Oregon IEEE ComSoc Chapter

Wireless Time Sensitive Networking (TSN) from Ethernet to Wi-Fi, 5G and beyond

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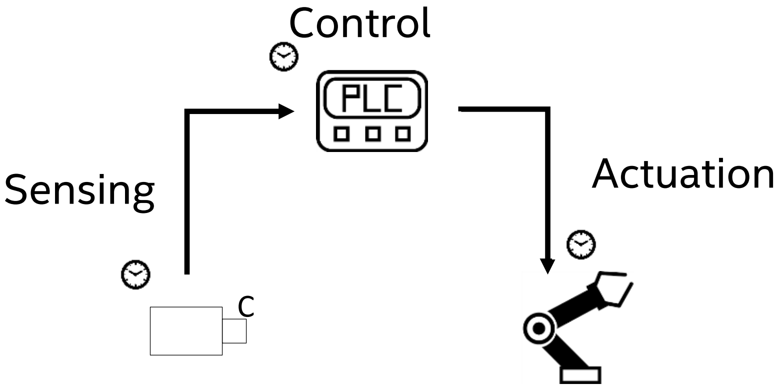
Time-sensitive Applications

Applications that require accurate time synchronization and predictable, usually low, latency with higher reliability

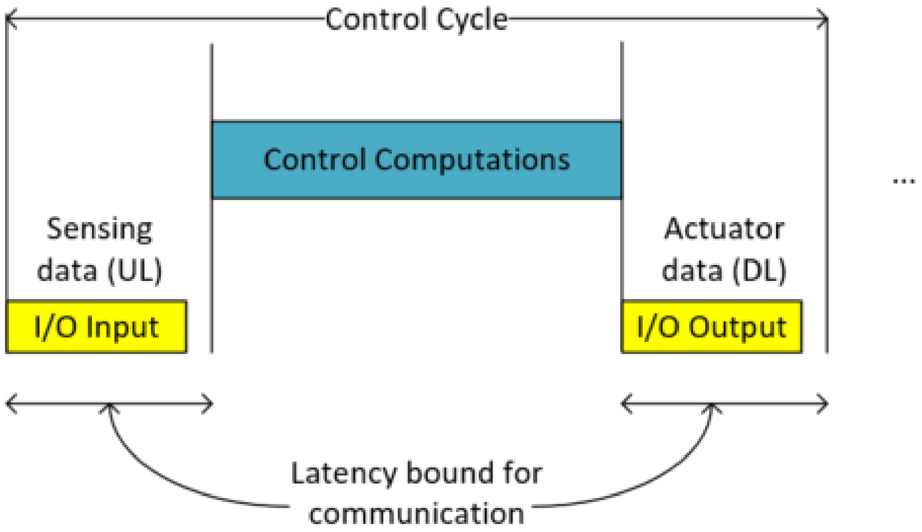
Industry 4.0, Robotics, Autonomous Systems

Immersive Experiences, AR/VR, Gaming

Example: basic industrial control system

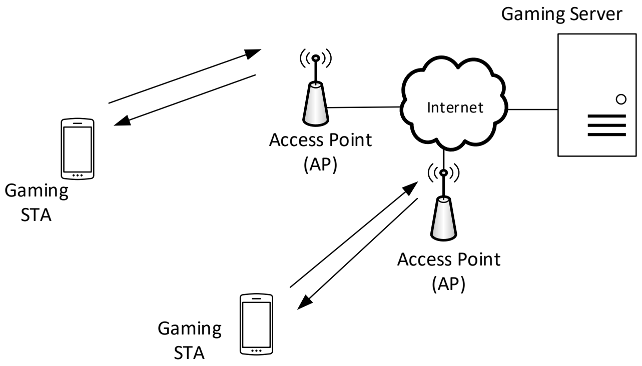


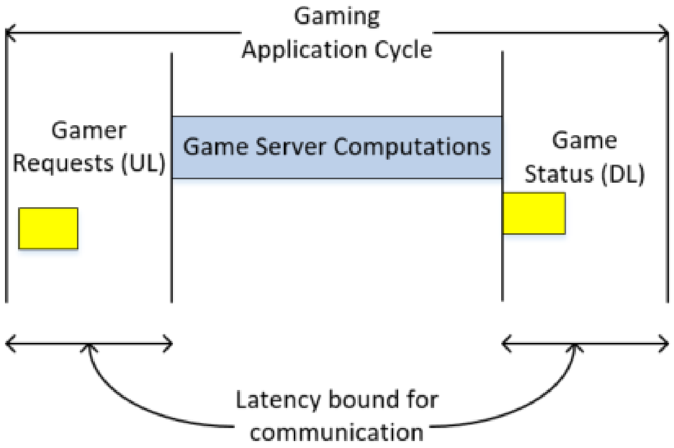
Time synchronized (isochronous) Control Cycle



Latency/jitter may cause instability of the system

Determinism (guaranteed low latency) is also a requirement for other applications





Latency/jitter cause lagging/bad user experience

Growing need for time-sensitive computing and communications

Industrial

AR/VR/Gaming

ProAV

Power and energy

Automotive

Transportation

Not all applications are time-sensitive, but they all benefit from sharing the network

