Versatile wireless TSN experimentation using openwifi

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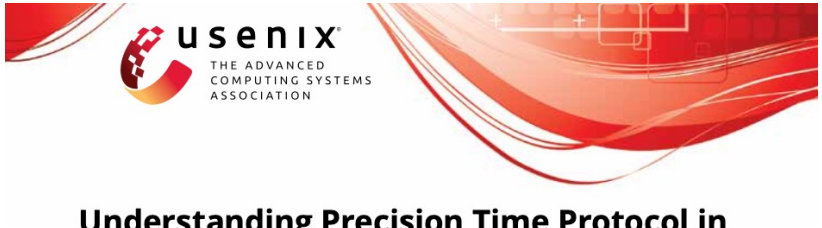
Limitations of COTS Wi-Fi for TSN (research)

1. Research

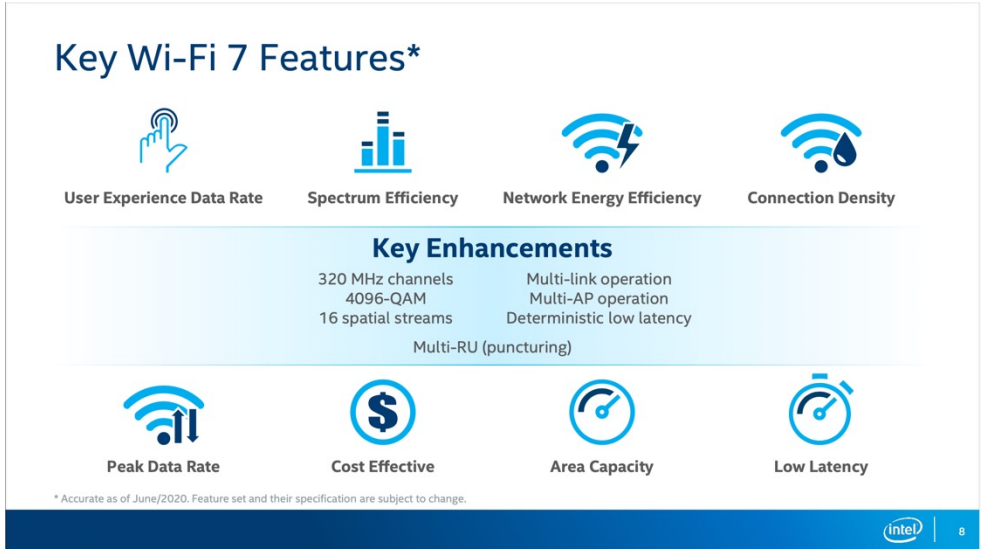
Time synchronization



- 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

2. Validation

Early validation of upcoming Wi-Fi features on real HW



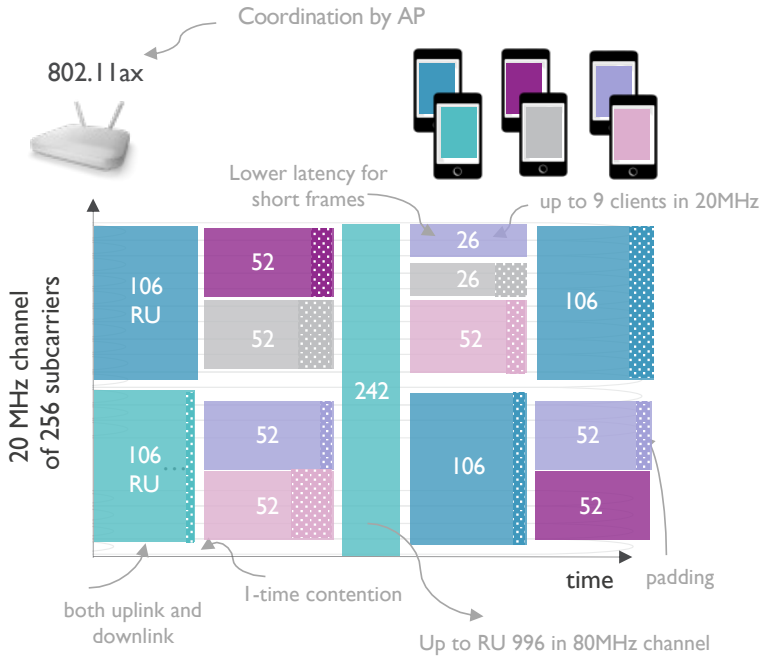
Source: C. Cordeiro, "Next-generation Wi-Fi – Wi-Fi 7 and beyond", Intel Corporation

Validation of feasibility and performance of concepts and algorithms

- Typically models and simulation studies
- Lack of validation opportunities on real system

3. Customization

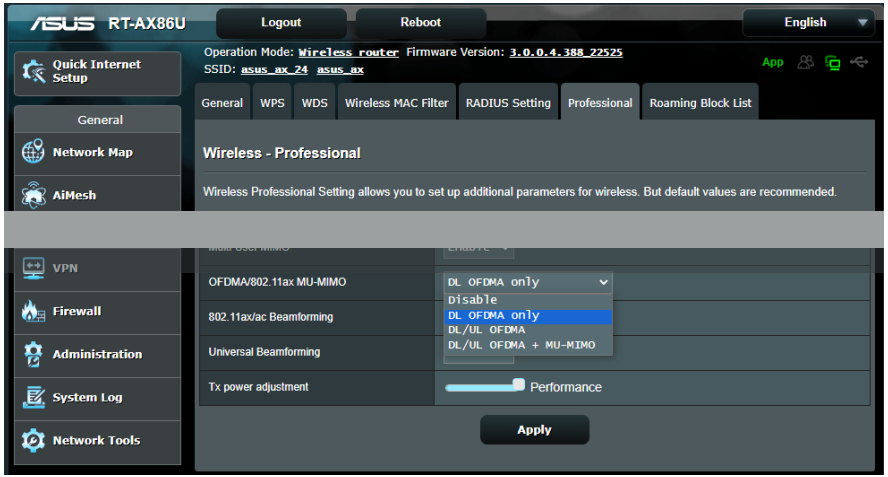
Control over OFDMA for latency reductions



