Running out of time

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IDLAB, IMEC RESEARCH GROUP AT GHENT UNIVERSITY AND ANTWERP UNIVERSITY

Deterministic communication systems

time-sensitive – reliable/safe - predictable

televic

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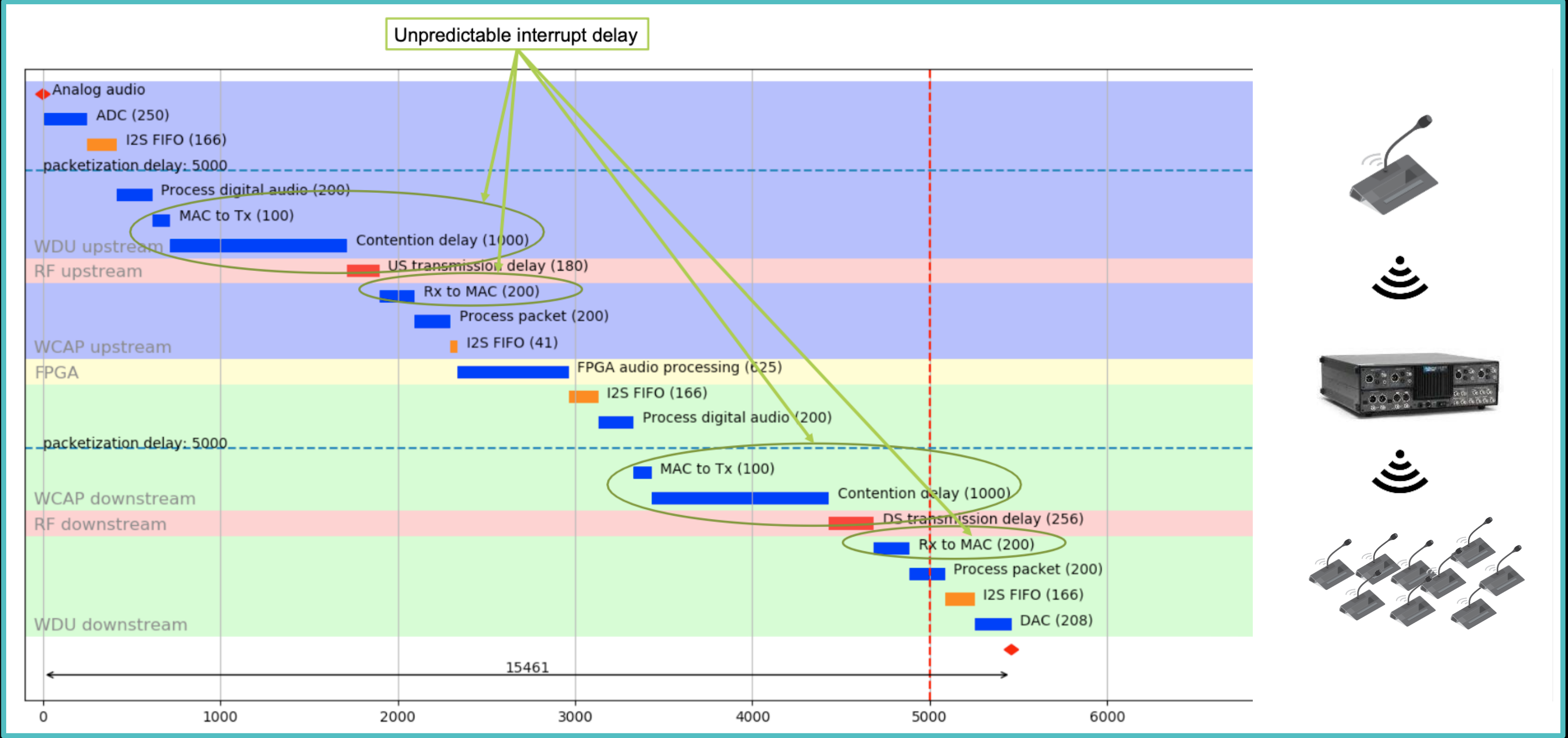
Audio processing and transmission time schedule



televic

- Fully controlled end-to-end system: engineered for its purpose
- Full quantification of system (HW+SW) aspects impacting latency
- Trimmed down communication stack
- Wireless communication: customized medium access control
- Central processing: FPGA-based
- Cost-sensitive

5G: 1ms radio latency spec

Tactile Internet

End-to-end (E2E) latencies < 5ms

Industrial automation

20us to 10ms latencies for M2M
Ultra-reliable

Social roboverse / Collaborative robotics

Multi-sensory input to remote decision-making < 10-100ms

Holographic-type communications

E2E latencies < 20ms
Gbps rates

Larger-scale, highly variable context!

