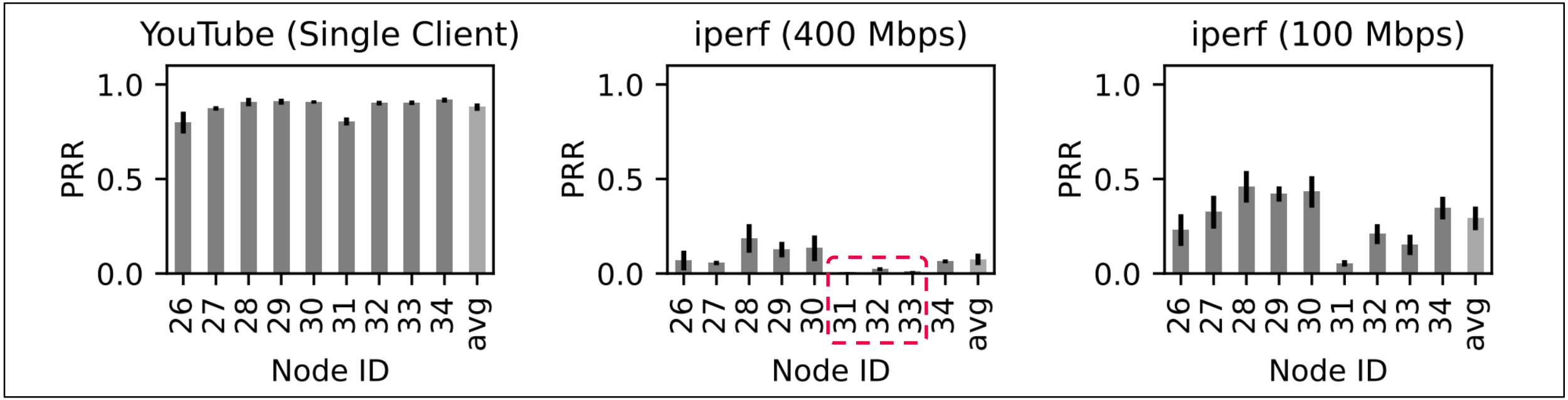
- #2: How is the packet loss spread across the testbed?
  - Office, node 36 as transmitter
  - Average PRR across office nodes only ~30%
    (was ~50% in the hallway)





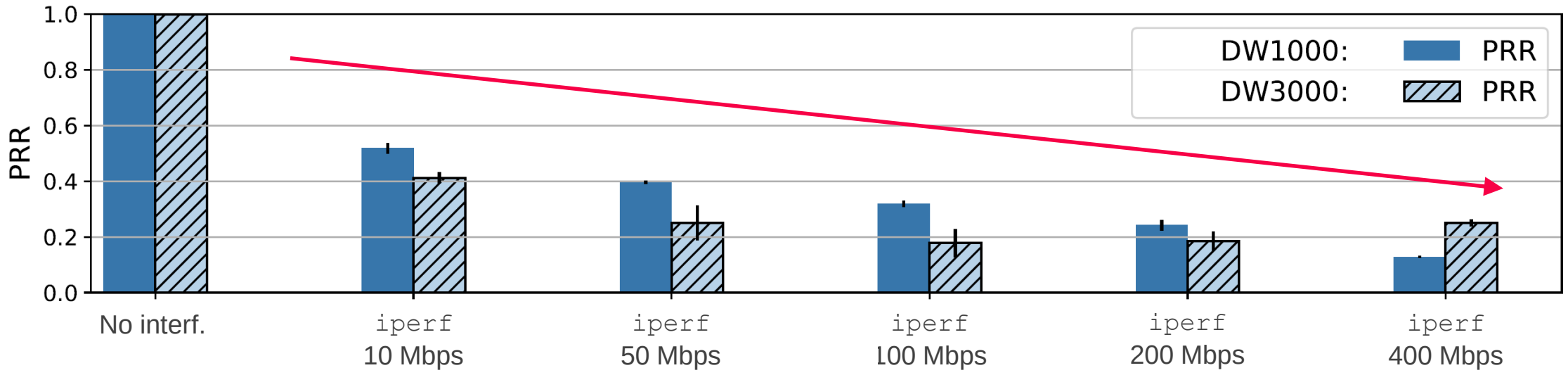
Experimental Findings

- #2: How is the packet loss spread across the testbed?
  - Office, node 36 as transmitter
  - PRR may even drop below 1% on some of the nodes
    (i.e., the link is essentially useless)



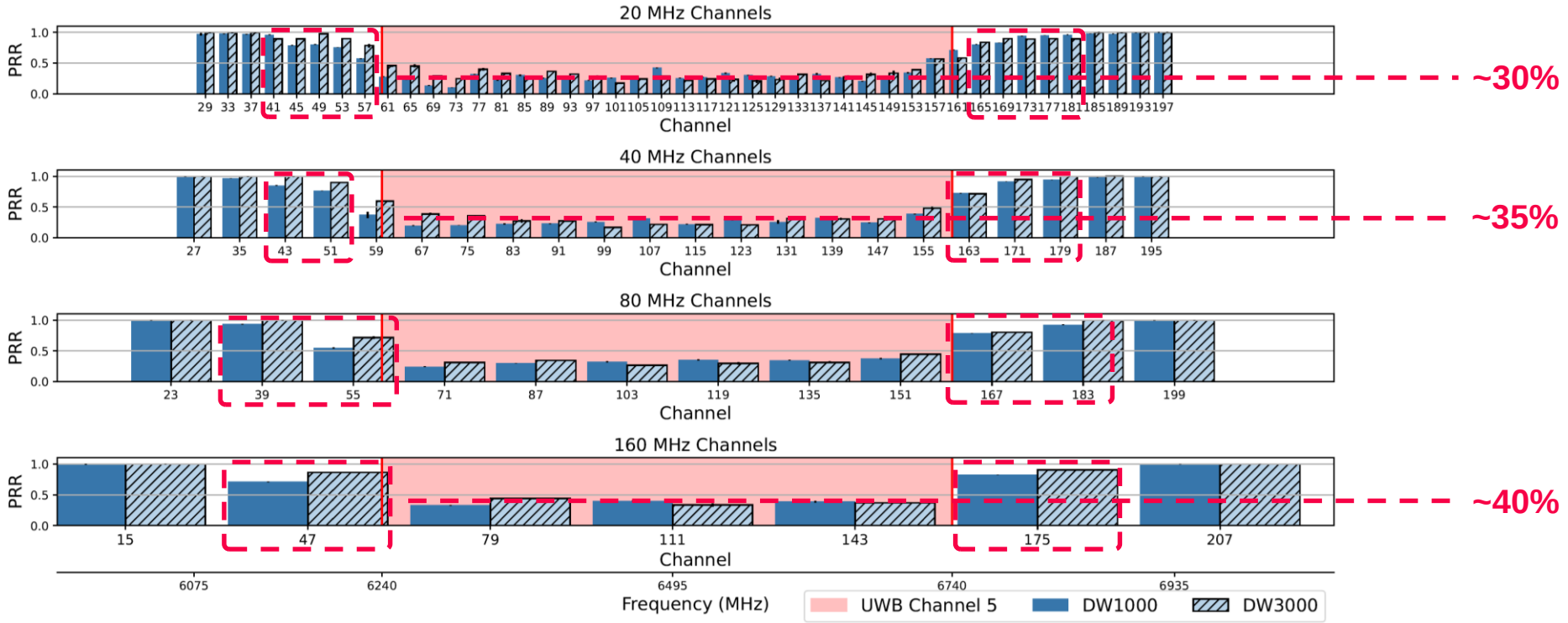
Experimental Findings

- #3: Do also new-generation chips suffer from these problems?
  - Yes: there is visible impact on both DW1000 (older) and DW3000 (newer) radios
  - Office, node 36 as transmitter, using `iperf` UDP streams with different throughput
  - New-generation chips do not necessarily exhibit a better performance