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

TSN research – core features

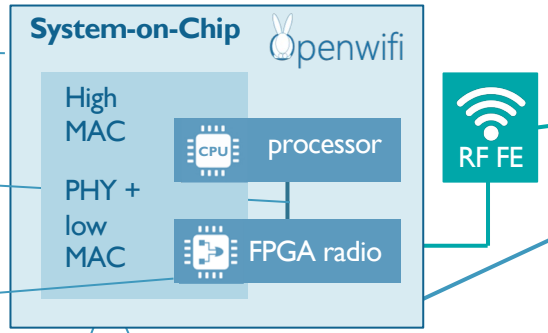
Enabled by 

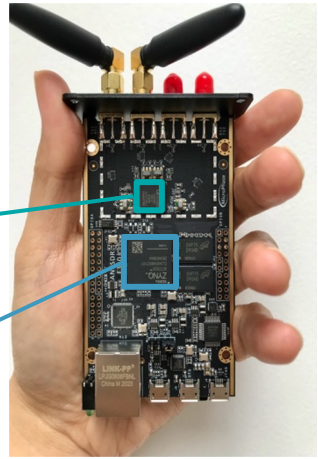
Openwifi :World's first free Wi-Fi open full-stack chip design

Single chip, combining radio/network/application processing

High-speed on-chip bus: ping RTT of 300µs (vs 1ms in COTS Wi-Fi)

Reprogrammable hardware (unlike ASIC)





Basic features

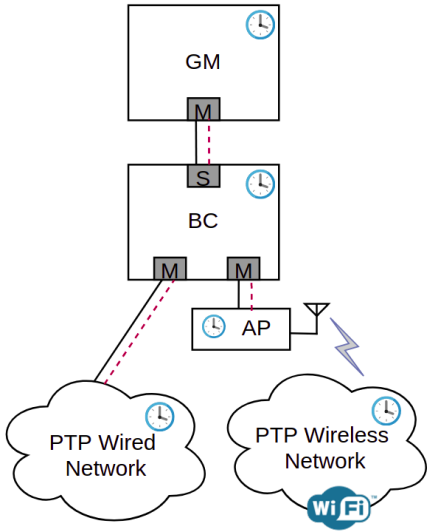
- IEEE 802.11a/g/n @ 20MHz
- Aggregation (AMPDU)
- Several RF optimizations for improved sensitivity
- Dynamic FPGA/driver reloading in seconds
- https://github.com/open-sdr/openwifi