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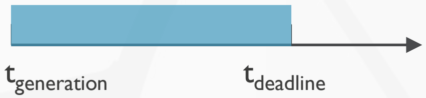
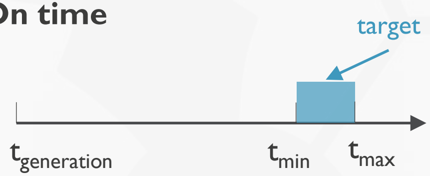
Mastering every aspect of time

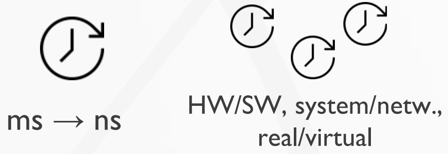
In time



On time

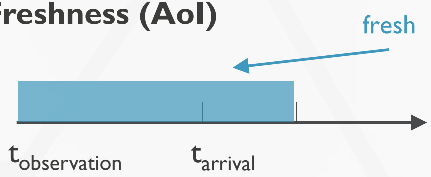


Granularity / clock types

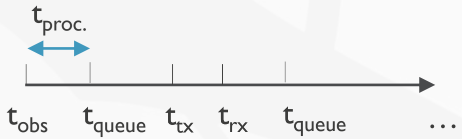


Simultaneity / causality

Freshness (AoI)



Latency breakdown



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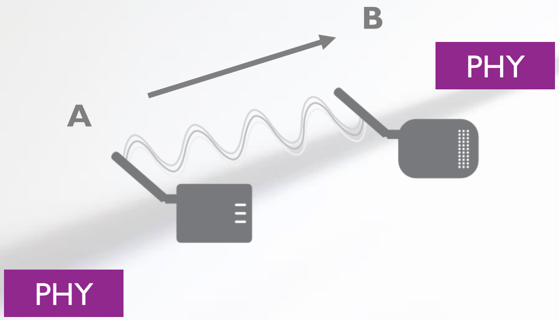
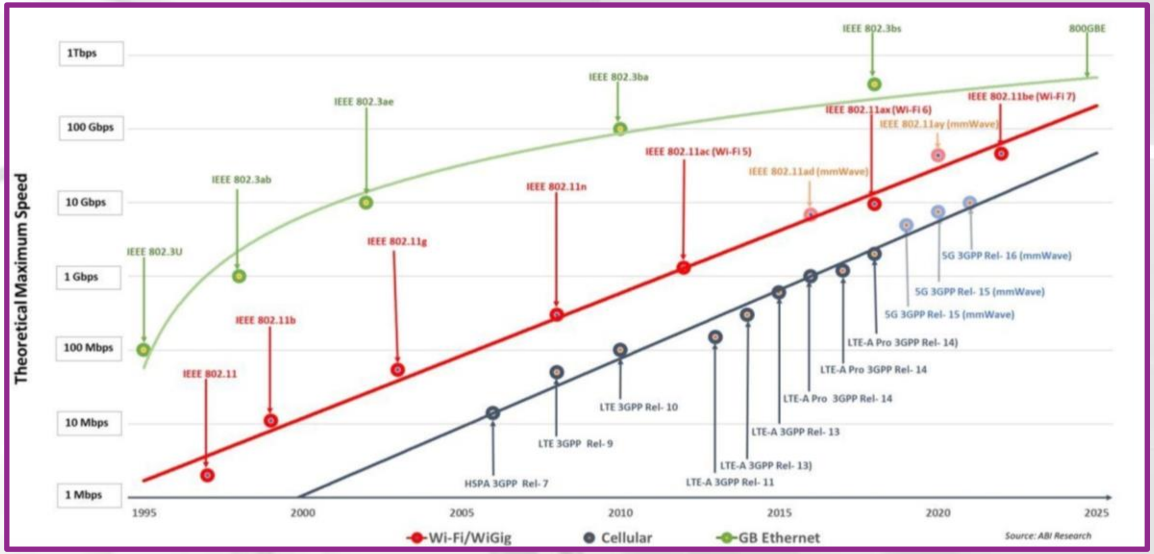
Are we on track?

The wireless link

Continuous increase in peak data rates → low Tx latencies





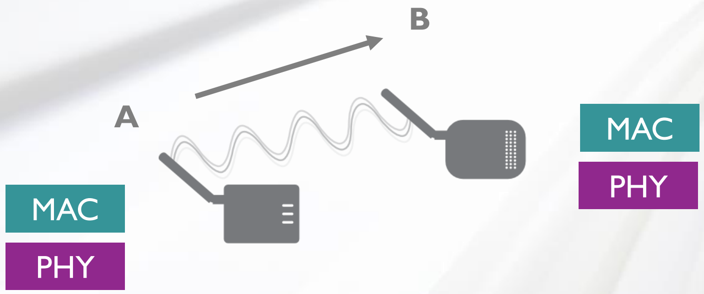
More to come: massive MIMO, THz wireless, RIS/IRS, JC&S…

The wireless link

Continuous increase in peak data rates → latency reduction?

Peak data rates only exist in a perfect (PHY) world.

Signalling overhead, rate versus distance, propagation characteristics of the environment, MAC complexity, coordination & joint processing, guaranteed latency (considering reliability), efficiency, protocol overhead / packetization, scheduling granularity, etc.