Monitoring & Analytics

Connected Workers

Closed-loop Control Systems

Autonomous & Mobile Robots

Delay-Tolerant

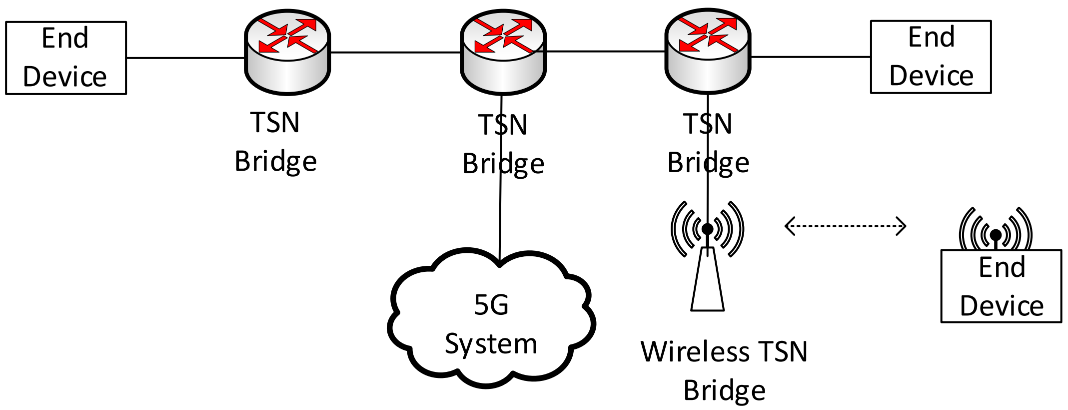
Real-Time

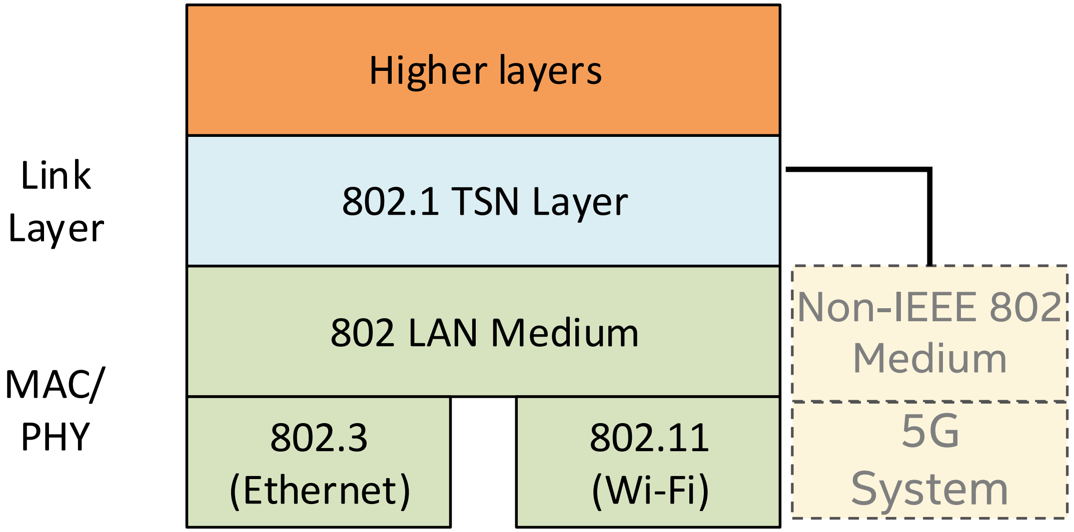
Time-Sensitive/Safety-Critical

What is TSN?

Time-Sensitive Networking (TSN) = deterministic data delivery with **bounded latency** without loss due to congestion or errors

Standards defined by the IEEE 802.1 TSN Task Group for IEEE 802 Local Area Networks (LAN)





Source: D. Cavalcanti, et al., "Extending Accurate Time Distribution and Timeliness Capabilities over the Air to Enable Future Wireless Industrial Automation Systems," Proceeding of the IEEE, Vol. 107, No. 6, June 2019.

TSN Requirements

- **Precise synchronization to a reference time**
  - accuracy from ns to ms range, but 1µs is expected to enable most applications
- **Deterministic end-to-end delivery latency**
  - maximum (bounded) latency from source to destination
  - average, mean or typical values are of NO INTEREST
- **Extremely low packet loss probability**
  - require highly reliable links/devices, losses are tolerated up to a given bound (process dependent)
  - consecutive losses (beyond a certain bound) may trigger fail-safe shutdown
- **Convergence**
  - time-sensitive streams and other traffic on the same network

Time-Sensitive Networking (TSN) Profiles (Selection and Use of TSN tools)

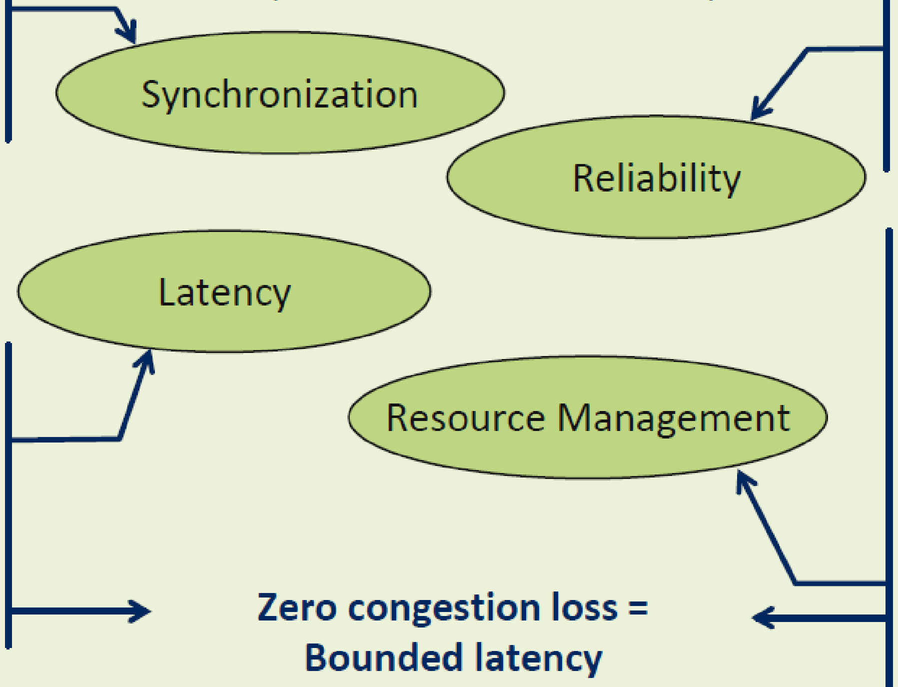
Audio Video Bridging [802.1BA]	Fronthaul [802.1CM/de]	Industrial Automation [IEC/IEEE 60802]	Automotive In-Vehicle [P802.1DG]	Service Provider [P802.1DF]	Aerospace [P802.1DP]

TSN Components

(Tools of the TSN toolbox)

Time synchronization:
Timing and Synchronization [802.1AS-2020]
(a profile of IEEE 1588)
Hot Standby [P802.1ASdm]
YANG [P802.1ASdn]

High availability / Ultra reliability:
Frame Replication and Elimination [802.1CB]
Path Control and Reservation [802.1Qca]
Per-Stream Filtering and Policing [802.1Qci]
Reliability for Time Sync [802.1AS-2020]



Bounded low latency:
Credit Based Shaper [802.1Qav]
Frame Preemption [802.1Qbu & 802.3br]
Scheduled Traffic [802.1Qbv]
Cyclic Queuing and Forwarding [802.1Qch]
Asynchronous Traffic Shaping [802.1Qcr]
QoS Provisions [P802.1DC]