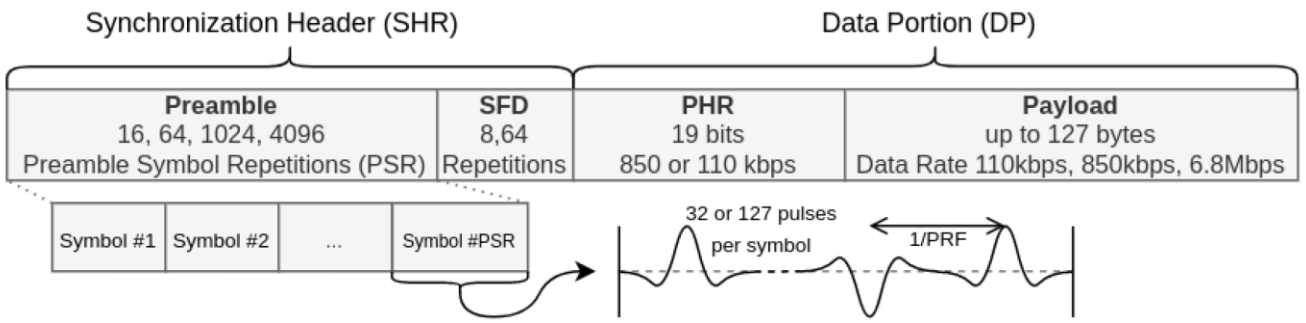
Experimental Findings

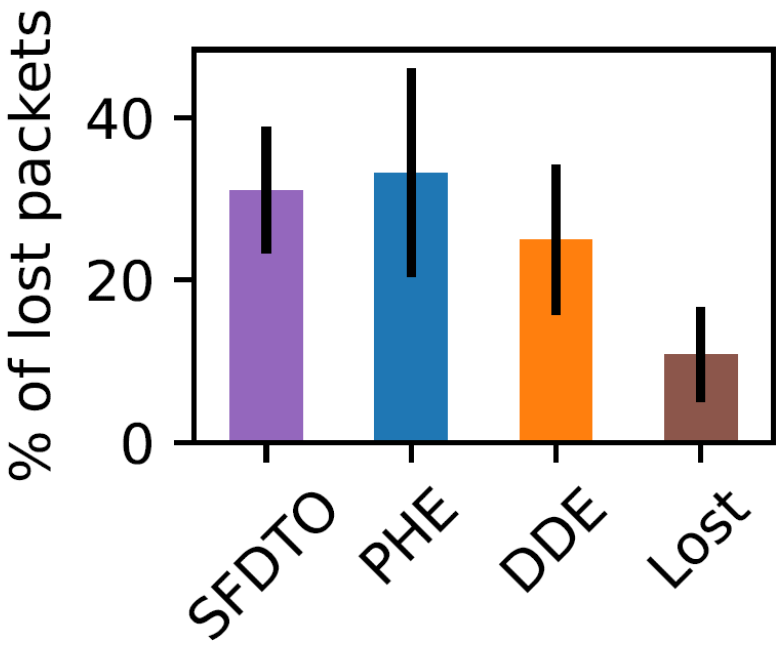
- #4: What is the impact as a function of the selected frequency/bandwidth?
  - Significant impact even when using Wi-Fi 6E channels that should not overlap with UWB (new-generation chips exhibit a slightly better performance)
  - The use of Wi-Fi 6E channels with smaller bandwidth results in a higher UWB packet loss



Experimental Findings

- #5: In what form does the loss manifest itself at UWB receivers?
  - Interestingly, only a few packets are never received (`Lost`)
  - In most of the cases, the receiver either experiences an SFD timeout (`SFDTO`) a physical header error (`PHE`), or a data decoding error (`DDE`)
  - This indicates that portions of the SHR could be successfully decoded





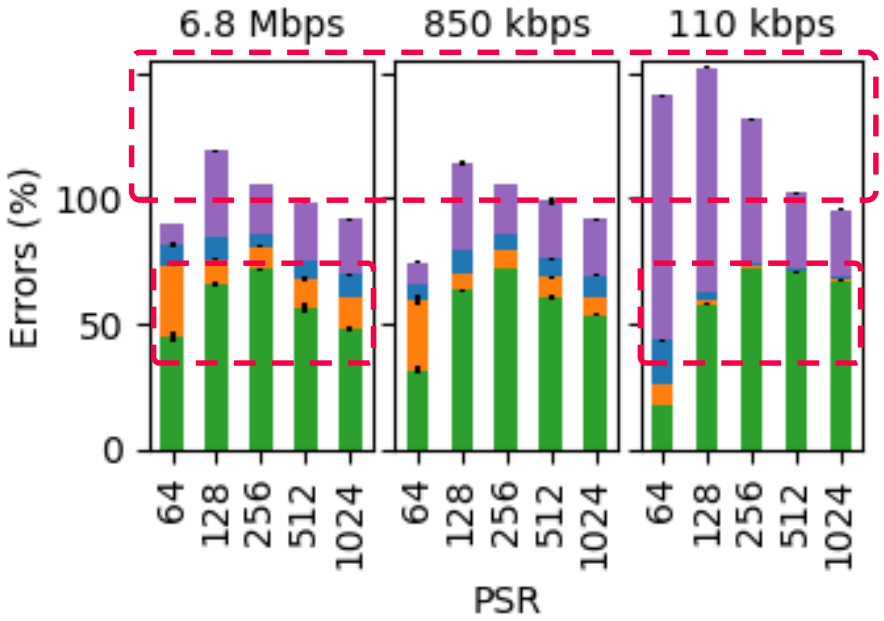
Experimental Findings

- #6: What is the performance as a function of the used UWB PHY settings?
  - Better performance with smaller payloads and shorter data rates (expected)
  - The number of preamble symbol repetitions (PSR) has a strong impact (too many and too few preamble symbols decrease the PRR)
  - Number of errors > Number of sent packets (!)

31x more energy! (only removes DDE)

PSR=256 exhibits the best performance

Looks like the Wi-Fi 6E signal tricks the UWB receiver in believing that there is a preamble even when there is not!



RXOK → Reception successful
DDE → Data decoding error
PHE → Physical header error
SFDTO → SFD timeout

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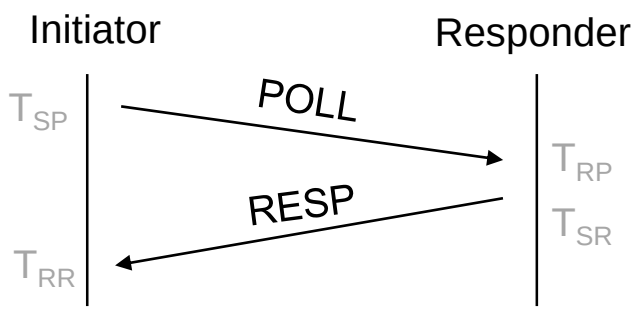
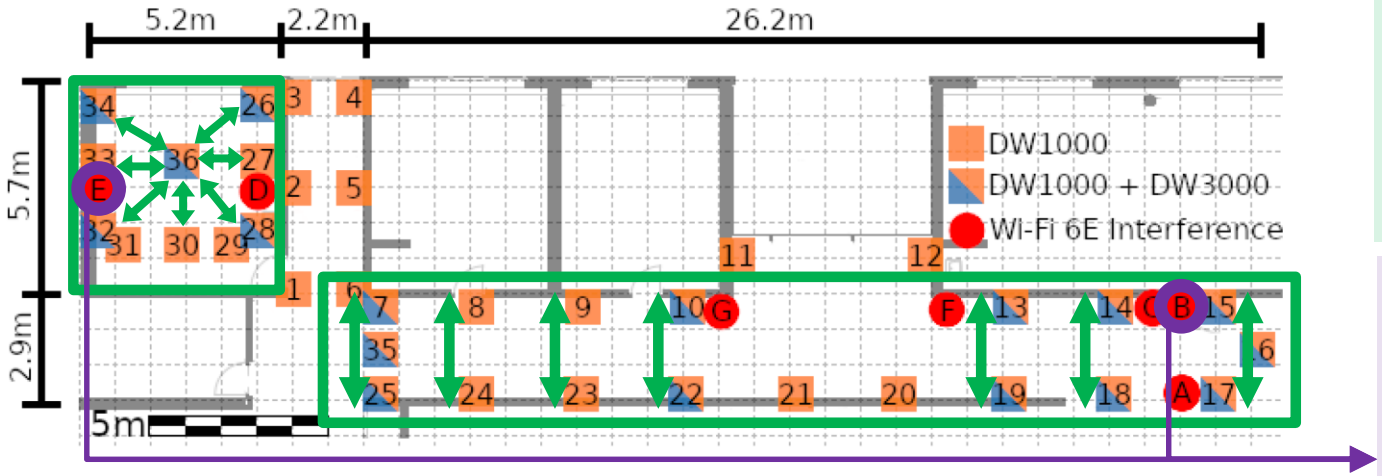
Experimental Findings

- Is the UWB ranging process affected by Wi-Fi 6E traffic?
  - We let several node pairs perform hundreds of single-sided two-way rangings (SS-TWR)
  - We monitor the reception of both messages separately
  - Both in the office and in the hallway