BRIDGE PHY-MAC GAP

- Benefits at PHY might come with complexities at MAC
- Co-design to properly understand latency trade-offs

TIME-AWARE KPIs

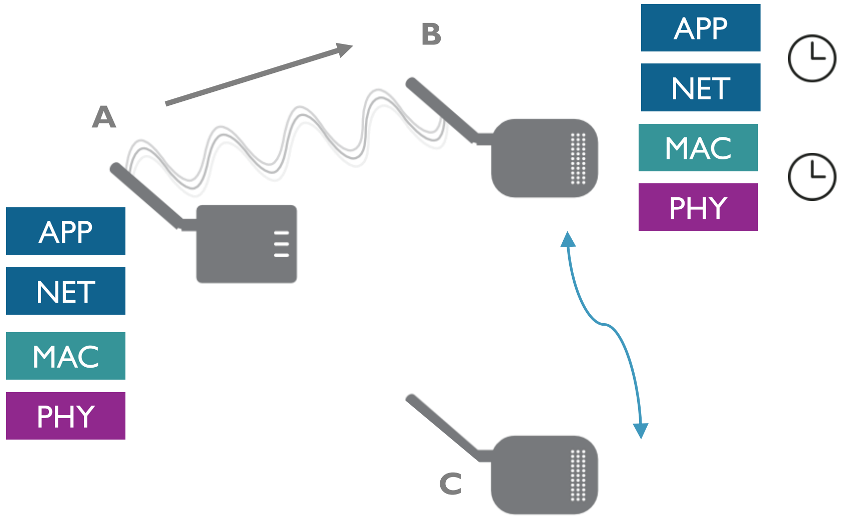
- Beyond PHY data rate
- Considering broader context
- Breakdown

BENCHMARKS

Quantify latency gains of new technologies

- Under realistic conditions
- Against 'legacy' systems

Wireless end device(s)



Deterministic application behavior (generation time, processing)

Aligned with network timings (per device, across devices)

Support for (intra/inter) flow differentiation and simultaneity

Limits of COTS (mass-market) HW, APIs and stacks

NOTION OF TIME

- Down to devices: accurate time synchronization as a network service
- Understanding of deterministic network capabilities (net → app)

APP & PROTOCOL DESIGN

- Predictable behavior
- Versatile packetization
- Adaptable to NW constraints (app → net)
- Lightweight

SYSTEM DESIGN

- More open chip design
- Co-design: HW-SW, processing + communication
- Interplay TS / non-TS components
- Skilled engineers

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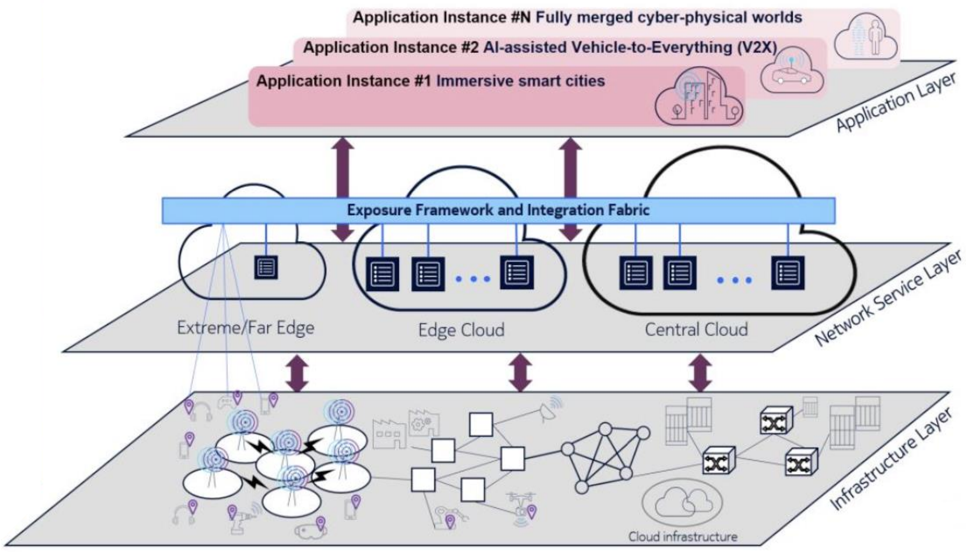
The end-to-end system

How to manage



Source: Hexa-X D1.3 – Initial E2E architecture

- Cloud-native, softwarization and service-based architecture
  Guaranteed execution times?
- Generalized, multi-purpose architecture
  Unnecessary complexity (and latency)?
- Traversal of different networks, possibly intermediate processing
  Protocol translations, how to oversee timings?

NOTION OF TIME

- Network of timelands: interconnected networks having same notion of time
- Support for various flavours of time: in-time, on-time, simultaneity, etc.

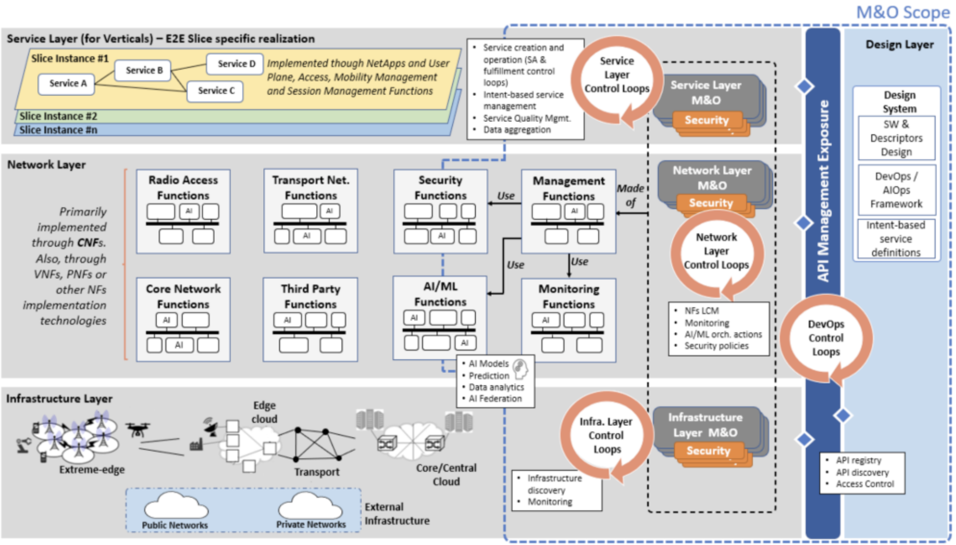
DETERMINISTIC END-TO-END

- Deterministic computing: bounded execution time of communication and computing services
- Hardware accelleration / HW programmability