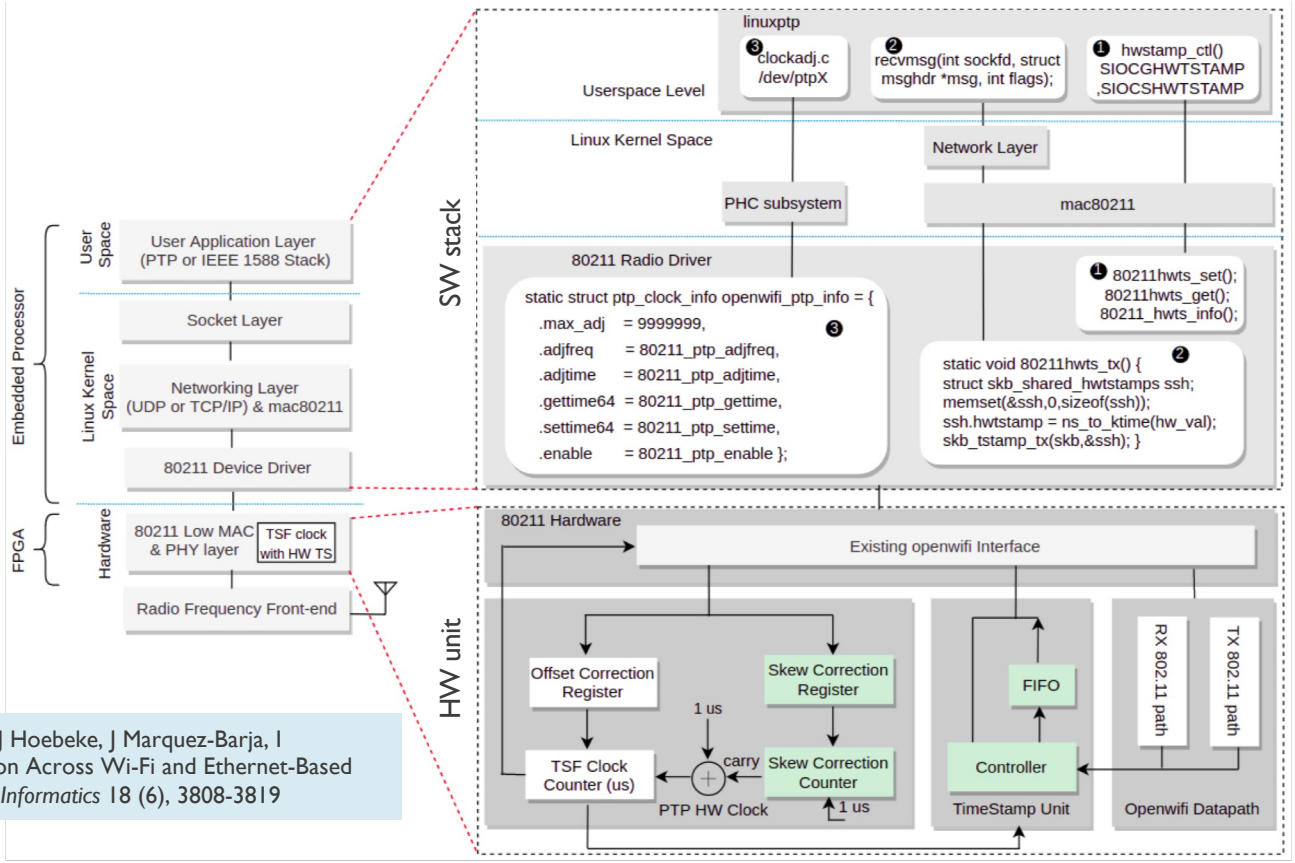
Advanced features

- IEEE 802.11ax (Wi-Fi 6) OFDMA
- 8 HW queues
- TSN features (see further)
- Increased robustness in multi-path environments
- CSI, CSI fuzzer, IQ samples…

Clock synchronisation & hardware timestamping

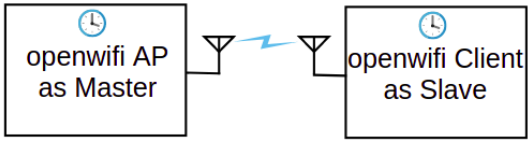
Architecture



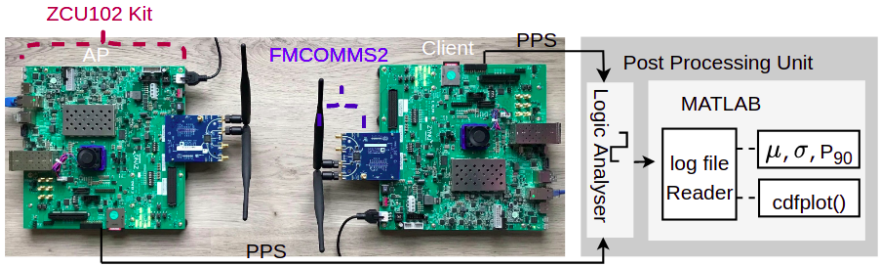


M Aslam, W Liu, X Jiao, J Haxhibeqiri, G Miranda, J Hoebeke, J Marquez-Barja, I Moerman, Hardware Efficient Clock Synchronization Across Wi-Fi and Ethernet-Based Network Using PTP, *IEEE Transactions on Industrial Informatics* 18 (6), 3808-3819

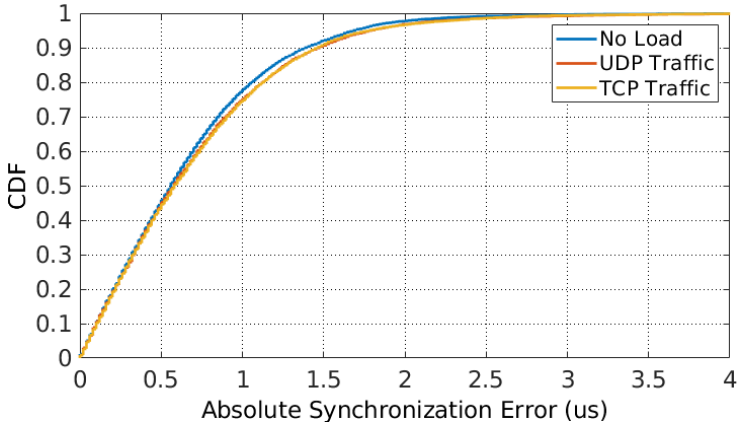
Time synchronization accuracy



Parameters	No Load	UDP Load	TCP Load
Mean (μ)	-0.279 μs	-0.330 μs	-0.325 μs
Standard deviation (σ)	0.820 μs	0.872 μs	0.868 μs
90% percentile (P_{90})	1.4 μs	1.48 μs	1.46 μs