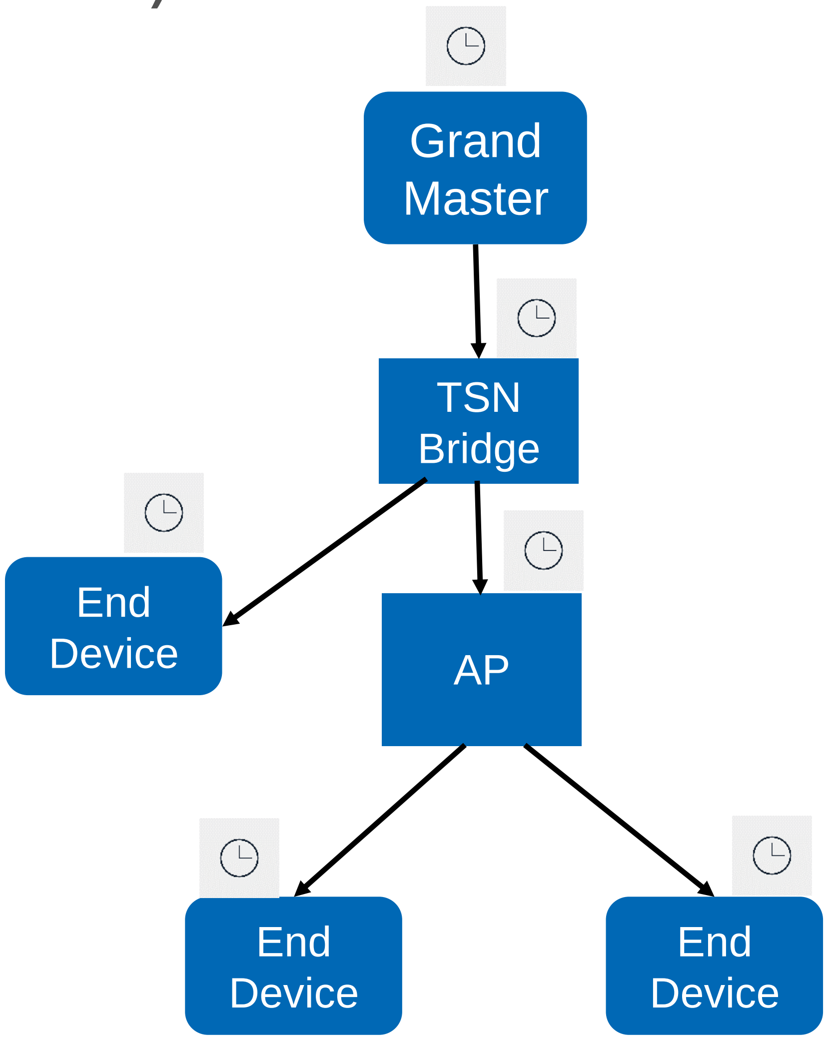
Dedicated resources & API:
Stream Reservation Protocol [802.1Qat]
Link-local Registration Protocol [802.1CS]
TSN Configuration [802.1Qcc]
Foundational Bridge YANG [802.1Qcp]
YANG for CFM [P802.1Qcx]
YANG for LLDP [P802.1ABcu]
YANG for 802.1Qbv/Qbu/Qci [P802.1Qcw]
YANG & MIB for FRER [P802.1CBcv]
Extended Stream Identification [P802.1CBdb]
Resource Allocation Protocol [P802.1Qdd]
TSN Configuration Enhancements [P802.1Qdj]
LLDPv2 for Multiframe Data Units [P802.1ABdh]
Multicast and Local Address Assignment [P802.1CQ]

Note: A 'P' in front of an ID indicates an ongoing Project.

Source: TSN Standards and ongoing projects @ www.ieee802.org/1/tsn

Time Synchronization (802.1AS)

- Enables the distribution of **a single, accurate, time reference across the network** (one time reference for the entire TSN domain)
  - Time is used to coordinate application behavior (sensors, controller, actuators)
  - Time is used to configure TSN tools (e.g., Time-Aware scheduling – 802.1Qbv)

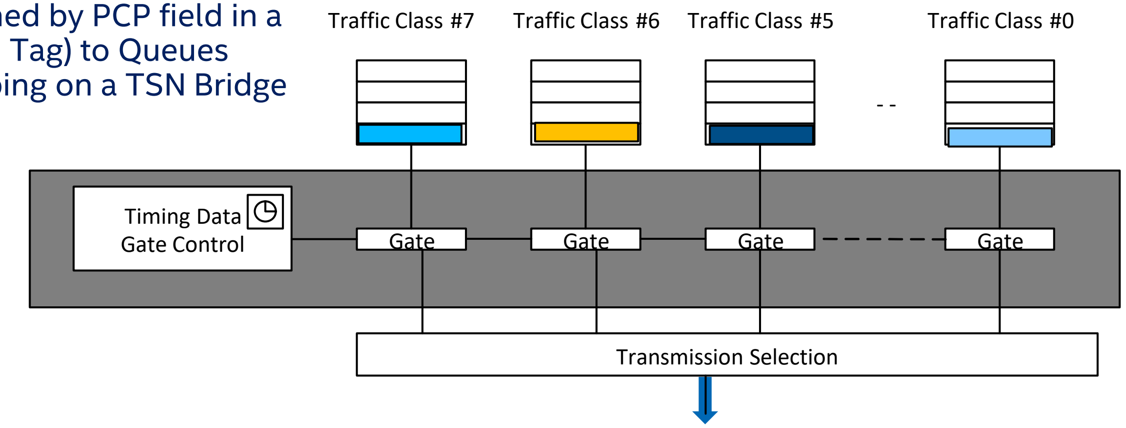


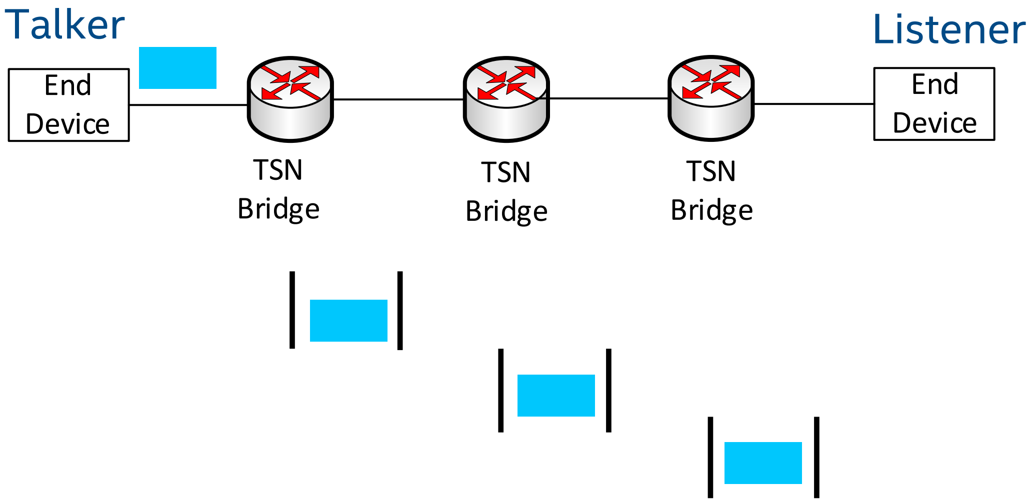
Latest specification: IEEE 802.1AS-2020

Time-Aware Scheduling (802.1Qbv)

Time-gated queues controlled by a cyclic schedule

8021.Q Traffic Classes (defined by PCP field in a VLAN Tag) to Queues Mapping on a TSN Bridge