5GRedCap → xGRedNet/SpecNet

- Lean, lightweight architecture
- Trimmed down architectural & protocol complexity
- Fit-for-purpose

The management



Source: Hexa-X D6.2 – Management and orchestration system – Structural view

- Cloud-native, softwarization and service-based architecture
  Determinism in control plane decisions?
- AI/ML-based network management
  Avoid unwanted side-effects on deterministic flows?
- Monitoring
  Continuous verification of timing requirements?

VERIFICATION

- Pre: predict packet forwarding latencies
- During: actual flow treatment (in-band)
- Post: expose analytics
- Using end-to-end notion of time

DETERMINISTIC CONTROL PLANE

- QoM: prioritization of management decisions
- Bounded execution time of mgmt
- Timescale = timescale data plane, or proactive

FLAWLESS AI/ML

- Guarantee any undesired side effects on deterministic flows
- Explainability
- No training in operational network: Digital Twin Network

The standardization, innovation and adoption

- Mass market first
  High-end low-volume markets?

- Ever-increasing feature sets / implementation complexity / backwards compatibility
  Large telco network ≠ private network / hampers entrance new market players / overshooting / cost

- At market time: closed commercial products
  Black box not having the right features/level of control

FIT-FOR-PURPOSE

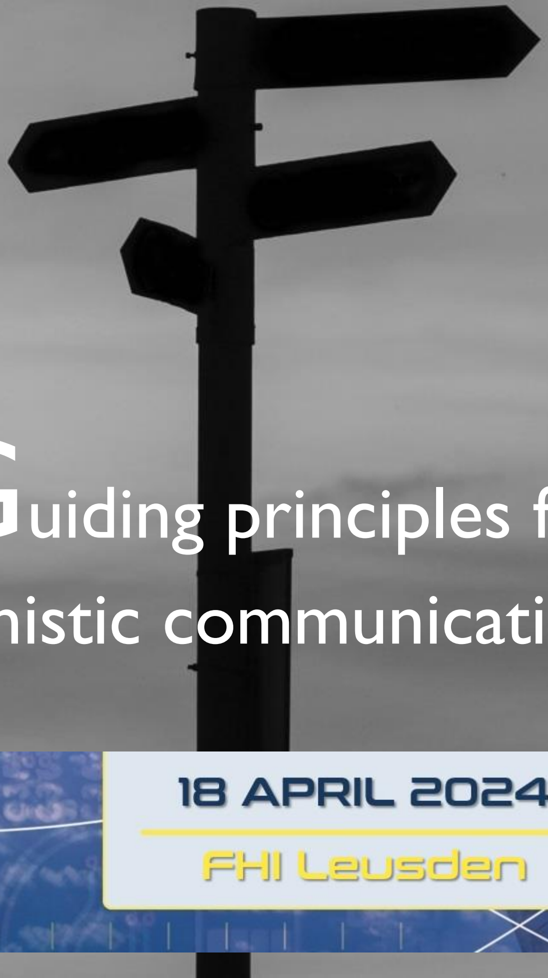
- Downsize number of features: master complexity, whilst fit for the job
- Flavours: baseline + selected features (cfr. profiles)

EARLY PROOF

- Early prototyping and system validation against requirements
- Cfr. IETF: consensus + running code

CUSTOMIZATION & INNOVATION

- No black box: richer APIs/control, programmability (SDR)
- Open source / reference implementations



7 Guiding principles for future deterministic communication systems

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END-TO-END NOTION OF TIME

CO-DESIGN PHY/MAC, SW/HW, APP/NET, COMM./PROC., E2E

DETERMINISTIC CONTROL PLANE & FLAWLESS AI/ML

xGRedNet/ SpecNet: LEAN, FIT-FOR-PURPOSE SOLUTIONS

TIME-AWARE KPIs & BENCHMARKS

EARLY PROOF & VERIFICATION

OPEN INNOVATION, MORE WHITE-BOX DESIGNS

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)