UWB transmissions

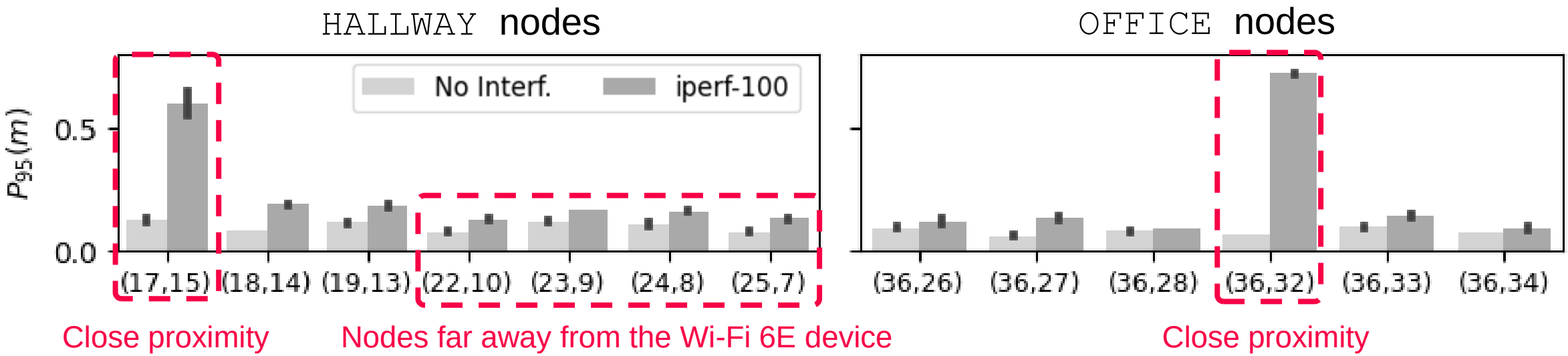
- Channel 5
  - 6.495 GHz center frequency, 500 MHz bandwidth
- Best PHY settings found previously
  - PSR = 256, DR = 6.8M, Payload = 16B, PRF = 64 MHz

Wi-Fi 6E traffic

- Channel 111
  - 6.495 GHz center frequency, 160 MHz bandwidth
- `iperf` with 100 Mbps

Experimental Findings

- Is the UWB ranging process affected by Wi-Fi 6E traffic?
  - Yes #1: prominent decrease in ranging precision in the presence of Wi-Fi 6E traffic (especially when a UWB node is in close proximity to a Wi-Fi device)
  - P_{95} = width of the interval in which 95% of the samplies lie
  - Precision in the presence of Wi-Fi 6E traffic ( ) worse than in the non-interfered case ( )
    - ~ 10 cm in the average case; significant spikes > 0.5m when UWB nodes near the Wi-Fi 6E transmitter



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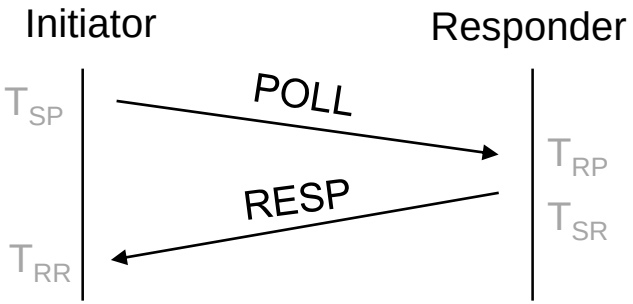
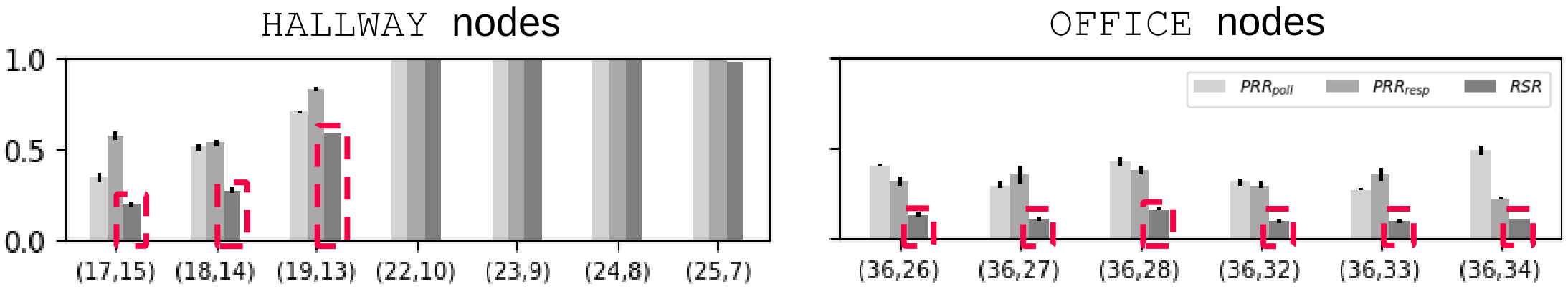
- What about the maximum ranging error observed (P_{100})?
  - ~ 12.3 cm in interference-free experiments
  - ~ 50 m in the hallway in the presence of Wi-Fi 6E traffic
  - ~ 30 m in the office in the presence of Wi-Fi 6E traffic

!

Experimental Findings

- Is the UWB ranging process affected by Wi-Fi 6E traffic?
  - Yes #2: much lower likelihood to successfully derive the distance between two devices (due to the high packet loss – as shown previously)
  - As low as < 15% of the rangings in the office succeed!





PRR_{poll} PRR_{resp} RSR → Ranging success ratio ($PRR_{poll} \cdot PRR_{resp}$)

Experimental Findings

- Severe implications for UWB localization systems
  - Less than 3% and 1% of the localization attempts in the hallway and office are successful!