Measurement setup



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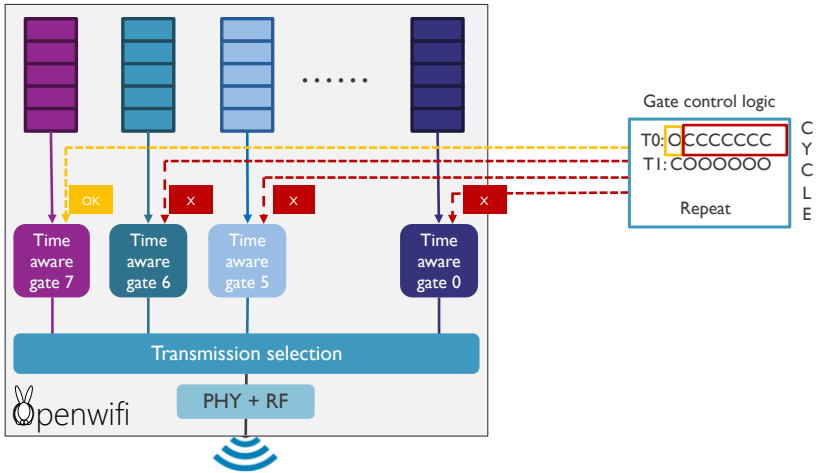
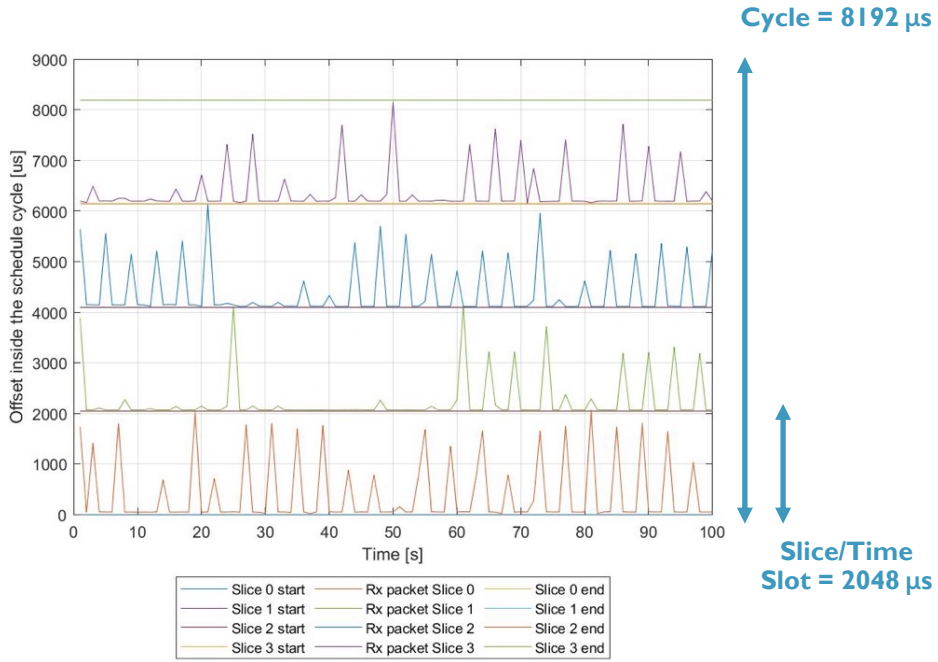
IEEE 802.1 Qbv time-aware scheduling over Wi-Fi

Gating mechanism + time-aware scheduling for APs and end devices





More than time-aware scheduling

Time-triggered configurations

bit position	meaning	queue specific
[09:00]	LBT threshold (dBm)	NO
[10:10]	NAV enable	NO
[11:11]	DIFS enable	NO
[12:12]	EIFS enable	NO
[14:13]	AIFS setting. 4 different AIFS. reserved for future	NO
[15:15]	CW enable	NO
[19:16]	CW min	YES
[23:20]	CW max	YES
[25:24]	TXOP setting. 4 different TXOP. reserved for future	NO
[29:26]	number of retransmission	NO
[30:30]	ACK Tx enable	NO
[31:31]	ACK Rx enable	NO
[41:32]	Rx sensitivity threshold (dBm)	NO
[43:42]	Tx digital attenuation. 0/1/2/3: -0dB/-6dB/-12dB/-18dB	NO
[45:44]	Rx gain control. reserved for future	NO
[48:46]	Tx freq channel	NO
[51:49]	Rx freq channel	NO
[53:52]	Tx CSI fuzzer control. 0: fuzzer off; 1/2/3: pattern 1/2/3	NO
[55:54]	Tx antenna control. reserved for future	NO
[57:56]	Rx antenna control. reserved for future	NO
[59:58]	Rx PHY control. smoothing; STF threshold; etc. reserved for future	NO

Adjust contention, e.g based on number of stations in shared slots
Disable contention, e.g. in case of private spectrum license

Adjust retransmissions, e.g. based on time slot duration and/or reliability needs

Adjust thresholds, sensitivity and Tx power to reduce interference and improve spatial reuse

And coordinate all this across multiple synchronized APs!

Monitoring features

Open API exposing advanced statistics

- Tx packet statistics
- Tx Queue statistics
- Rx packet statistics
- Rx gain statistics

name	meaning
tx_data_pkt_need_ack_num_total	number of tx data packet reported in openwifi_tx_interrupt() (both fail and succeed)

name	meaning
rx_data_pkt_num_total	number of rx data packet with both FCS ok and failed
rx_data_pkt_num_fail	number of rx data packet with FCS failed

name	meaning
rx_data_ok_agc_gain_value_realtime	agc gain value of rx data packet with FCS ok
rx_data_fa	
rx_mgmt_	
rx_mgmt_fail_agc_gain_value_realtime	agc gain value of rx management packet with FCS failed
rx_ack_ok_agc_gain_value_realtime	agc gain value of rx ACK packet with FCS ok

Enabling advanced monitoring

rx_mgmt_pkt_fail_mcs_realtime	MCS (10*Mbps) of rx management packet with FCS failed
rx_ack_pkt_mcs_realtime	MCS (10*Mbps) of rx ACK packet with both FCS ok and failed
rx_data_ok_agc_gain_value_realtime	agc gain value of rx data packet with FCS ok
rx_data_fail_agc_gain_value_realtime	agc gain value of rx data packet with FCS failed
rx_mgmt_ok_agc_gain_value_realtime	agc gain value of rx management packet with FCS ok
rx_mgmt_fail_agc_gain_value_realtime	agc gain value of rx management packet with FCS failed
rx_ack_ok_agc_gain_value_realtime	agc gain value of rx ACK packet with FCS ok