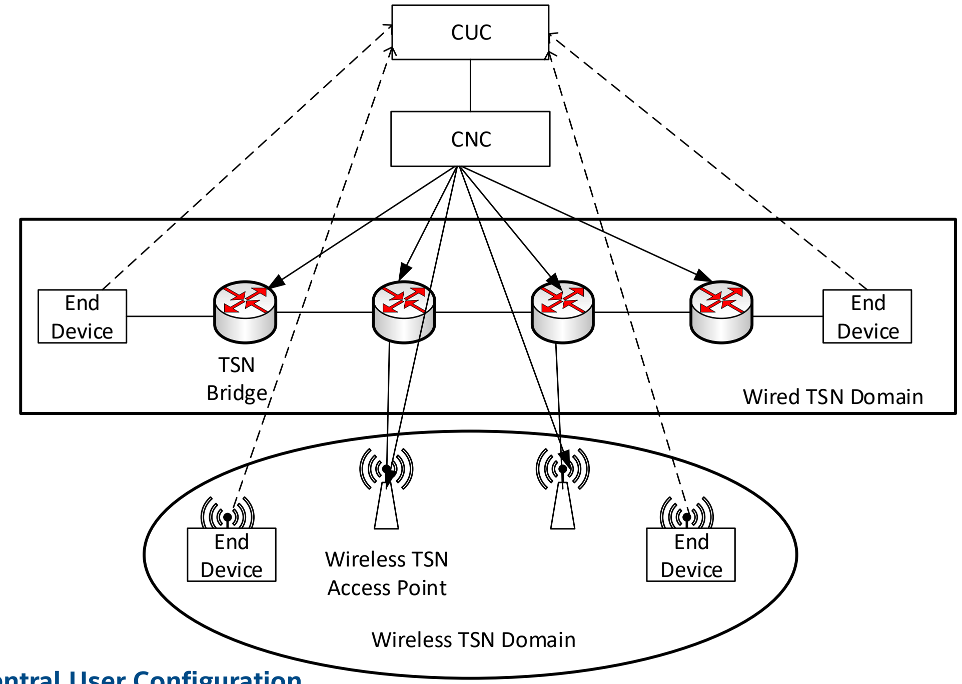




Protected Windows for time-sensitive traffic along the end-to-end path (avoid congestion delay caused by low priority traffic)

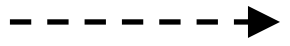
TSN Configuration Model and Assumptions

802.1Qcc Centralized Model



CUC: Central User Configuration

CNC: Central Network Configuration



Control plane (logical connection) between CUC and End Devices

Control plane (logical connection) between CNC and TSN bridges

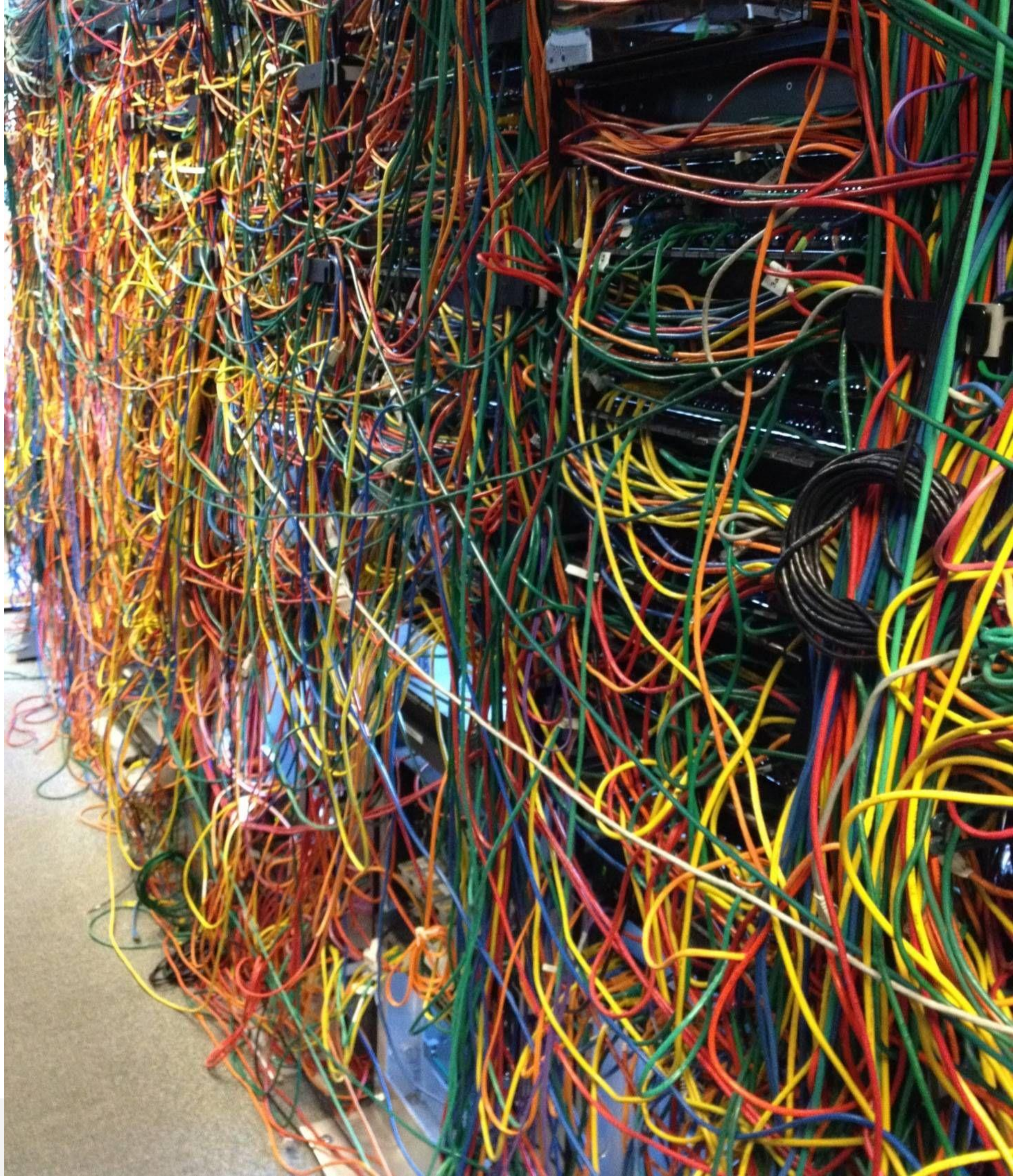
The IEEE 802.1Qcc std defines several configuration models (centralized and distribute)

Assumptions:

- Time-critical traffic streams (max packet size and inter-arrival time) are known a priori (at configuration stage)
- All TSN devices are synchronized to the same reference clock (through 802.1AS)
- The CUC collects the traffic stream requirements from end devices (Talkers/Listeners) and the CNC discovers the network topology
- The CNC computes the **transmission schedule and the end-to-end path** for each traffic stream and communicate the schedule to the CUC
- The CNC configures the schedule at TSN Bridges, and the CUC configures the schedule in the end devices (e.g. control plane using YANG/NETCONF)

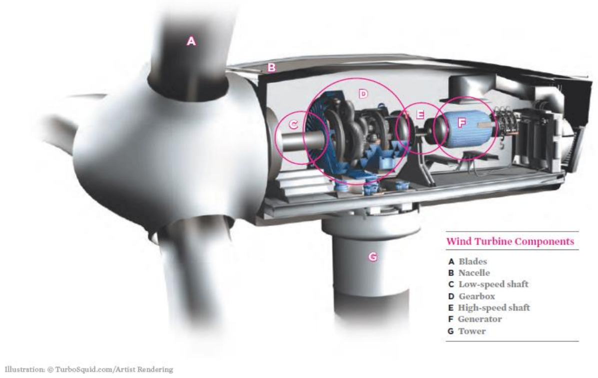
Flexibility,
Re-configurability,
Mobility,
Lower maintenance costs, …