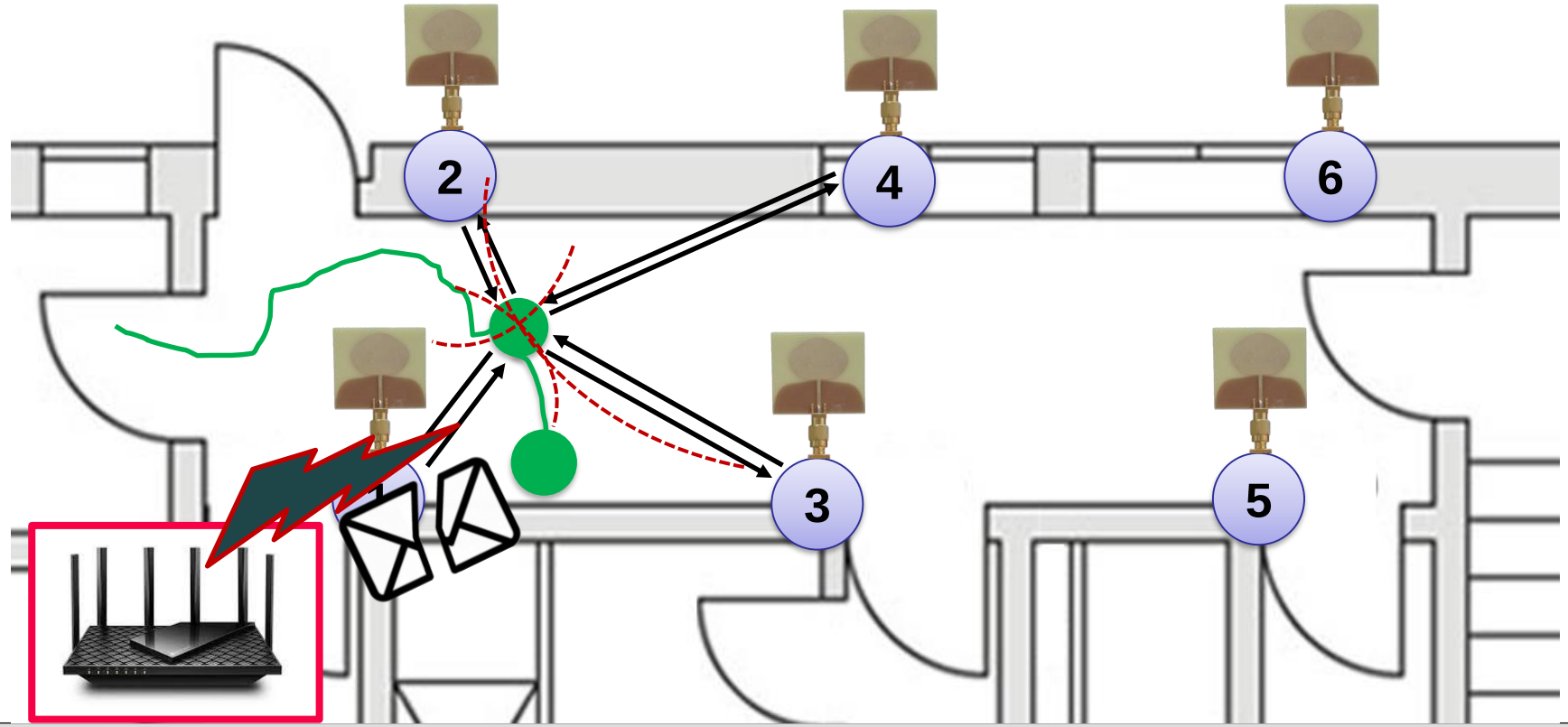


Image source: 3D Warrior

Outline

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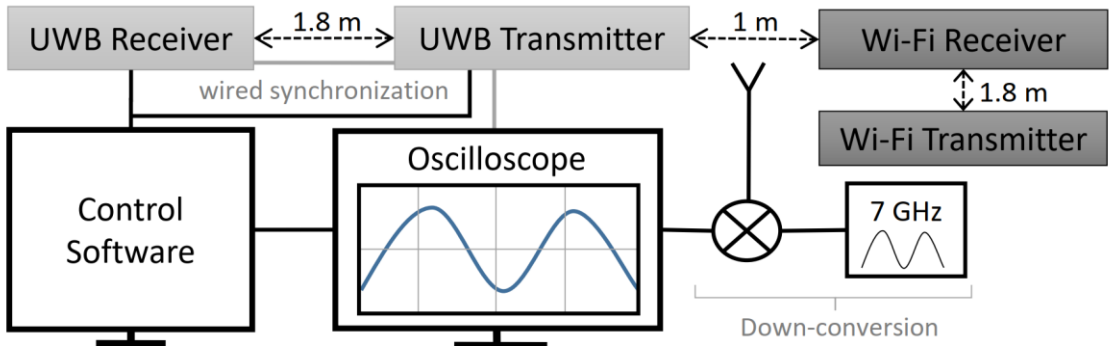
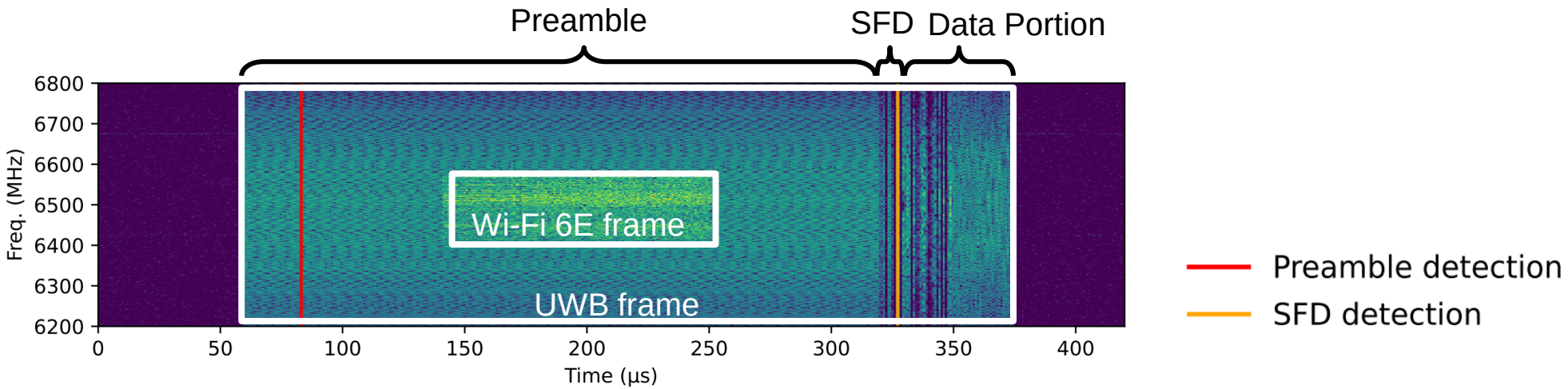
- Mitigating the impact of Wi-Fi 6E traffic on UWB systems
- Open questions & next steps

Anatomy of the Wi-Fi 6E Impact on UWB

- We record 48 hours of oscilloscope traces capturing UWB transmissions in presence of Wi-Fi 6E traffic
  - Diagnostic data (UWB reception errors, preamble detection timestamps, …)
  - This setup allows us to determine the exact position of the packet collision and its outcome



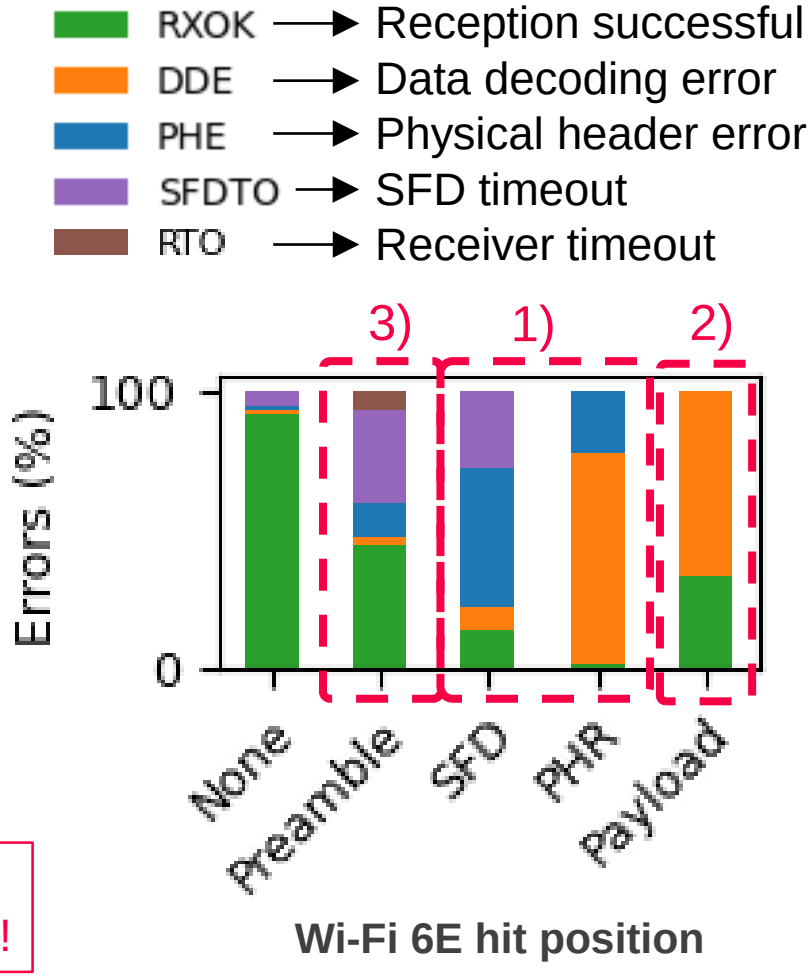


Anatomy of the Wi-Fi 6E Impact on UWB

- Error rate as a function of the Wi-Fi 6E hit position
  1) UWB receiver cannot recover from hits in SFD / PHR
  2) UWB receiver hardly recovers from hits in the payload
     (it mostly recovers if the hit occurs at the very end of the frame)
  3) The UWB receiver can recover from hits in the preamble
     (if enough preamble symbols can be accumulated)
     - Longer preambles allow to recover from a Wi-Fi 6E hit
     - But they are more likely to be hit multiple times

Preamble length (symbols)	64	128	256	512	1024
Recovered packets with single hit in preamble (%)	5.9	27.8	56.4	57.4	61.9
Max. length of preamble hit for recovered packets (µs)	28	93	134	258	396
Packets with multiple hits in preamble (%)	23.0	22.9	26.5	58.4	91.44
Recovered packets with one or more hits in preamble (%)	7.6	41.0	60.7	42.3	27.9

best trade-off!



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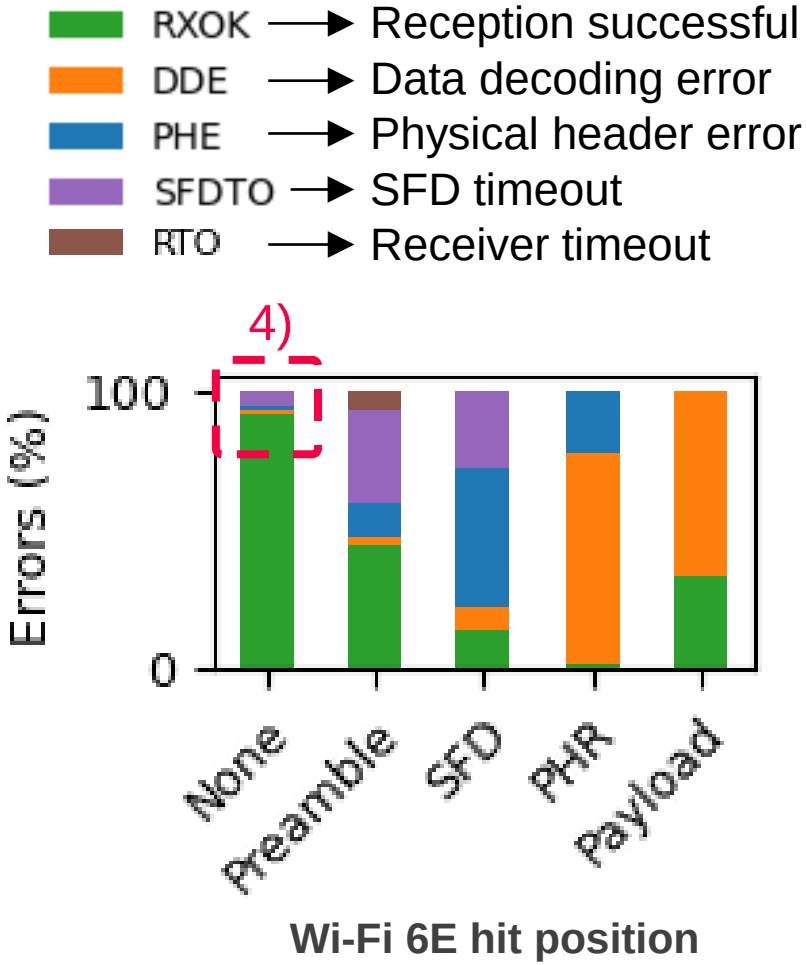
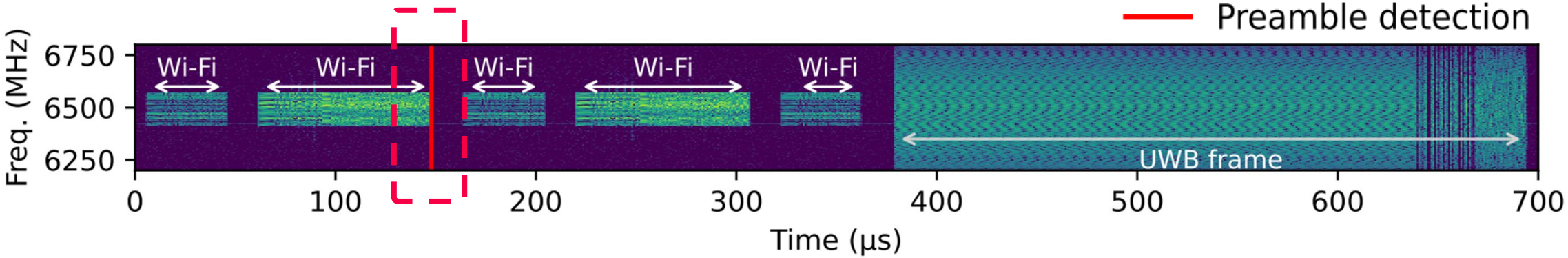
     - But they are more likely to be hit multiple times
  4) The UWB receiver reports reception errors, even if no Wi-Fi 6E hit occurs