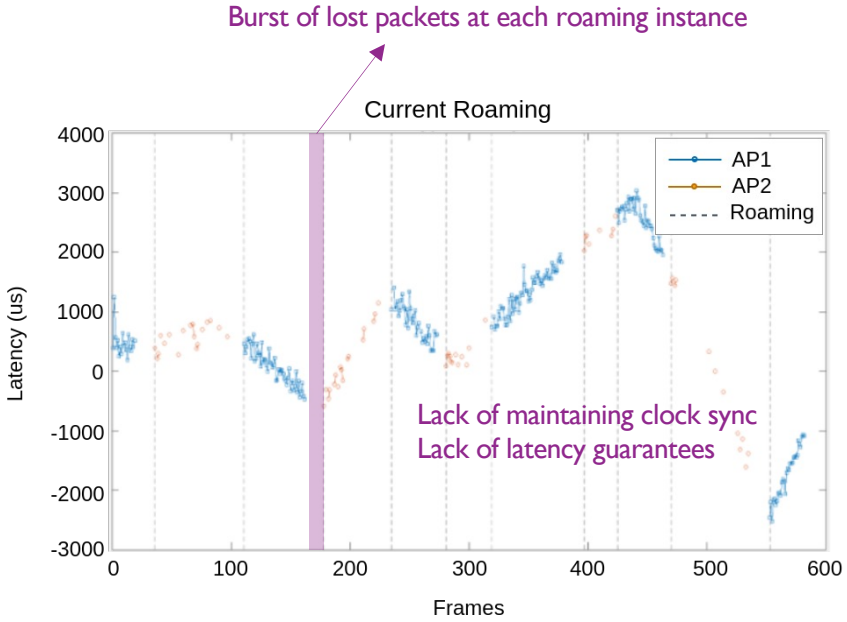
https://github.com/open-sdr/openwifi/blob/master/doc/app_notes/driver_stat.md

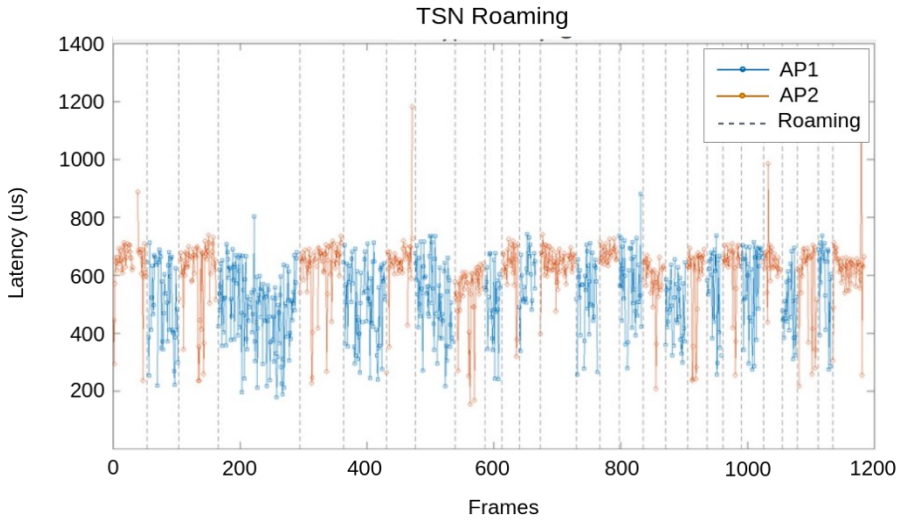
penwifi + TSN

Driver for innovation/exploration

Impactless association and roaming

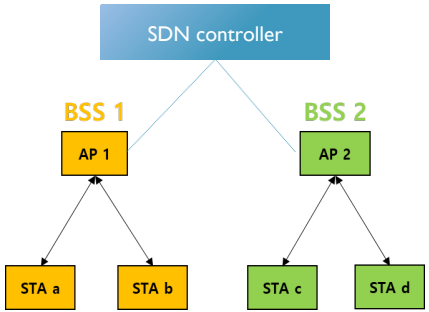
Guaranteed latencies and no/very few packet loss

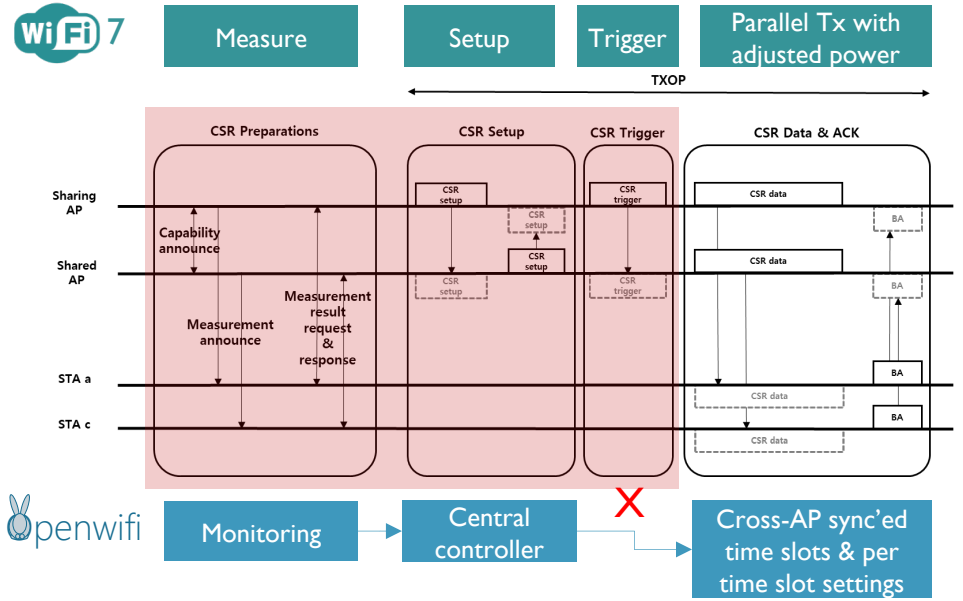




Coordinated Spatial Reuse (C-SR) in dense deployments

Parallel interference-free transmissions – validation using openwifi + TSN features