System-on-Chip openwifi

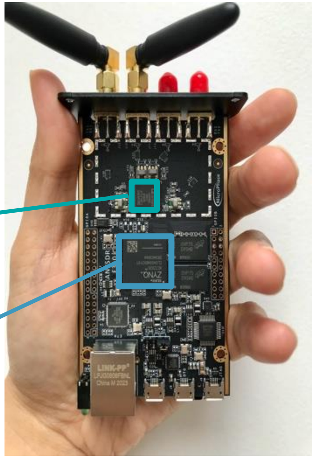
High MAC

PHY + low MAC

processor

FPGA radio

RF FE



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…

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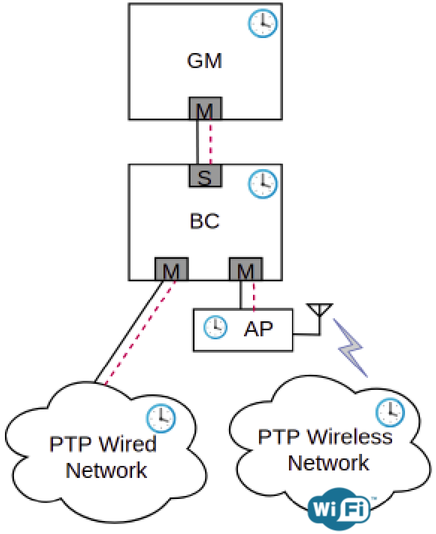
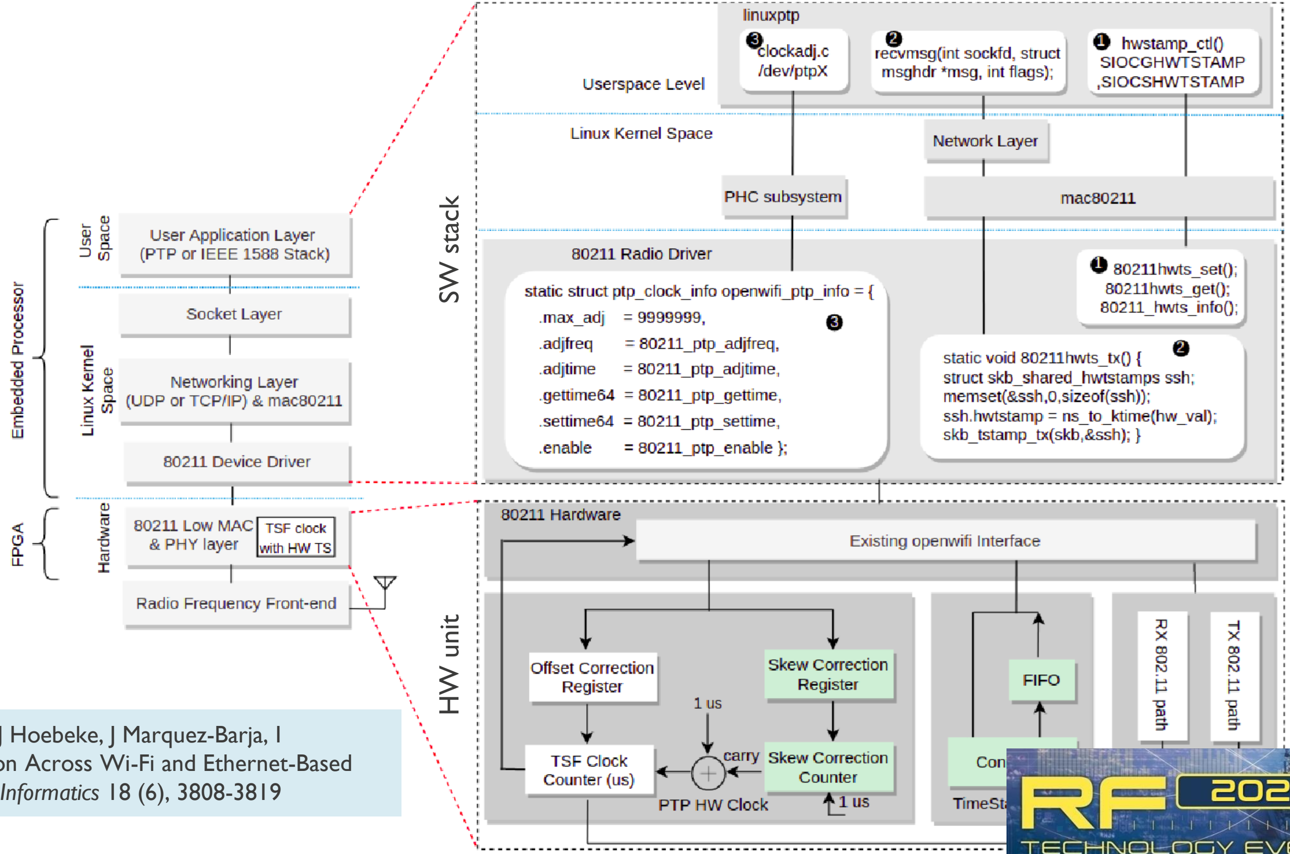
Clock synchronisation & hardware timestamping

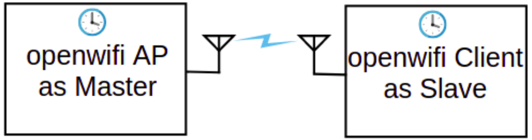
Architecture



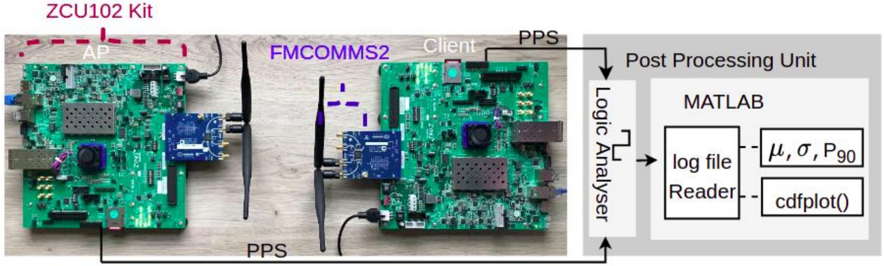


M Aslam, W Liu, X Jiao, J Haxhibeqiri, G Miranda, J Hoebeke, J Marquez-Barja, I Moerman, Hardware Efficient Clock Synchronization Across Wi-Fi and Ethernet-Based Network Using PTP, *IEEE Transactions on Industrial Informatics* 18 (6), 3808-3819