     → Why?



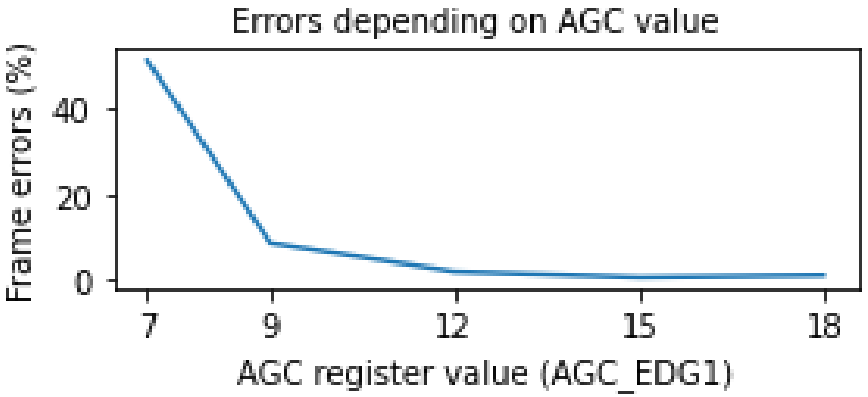
Anatomy of the Wi-Fi 6E Impact on UWB

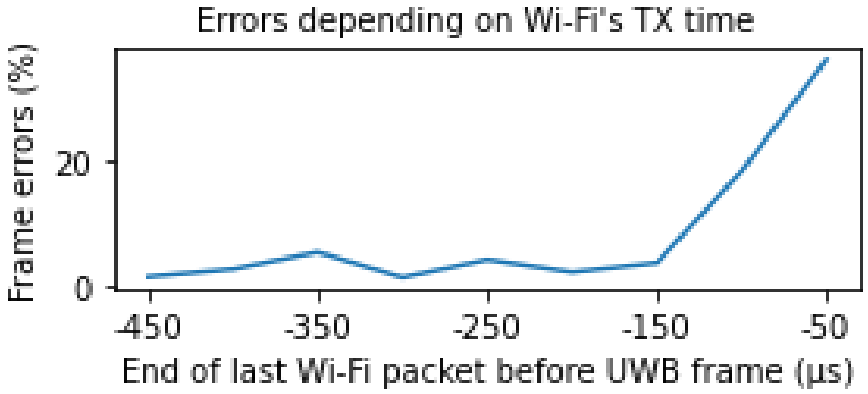
- Wi-Fi 6E falsely classified as UWB preamble
  - UWB receivers remain awake to look for the SFD until reception is stopped
    (→ waste of energy!)



Anatomy of the Wi-Fi 6E Impact on UWB

- Wi-Fi 6E traffic causes a saturation of the automatic gain control (AGC)
  - Due to the high power of Wi-Fi 6E signals, their presence causes the AGC to reduce the gain, thus leaving the UWB receiver insensitive to incoming frames
  - UWB receiver remains ‘deaf’
  - Visible correlation between frame errors and:
    - The values of the AGC diagnostic register
    - How close Wi-Fi 6E traffic appears before the UWB transmission





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Mitigating the Wi-Fi 6E Impact on UWB

- What can be done?
  - Increasing the transmission power of UWB devices
  - Avoid overlapping channels
  - Use large channel bandwidths / adaptive frequency hopping
  - Clear channel assessment (CSMA-style)
    - UWB radios do not support energy detection
- Can we exploit the AGC register to detect the presence of Wi-Fi 6E traffic?

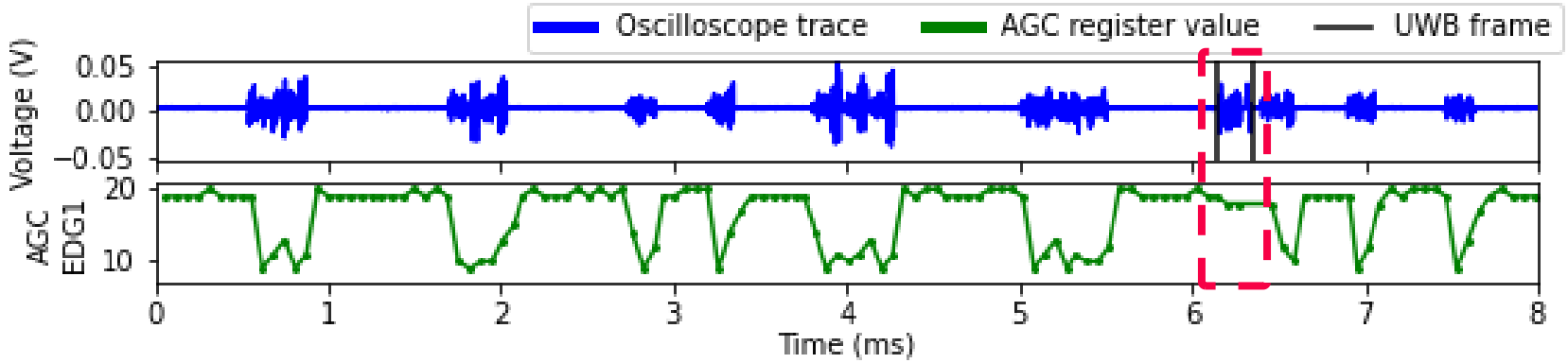


Image sources: freesvg.org and freesvg.org

Mitigating the Wi-Fi 6E Impact on UWB

- Detect Wi-Fi 6E traffic and defer transmissions
  - By exploiting the AGC register values

CCA

- Optimal selection of PHY settings
  - Especially the number of preamble symbol repetition
    - Neither too long, nor too short
    - Ideally adaptive at runtime based on the Wi-Fi 6E traffic characteristics

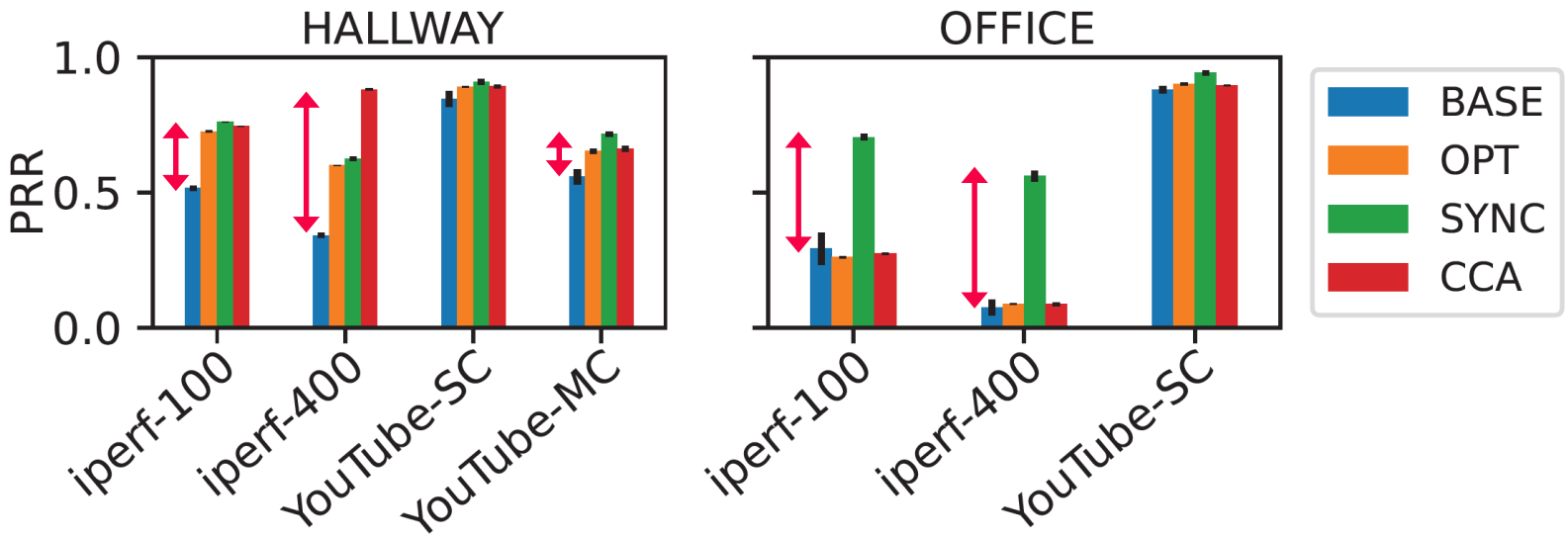
OPT

- Late wake-up
  - UWB receiver should wake up just in time prior to reception
    - To avoid falsely detected Wi-Fi 6E packets
    - To avoid saturation of AGC