Source: IEEE 802.11-20/410r4

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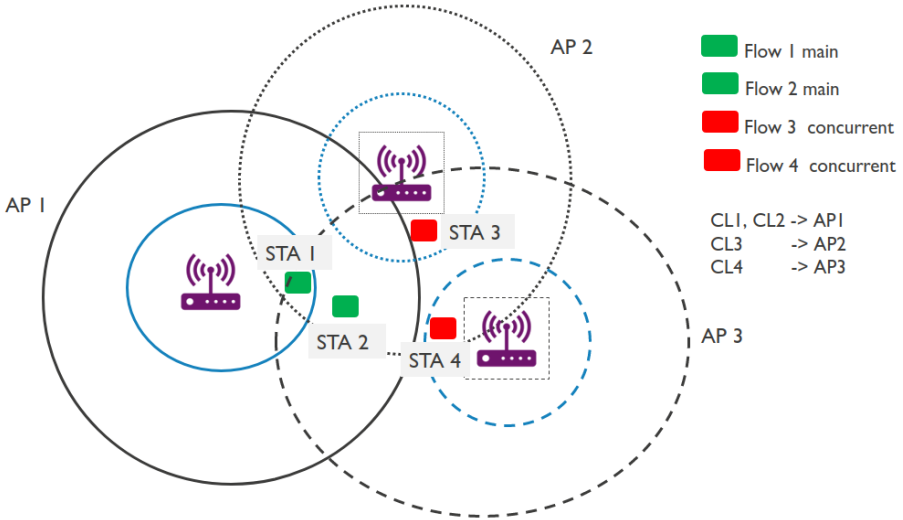
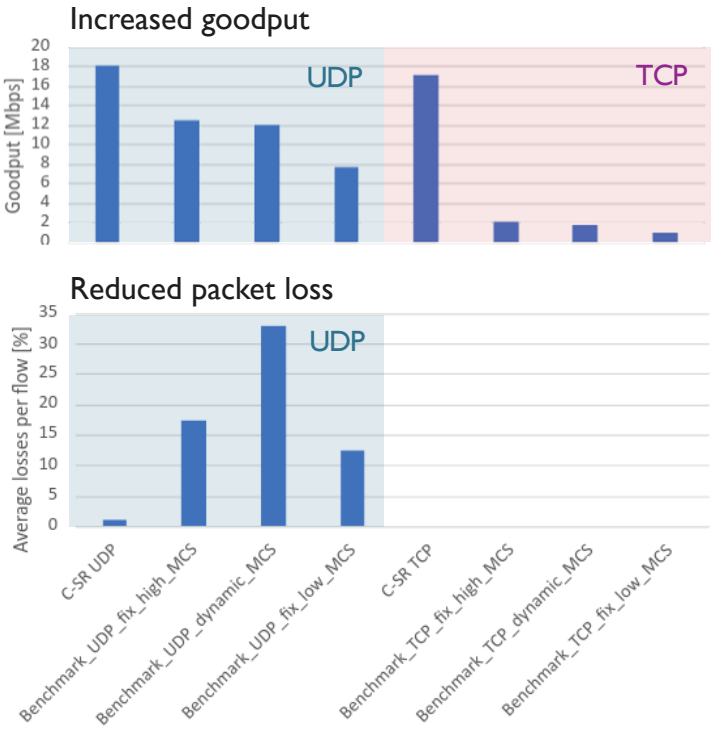


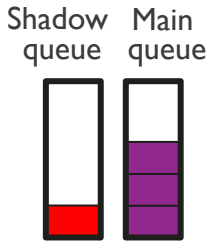


Handling unexpected low-latency events

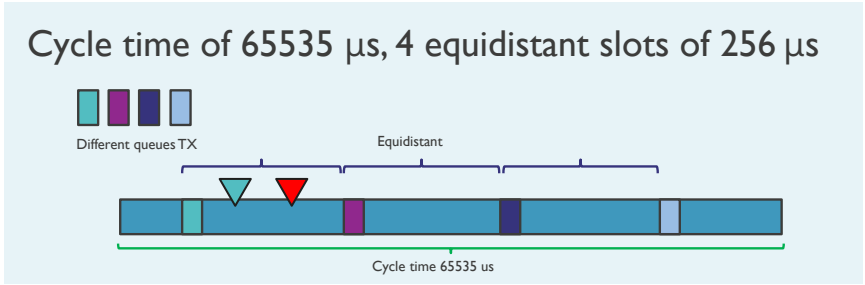
Dynamic traffic classification

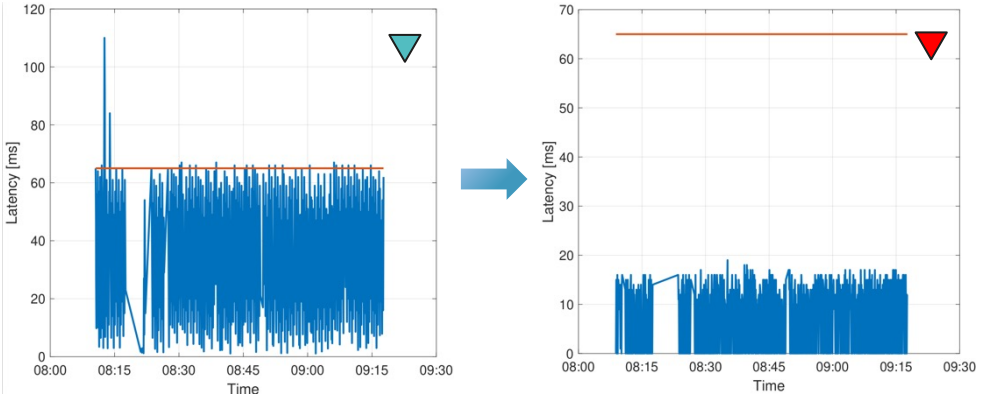
Approach

- openwifi shadow queues, served before main queue when not empty



- Dynamically reclassify incoming event to next available/suitable shadow queue
- No need to update existing schedule