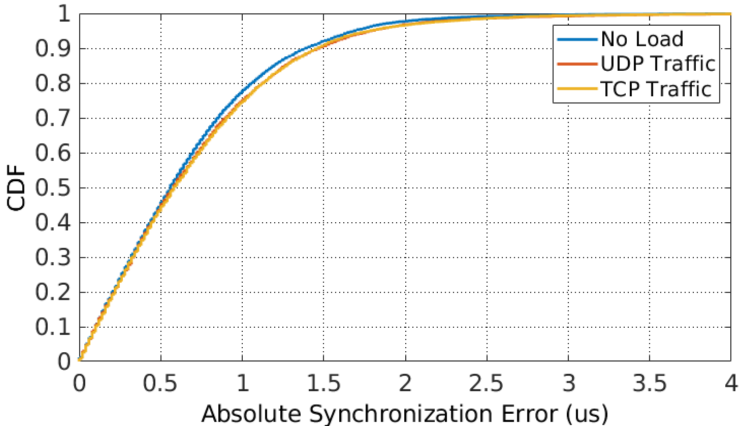
Time synchronization accuracy



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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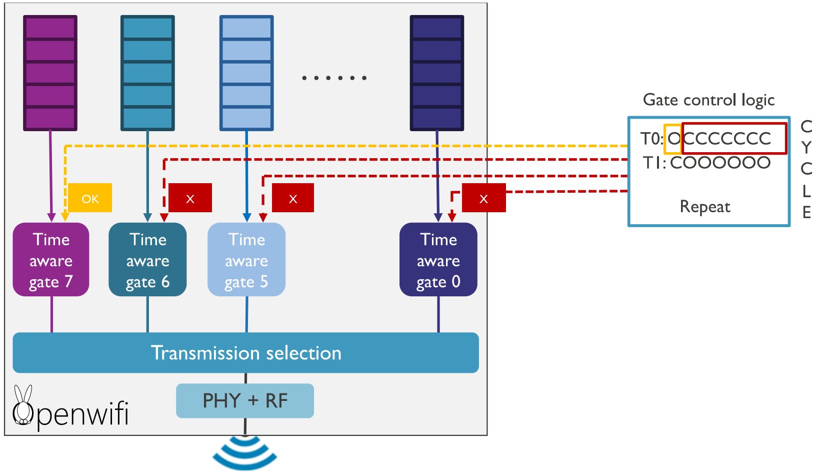
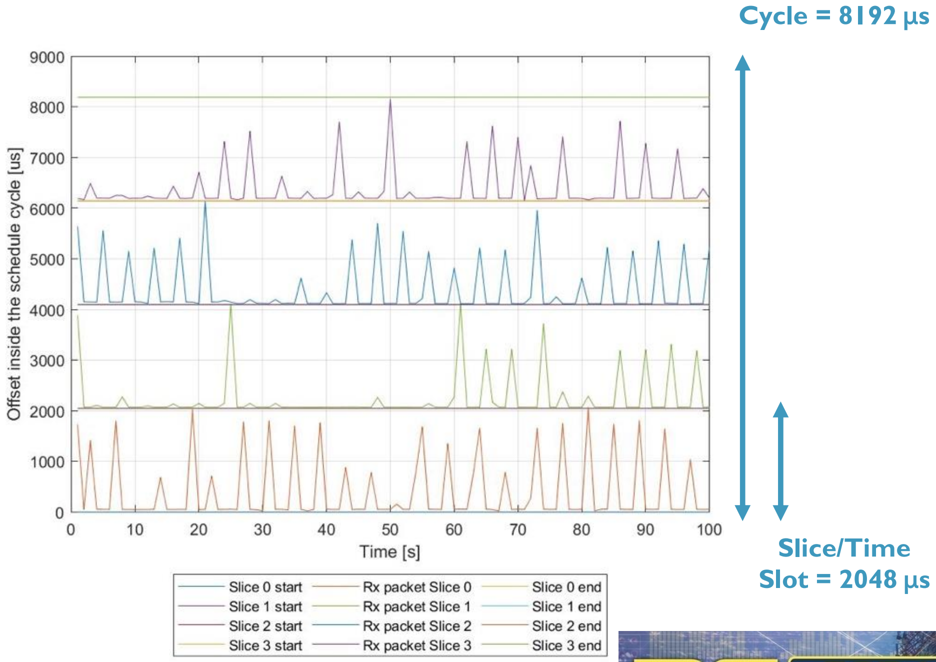
IEEE 802.1 Qbv time-aware scheduling over Wi-Fi

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!