SYNC

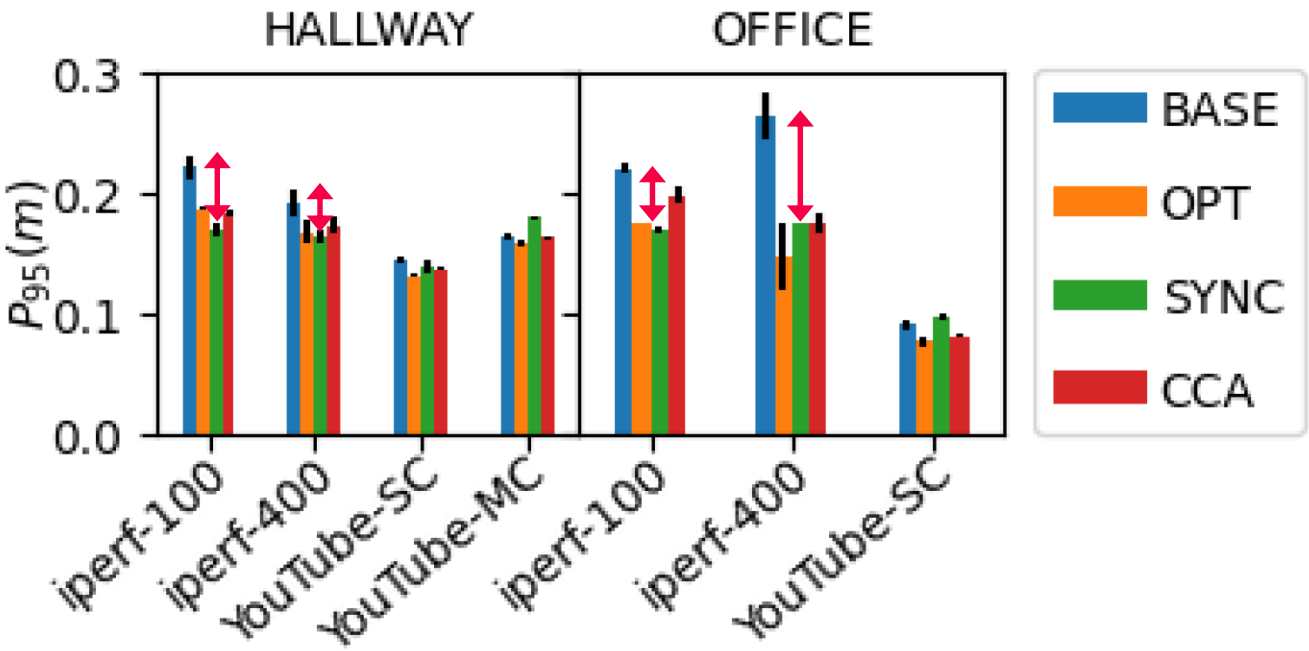
Mitigating the Wi-Fi 6E Impact on UWB

- Effectiveness of proposed countermeasures against Wi-Fi 6E traffic
  - OPT improves PRR by up to 25% compared to default UWB PHY settings (BASE)
  - SYNC improves PRR by up to 47% compared to OPT
    (mainly beneficial for UWB nodes close to Wi-Fi 6E devices)
  - CCA improves PRR by up to 28% compared to OPT
    (mainly beneficial for UWB nodes far from Wi-Fi 6E device)



Mitigating the Wi-Fi 6E Impact on UWB

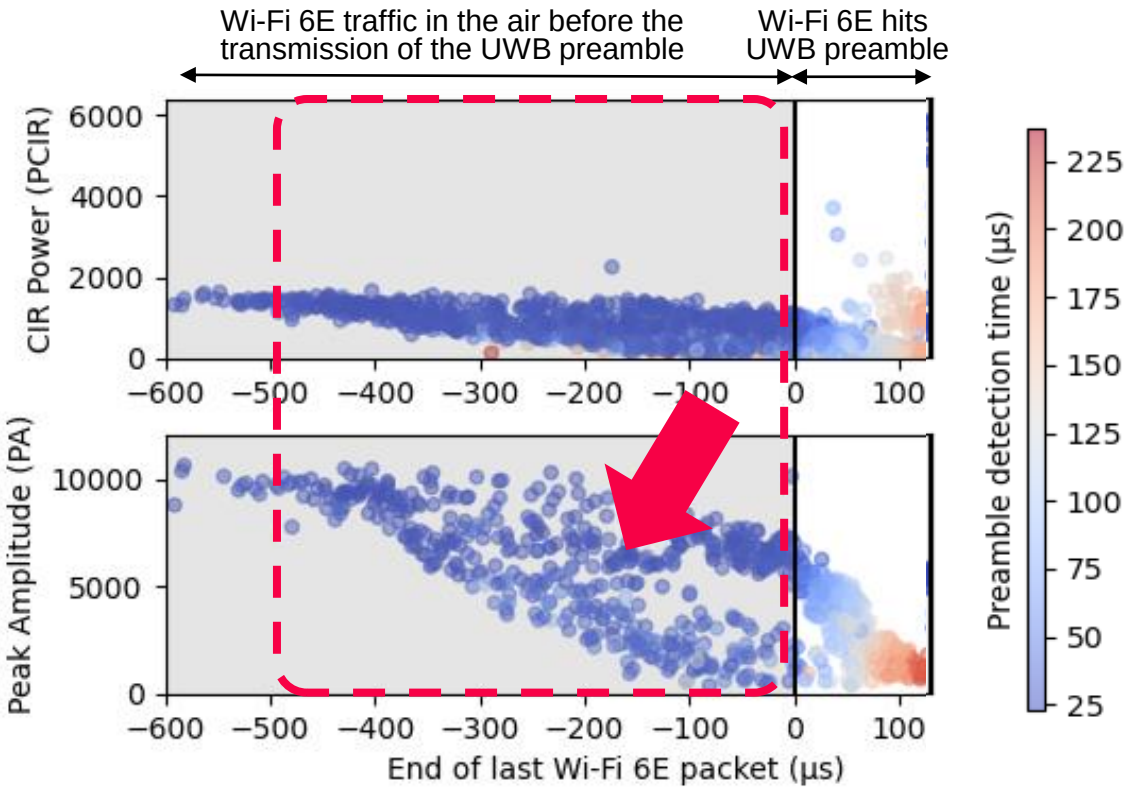
- These countermeasures also increase the ranging precision in the presence of Wi-Fi 6E traffic
  - Improvements up to 46% because they avoid a distortion of the CIR estimate



Mitigating the Wi-Fi 6E Impact on UWB

- Wi-Fi 6E hits lead to a distortion of the CIR estimate
  - Likely the reason for the observed ranging errors

From the diagnostic registers:
- PCIR = CIR power
- PA = Peak amplitude



- Wi-Fi 6E traffic in the air just before the UWB frame
  - → PCIR and PA drop (AGC)
  - → Affects the properties of the CIR
  - → Affects the ToA estimation!
- Wi-Fi 6E hits UWB early
  - → PCIR and PA drop (preamble detection delayed)
- Wi-Fi 6E hits UWB late
  - → PCIR and PA rise (accumulation over Wi-Fi 6E packet)