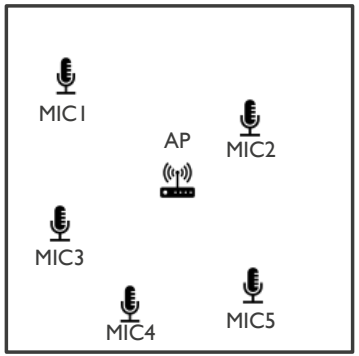


Customized OFDMA behavior

In progress…

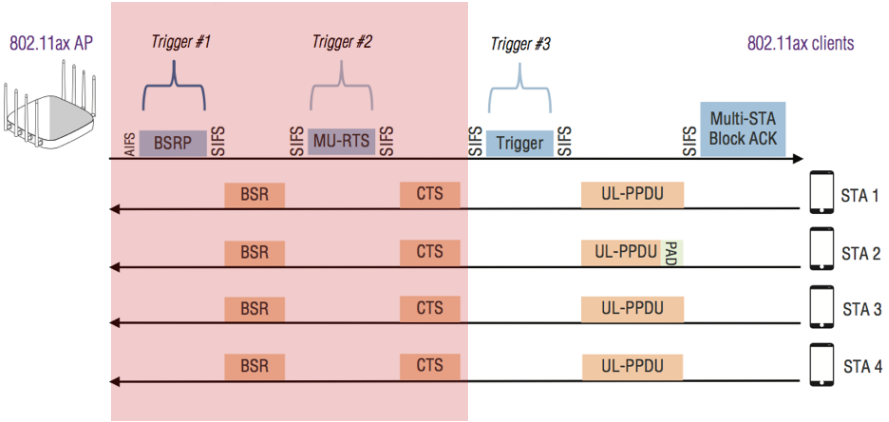
Context

- Audio use case
- Strict latency requirements
- Known communication patterns



Approach

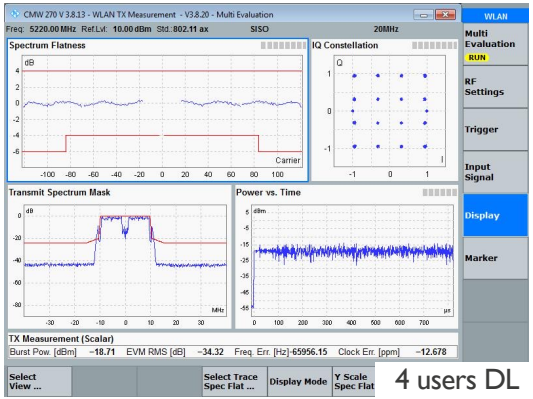
- OFDMA for low-latency and scalability



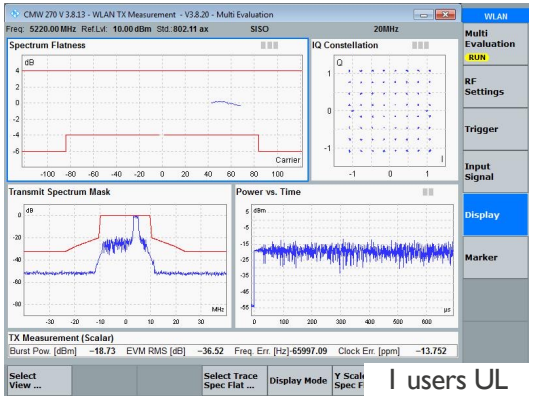
Source: https://cradtech.com/2018/10/25/802-11ax-ofdma-overview/