Wireless has obvious benefits for many time-sensitive applications



Wireless Applications

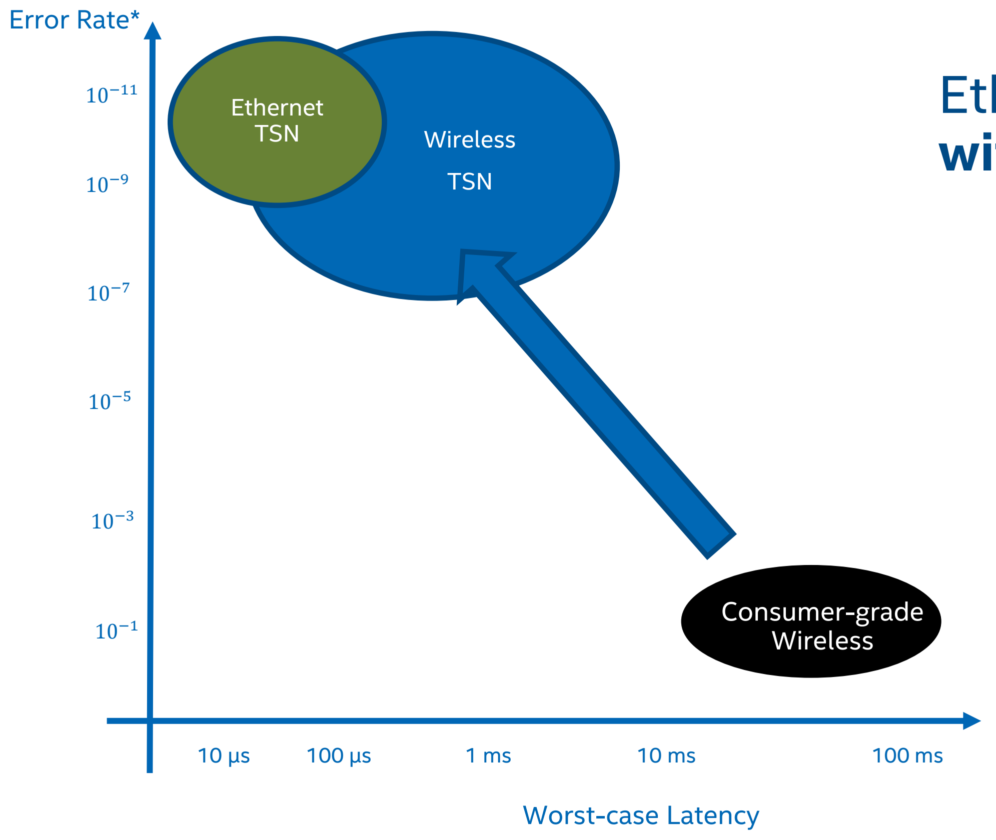
Flexibility, speed, efficiency with mobile robots. Edge/remote control via deterministic wireless enables lower power/cost robots
[Next generation smart manufacturing]



"It would be desirable to use wireless communication to connect the nacelle and the rotor, because of the very expensive slip rings, but existing wireless solutions are lacking the necessary determinism and reliability."
Automation device vendor

"The wiring harness is the 3rd highest cost component in a car (behind the engine and chassis) and comprise 50% of the cost of labor for the entire car".
[Automotive Ethernet: An Overview]

Closing the Performance Gap with wired TSN



Ethernet (802.3 MAC/PHY) provides **stable links with predictable capacity**

Wireless requires special considerations

- Stochastic in nature (variable capacity)
- Time/frequency/space varying (shadowing, multipath, …)
- Harsh environment (obstructions, noise, interference)
- Typically, high error rate compared to wires

* Packets lost or that miss the deadline

New wireless capabilities

Higher speed, lower latency, higher reliability

Based on 3GPP Rel 16

mmwave and <7 GHz*
(licensed and unlicensed)

5G New Radio, OFDMA flexible frame structure, 256 QAM (DL)

Ultra-Reliable Low Latency (URLLC)

Wi-Fi 6/6E

Based on IEEE 802.11ax

2.4, 5, 6 GHz band operation (unlicensed)

OFDMA, UL and DL MU-MIMO, 1024-QAM

Wi-Fi 6E
Extends Wi-Fi 6 with 6 GHz band operation*

* 6 GHz operation subject to regulatory rules in each country.

Wi-Fi TSN

Current Generations of Wi-Fi

Wi-Fi 6

- Based on IEEE 802.11ax
- 2.4, 5, 6 GHz band operation
- OFDMA, UL and DL MU-MIMO, target wake time (TWT), 1024-QAM
- Best-in-class WPA3 security
- Max data rate: 9.6 Gbps
- Launched Aug/2019

Wi-Fi 6E

- Extends Wi-Fi 6 with 6 GHz band operation*
- Launched Jan'21

Wi-Fi 5

- Based on IEEE 802.11ac
- 5 GHz band operation
- Up to 8x8 MIMO, DL MU-MIMO, 80 MHz and 160 MHz channels, 256-QAM
- Max data rate: ~7 Gbps
- Launched June/2013