Mitigating the Wi-Fi 6E Impact on UWB

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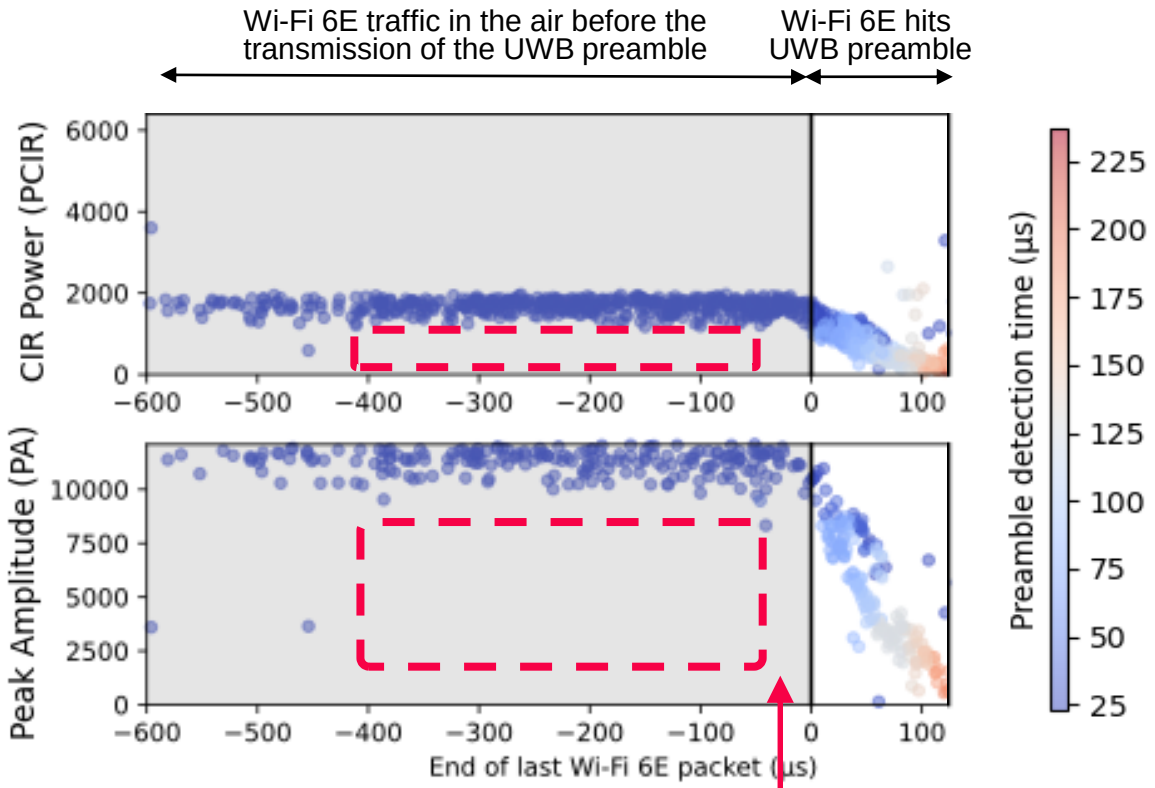

Receiver turned on just before UWB packet (SYNC)

- Wi-Fi 6E traffic in the air just before the UWB frame
  - → PCIR and PA ~~drop (AGC)~~ constant
  - → Much less impact on CIR properties & ToA estimation!
- Wi-Fi 6E hits UWB early
  - → PCIR and PA drop (preamble detection delayed)
- Wi-Fi 6E hits UWB late
  - → PCIR and PA rise (accumulation over Wi-Fi 6E packet)

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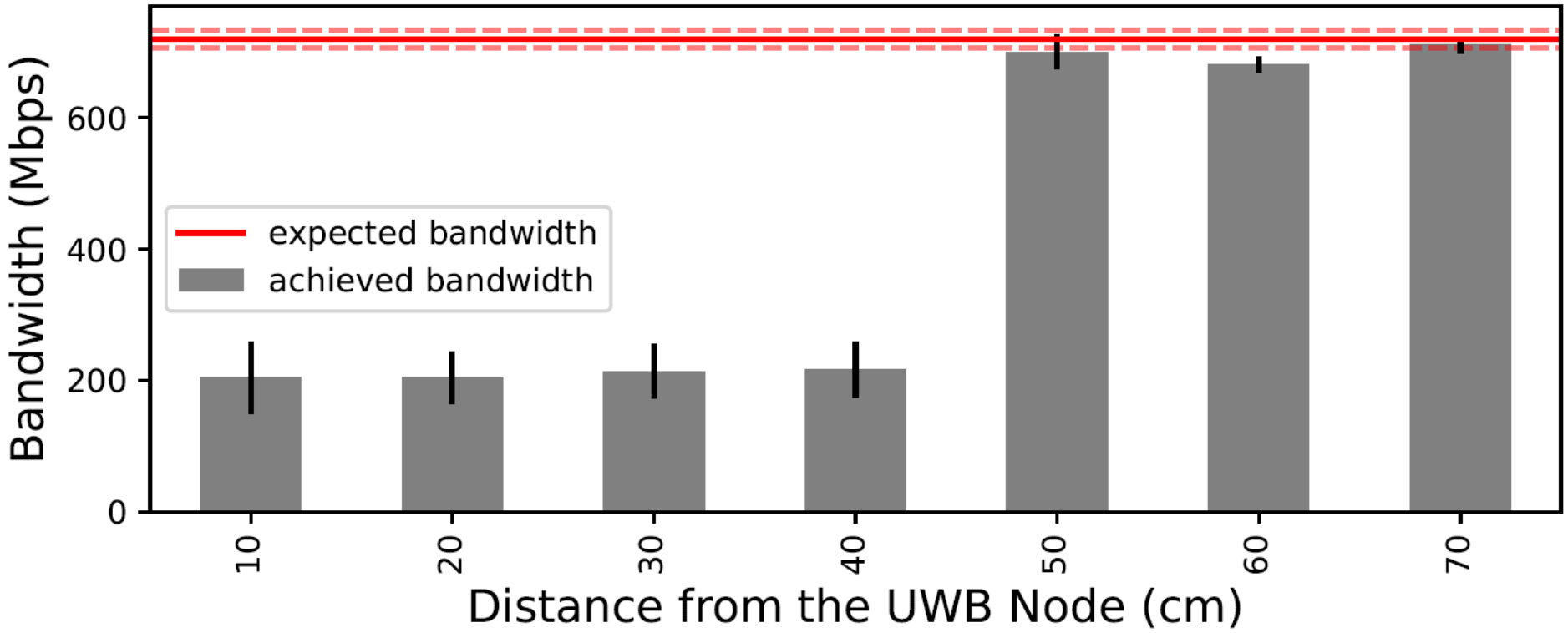
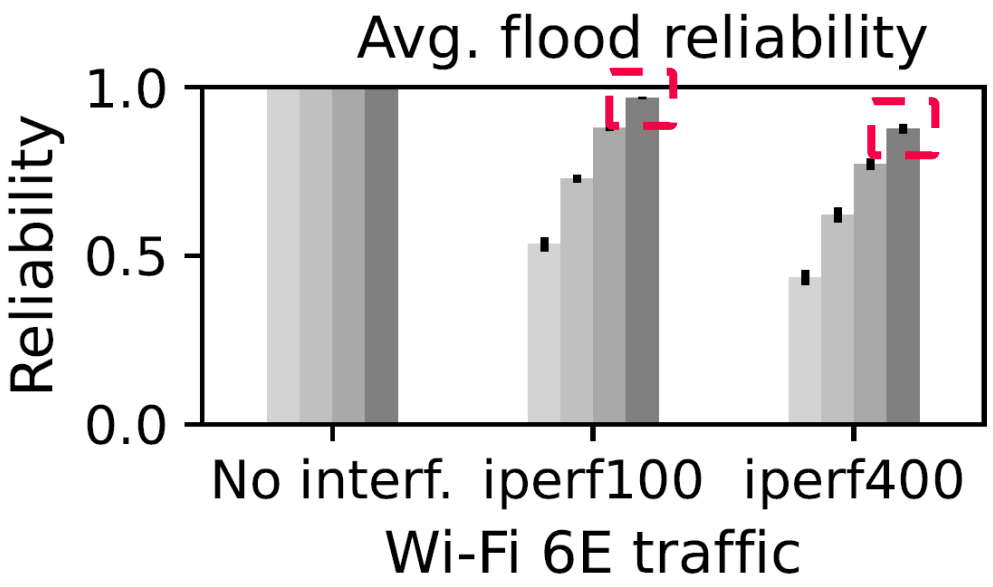
Open Questions & Next Steps