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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

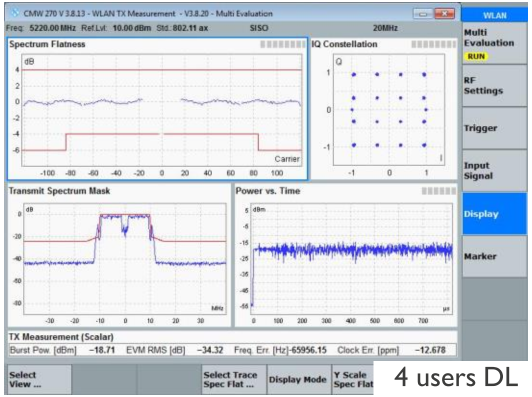
name	meaning
rx_data_ok_agc_gain_value_realtime	agc gain value of rx data packet with FCS ok
rx_data_fa	
rx_mgmt_	
rx_mgmt_fail_agc_gain_value_realtime	agc gain value of rx management packet with FCS failed
rx_ack_ok_agc_gain_value_realtime	agc gain value of rx ACK packet with FCS ok

Enabling advanced monitoring

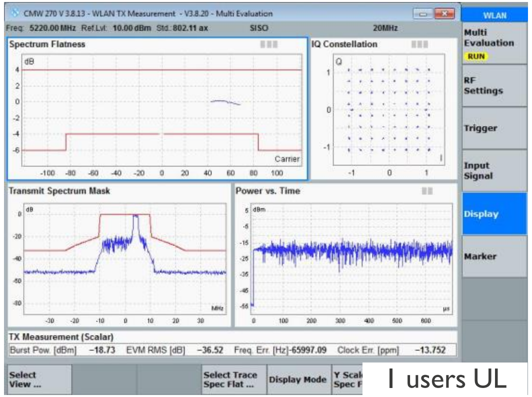
rx_mgmt_pkt_fail_mcs_realtime	MCS (10*Mbps) of rx management packet with FCS failed
rx_ack_pkt_mcs_realtime	MCS (10*Mbps) of rx ACK packet with both FCS ok and failed
rx_data_ok_agc_gain_value_realtime	agc gain value of rx data packet with FCS ok
rx_data_fail_agc_gain_value_realtime	agc gain value of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