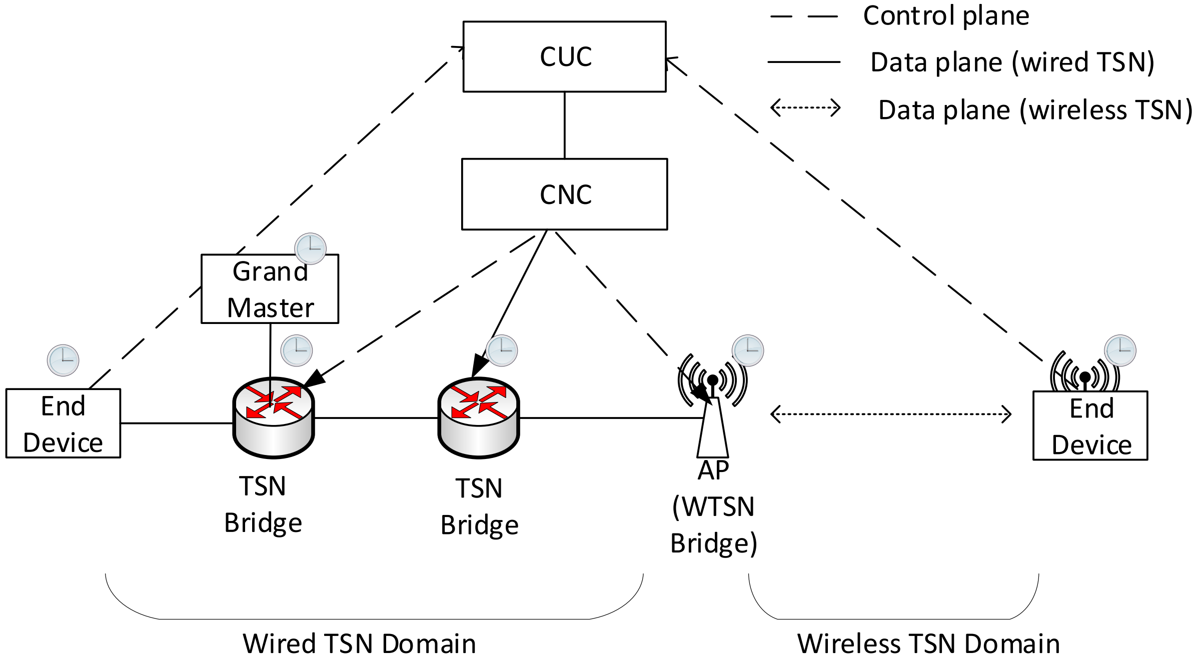
Wi-Fi 4

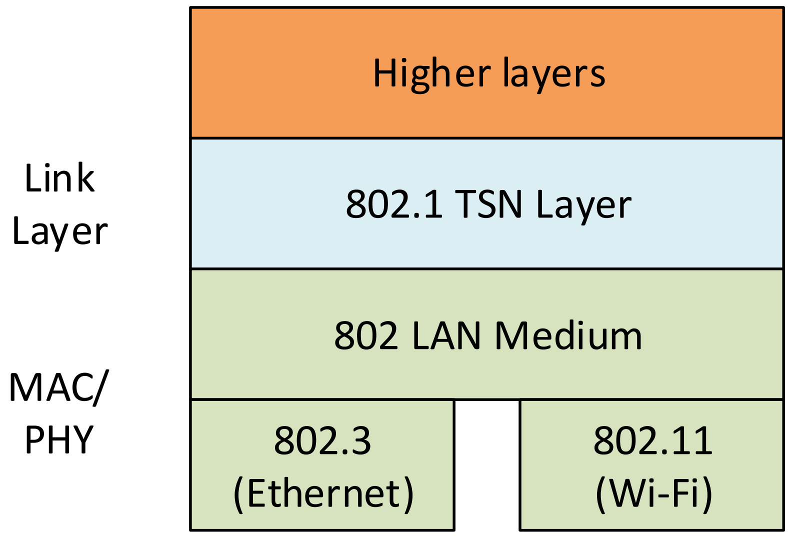
- Launched in 2007
- Max data rate: ~600 Mbps
- Up to 4x4 MIMO, 40 MHz channels, 64-QAM
- 2.4 and 5 GHz band operation
- Based on IEEE 802.11n

* 6 GHz operation subject to regulatory rules in each country.

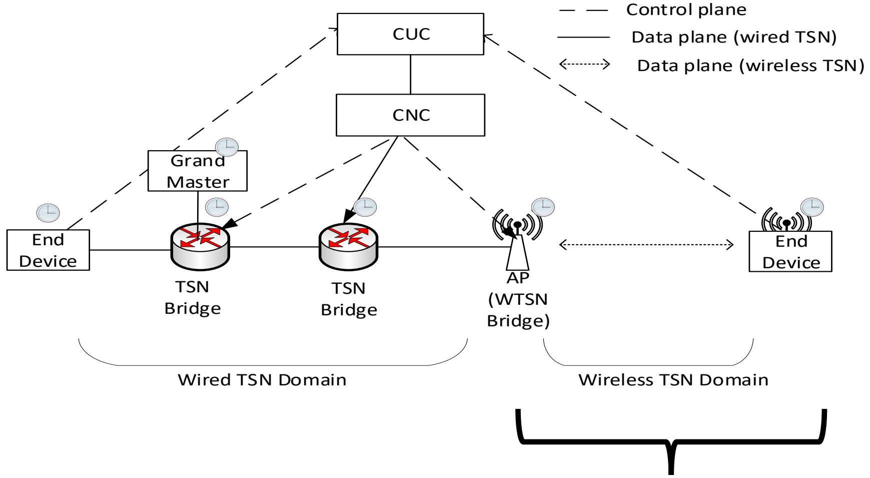
Source: https://www.intel.com/content/dam/www/public/us/en/documents/pdf/wi-fi-7-and-beyond.pdf

Ethernet and Wi-Fi in a TSN Capable LAN

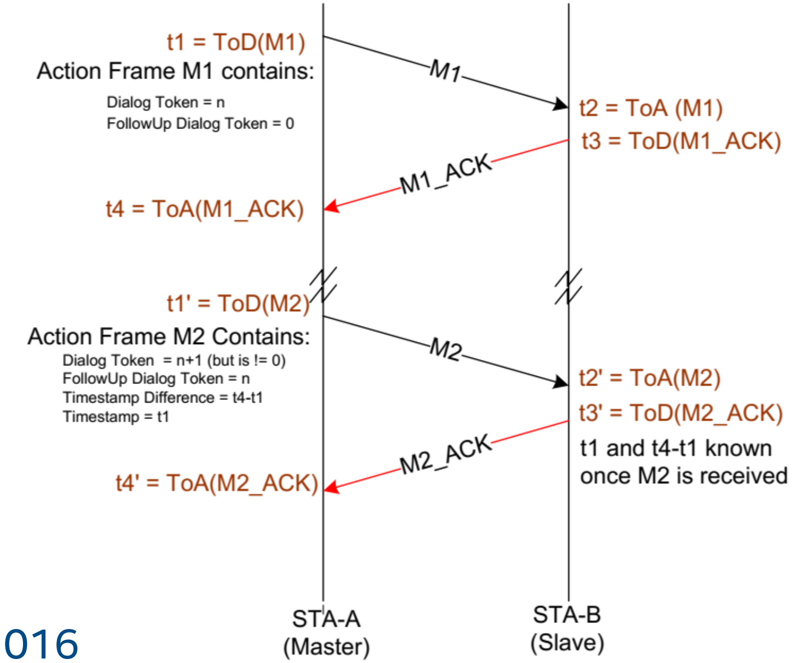




802.1AS Time Synchronization over 802.11



802.11 TM Procedure



802.11 action frames are used to compute:

LinkDelay = [(t4-t1)-(t3-t2)]/2

NeighborRateRatio* = (t1’-t1)/(t2’-t2)

TimeOffset = [(t2-t1)-(t4-t3)]/2

802.1AS over 802.11 defined enabled by:

- Timing Measurement (TM) – IEEE 802.11-2012
- Fine Timing Measurement (FTM) IEEE 802.11-2016

*PPM offset to neighbor

802.1AS over 802.11 FTM

FTM procedure

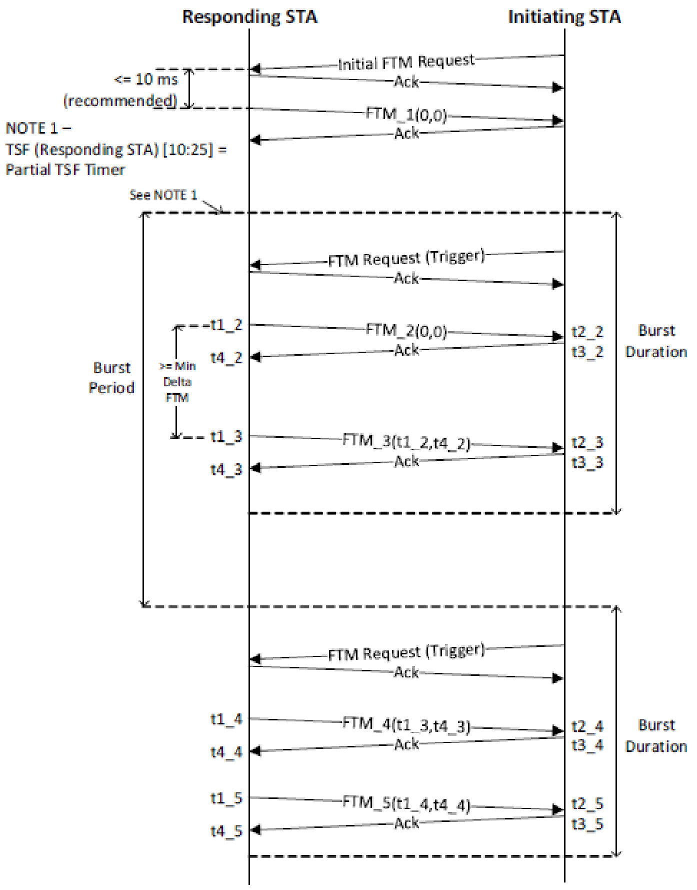


Figure 11-35—Example negotiation and measurement exchange sequence, ASAP=0, and FTMs per Burst = 2