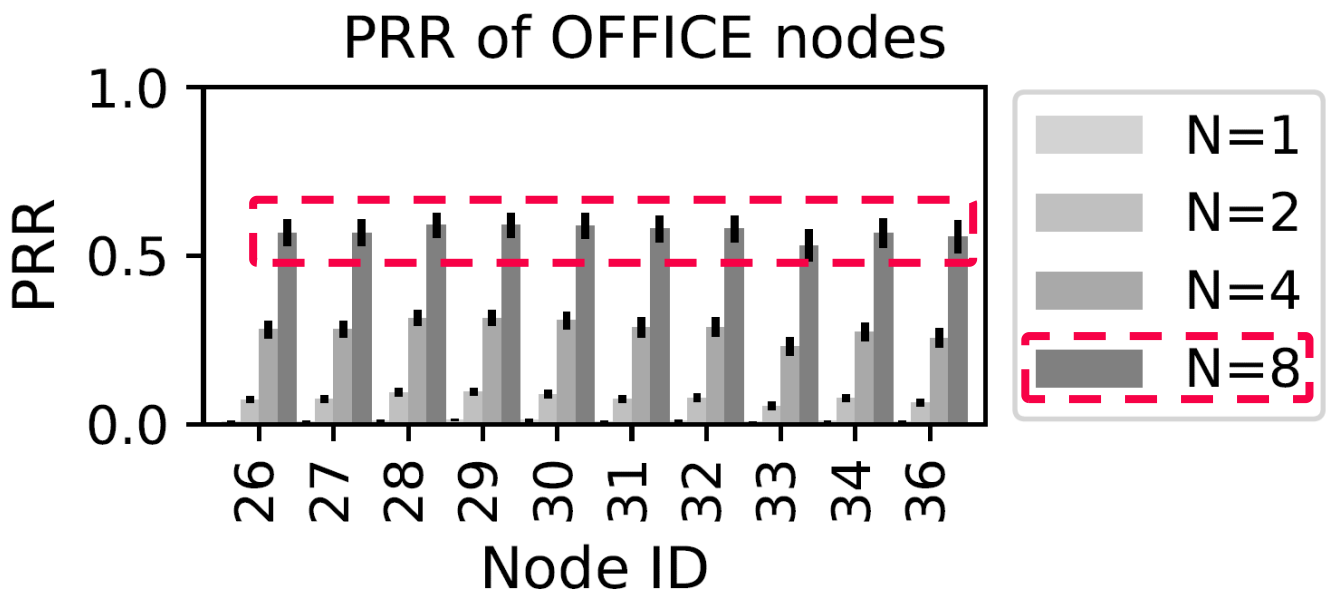
- Does UWB traffic also have an impact on Wi-Fi 6E transmissions?
  - Yes, although only when UWB are in very close proximity



Open Questions & Next Steps

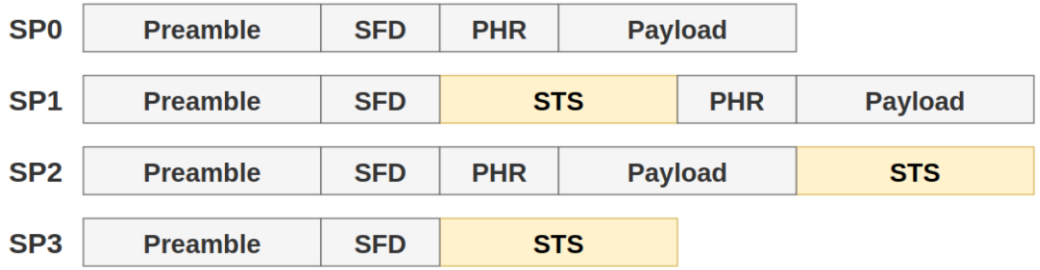
- Could Glossy be used to mitigate the impact of Wi-Fi 6E interference?
  - By design, it allows a tight synchronization and late wake-up
  - Example: disseminating 20.000 packets from node 16 to all other nodes



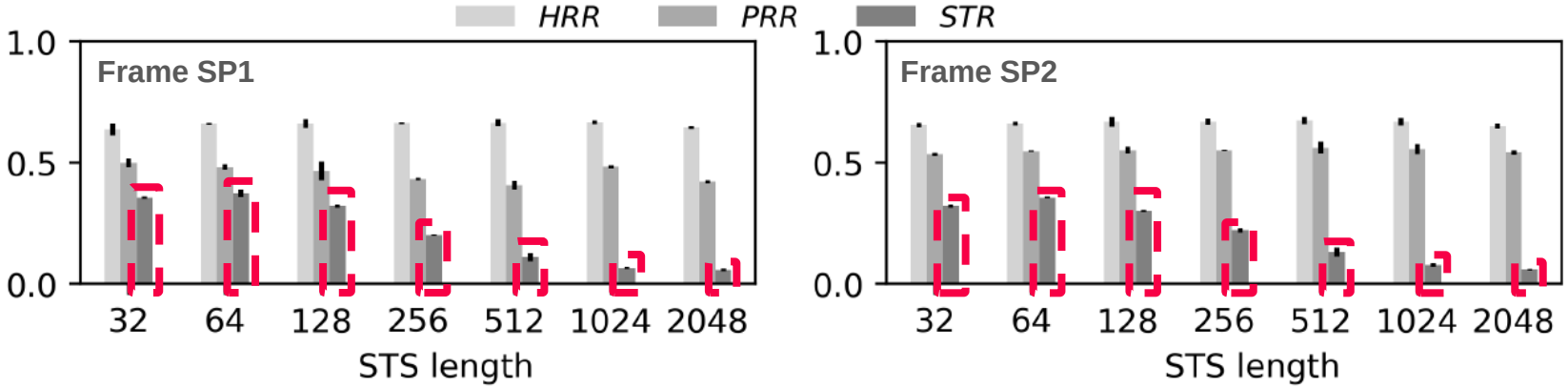


Open Questions & Next Steps

- Does Wi-Fi 6E interference affect UWB security features?
  - Length of the Scrambled Time Sequence (STS)
    - IEEE 802.15.4z introduced a sequence of pseudo-randomly generated pulses using a shared secret between requester and responder
  - The STS can be inserted at different positions within the UWB frame (SP0 – SP3)

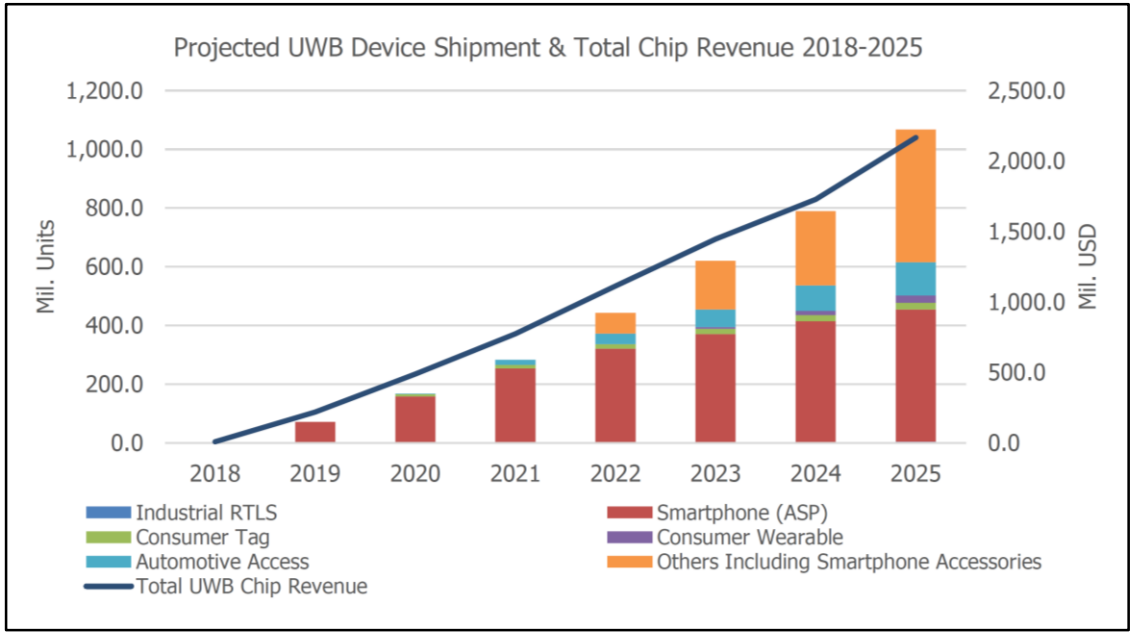


  - The number of successful ToA estimates (STR) drops significantly under Wi-Fi 6E traffic



Takeaway Message

- UWB systems strongly affected by Wi-Fi 6E interference
  - # of UWB devices will quadruple by 2025
  - Urgent need for coexistence techniques to avoid severe implications on UWB systems
  - Our results should provide stimuli to the community for further investigation



Source: UWB Alliance

- Additional info & references

- H. Brunner, M. Stocker, M. Schuh, M. Schuß, C.A. Boano, and K. Römer. *Understanding and Mitigating the Impact of Wi-Fi 6E Interference on Ultra-Wideband Communications and Ranging*. In Proceedings of the IPSN'22 Conference. May 2022. (link)
- M. Schuh, H. Brunner, M. Stocker, M. Schuß, C.A. Boano, and K. Römer. *First Steps in Benchmarking the Performance of Heterogeneous Ultra-Wideband Platforms*. In Proceedings of the CPS-IoTBench'22 Workshop. May 2022. (link)
- M. Stocker, M. Schuh, H. Brunner, C.A. Boano, and K. Römer. *On the Performance of IEEE 802.15.4z-Compliant Ultra-Wideband Devices*. In Proceedings of the CPS-IoTBench'22 Workshop. May 2022. (link)

Images from adobe.com