- Customized OFDMA algorithm using openwifi

Openwifi - Wi-Fi 6 OFDMA

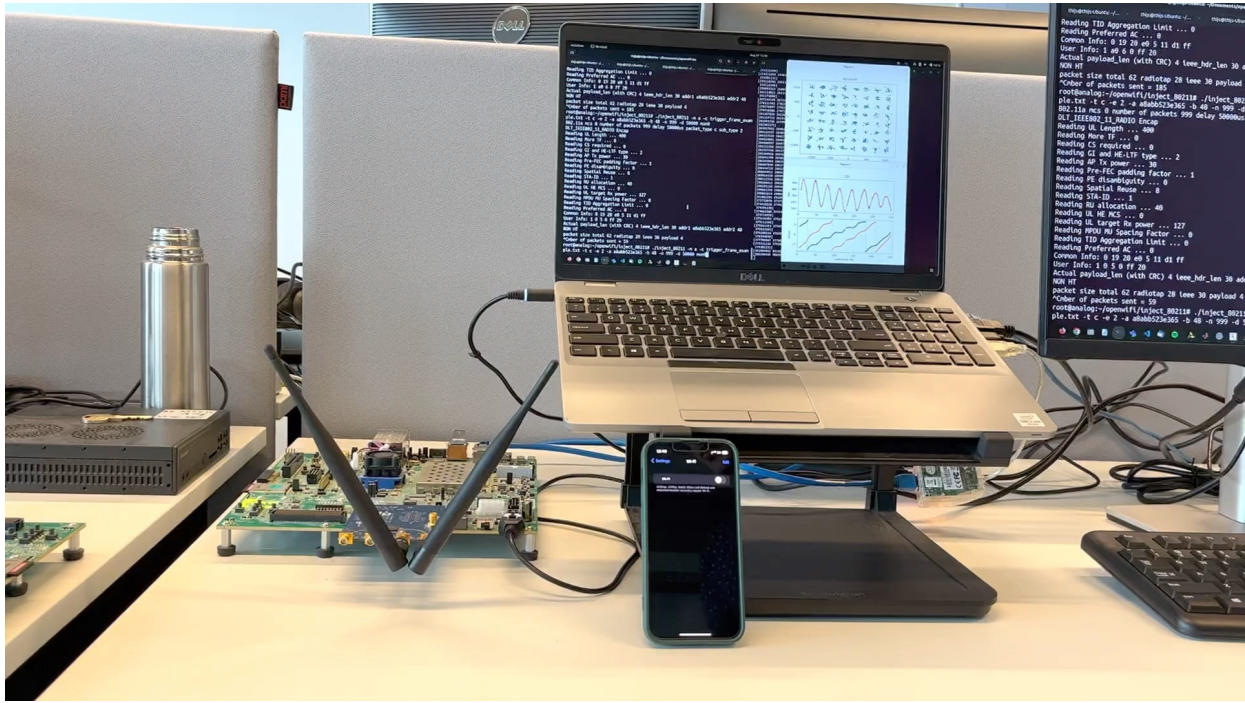


4 users DL



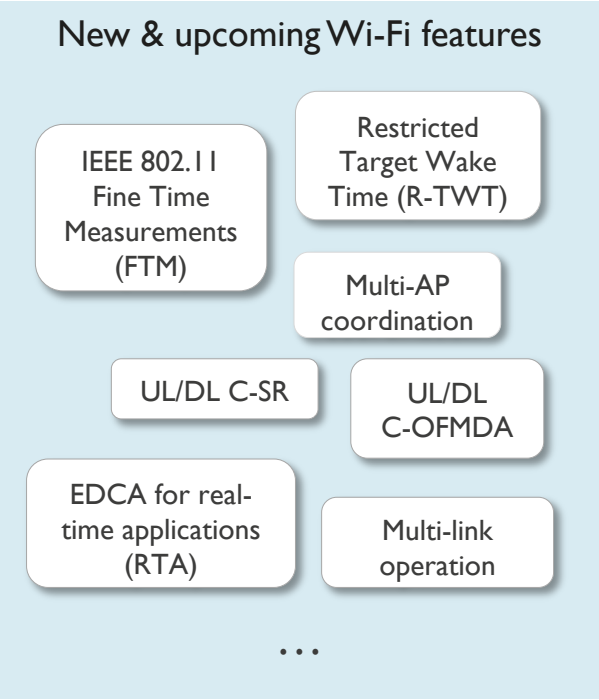
1 users UL

DEMO: openwifi AP triggering UL OFDMA on COTS client



What's next

TSN vision & roadmap



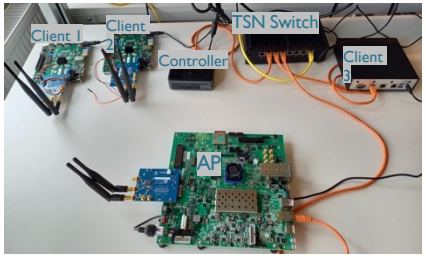
- ***Focus on professional private markets***
  - Lower volumes, need for high-end customized solutions
  - COTS solutions: focus on speed, closed-box, limited controllable features, customization not feasible
- ***Focus on research & innovation on relevant features***
  - No need for full-blown implementation of Wi-Fi standard: many Wi-Fi features are not relevant for TSN use cases
  - Anticipate and validate specific new/upcoming features, e.g., roaming, advanced monitoring & control, distributed coordinated operation (C-SR, C-OFDMA, beamforming, etc.)…
- ***PoC validation of TSN operation in realistic use cases and real-life environments***
  - Need for open prototyping platform openwifi
  - Fully customized (fast innovation)
  - Standard compliance (e.g., customized APs and COTS clients)

Wireless Lab & Industrial IoT Lab

Large-scale validation in realistic environments

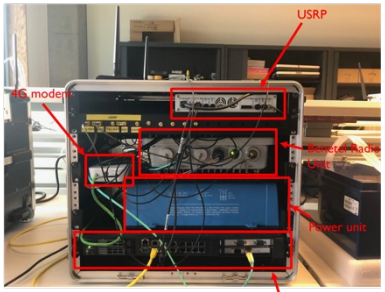
TSN Time-Sensitive Networking

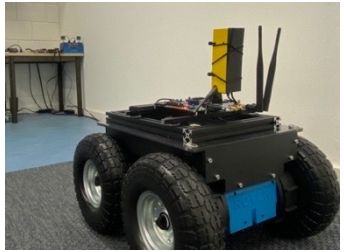
Openwifi

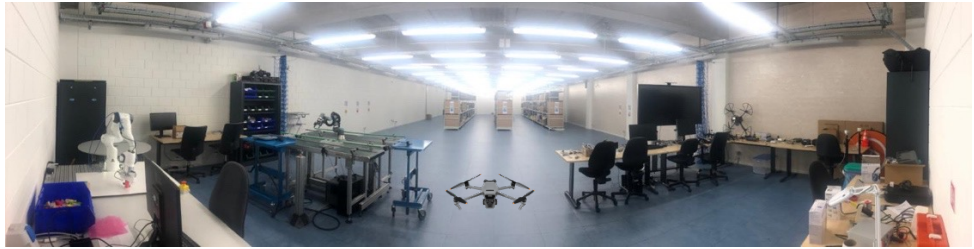


Evaluation kit

5G 6G







COTS as well as SDR RUs

embracing a better life

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