Source: IEEE 802.11-2020

802.11 action frames are used to compute:

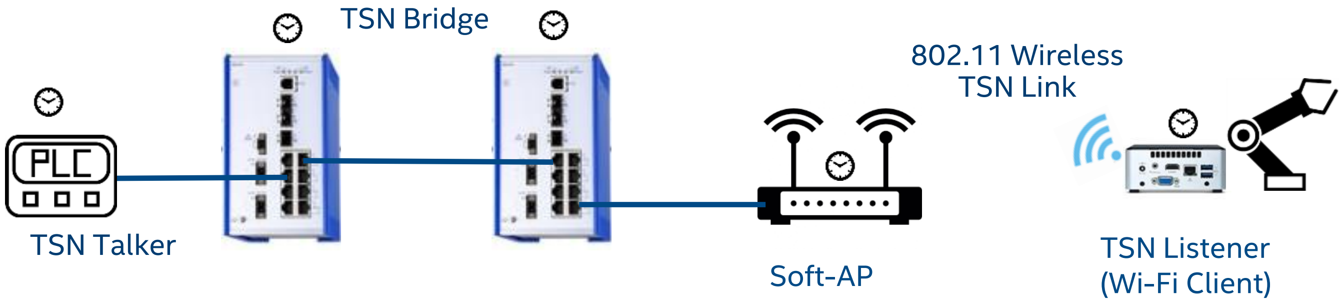
LinkDelay = [(t4-t1)-(t3-t2)]/2

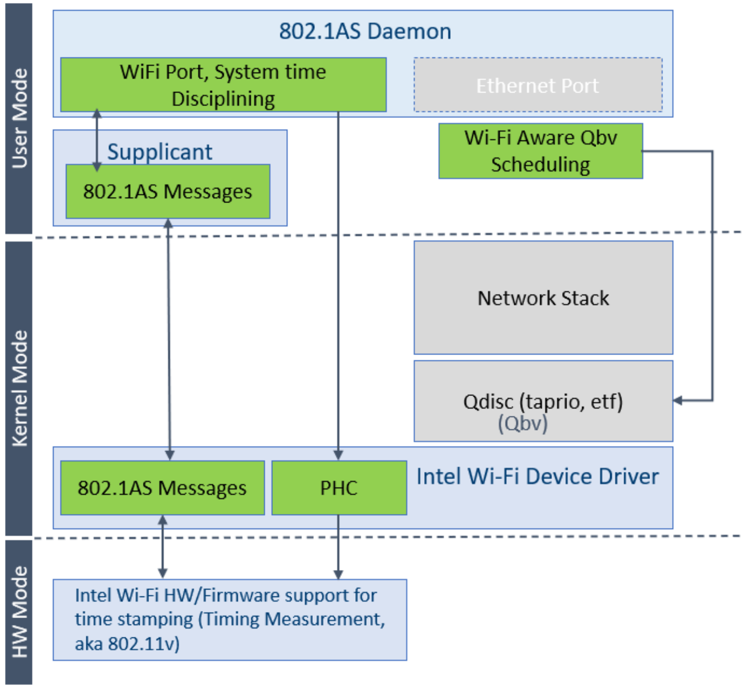
NeighborRateRatio = (t1'-t1)/(t2'-t2)

TimeOffset = [(t2-t1)-(t4-t3)]/2

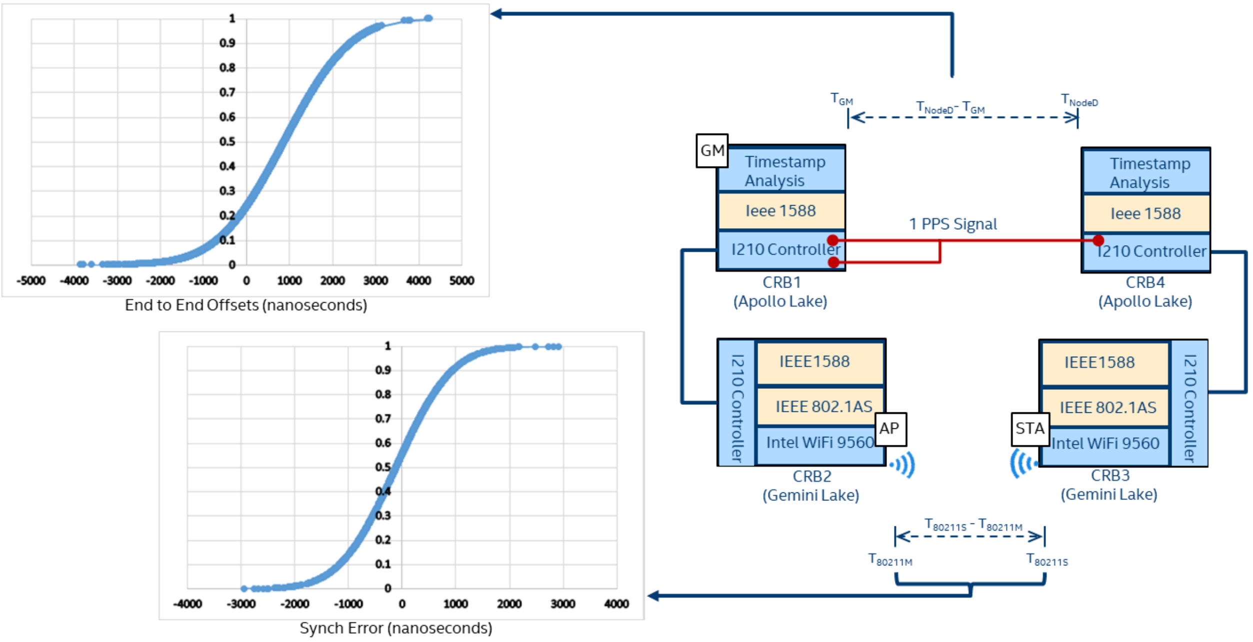
In addition to TSN time sync, FTM also enables positioning/ranging relative to the peer (<1m ranging accuracy in line of sight)