openwifi - Wi-Fi 6 OFDMA

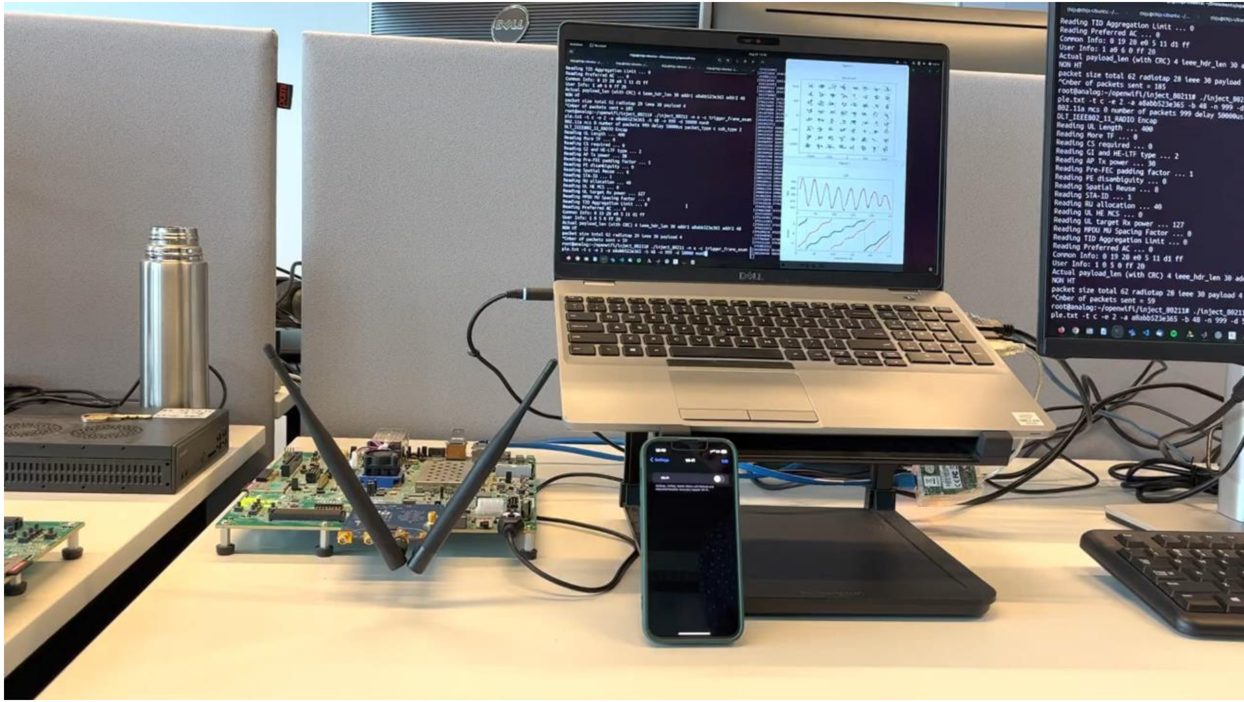


4 users DL



1 users UL

DEMO: openwifi AP triggering UL OFDMA on COTS client



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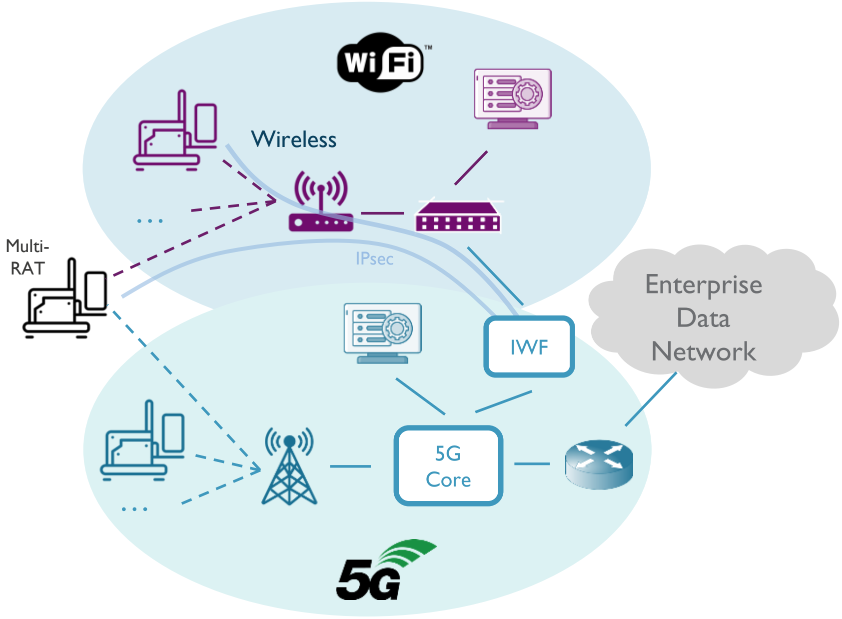
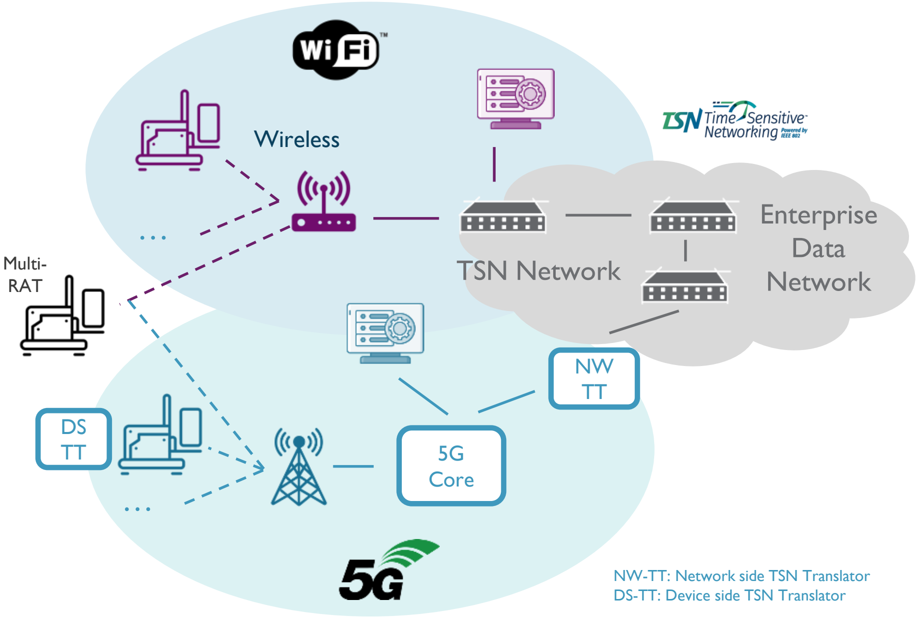
Converged private 5G – Wi-Fi (TSN) networks



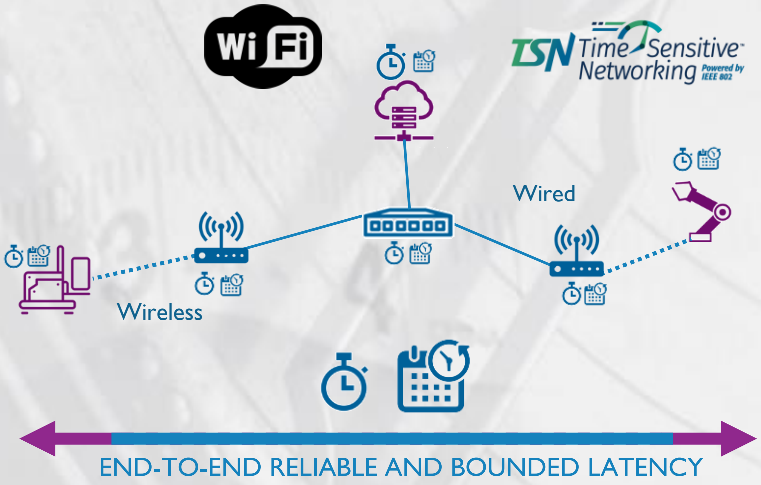
a) 5G – Wi-Fi convergence via the Non-3GPP Interworking Function



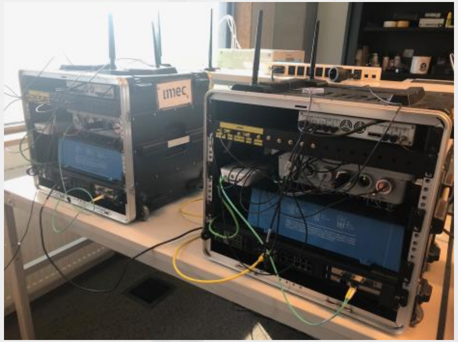
b) TSN technology expanding to the Wi-Fi and 5G domain

Converged private 5G – Wi-Fi (TSN) networks

Validated using imec's lab facilities



5G



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