WTSN time synchronization implementation





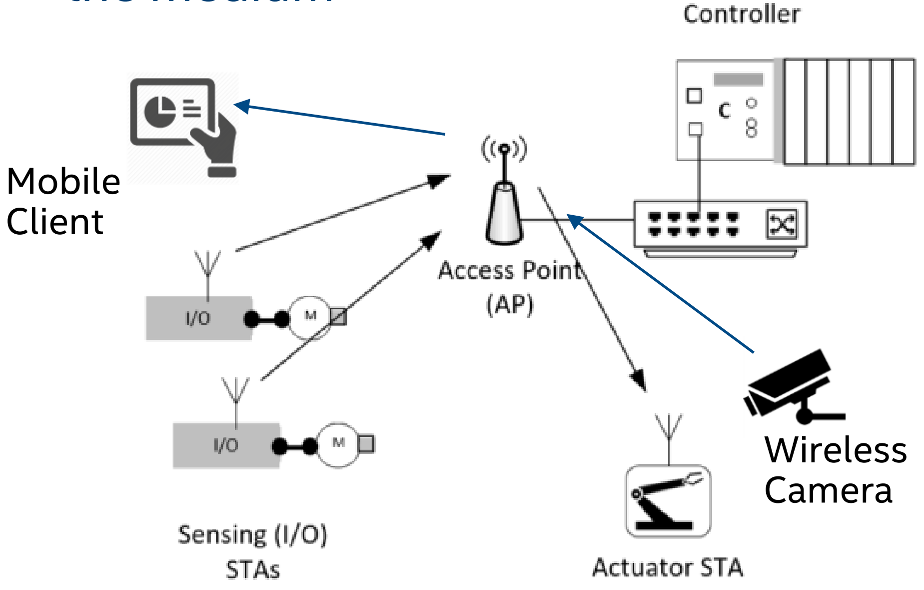
WTSN SW Stack

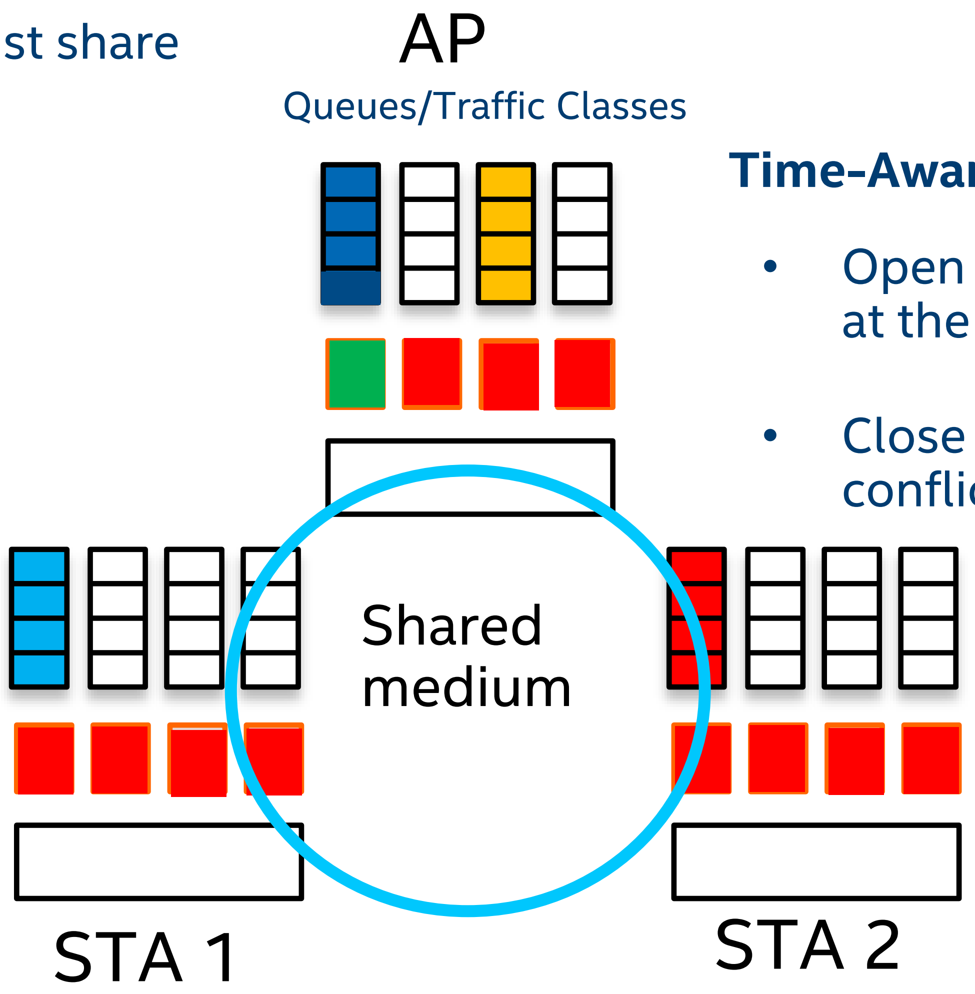


End to End Hybrid (wired-wireless) Time Synchronization (TM Based, Integrated)

Time-Aware Shaping (802.1Qbv) over Wireless

Time-sensitive and Best-effort traffic must share the medium



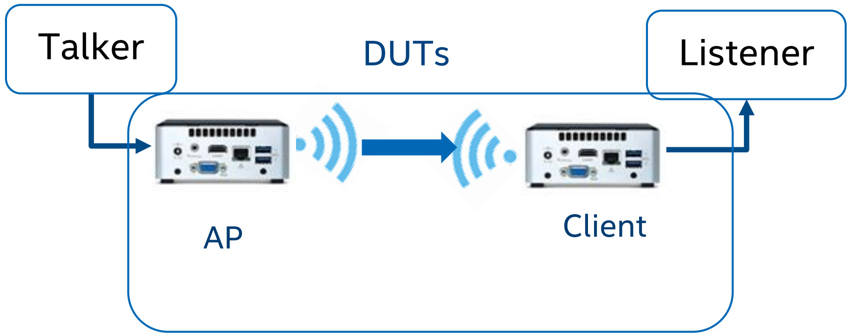


Time-Aware traffic shaping

- Open a time-sensitive queue at the right time
- Close other queues to avoid conflicts

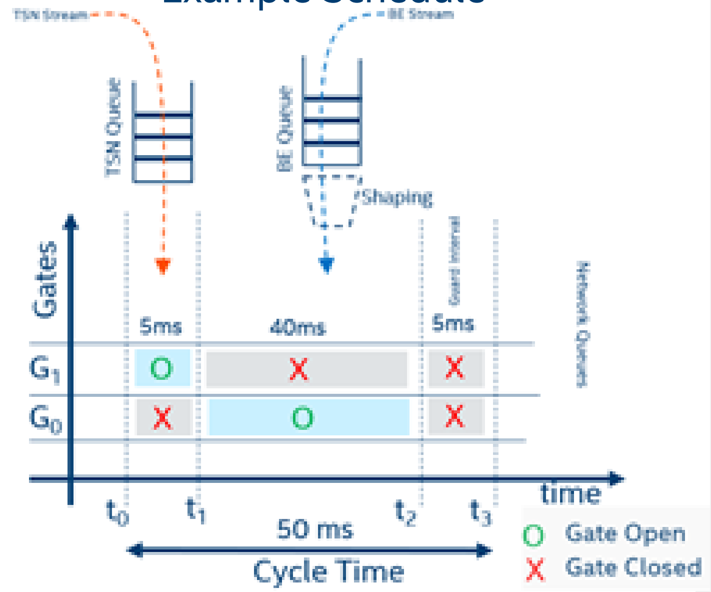
The wireless system is responsible for meeting **hard deadlines** (bounded latency)

802.1Qbv over (EDCA) Wi-Fi 5

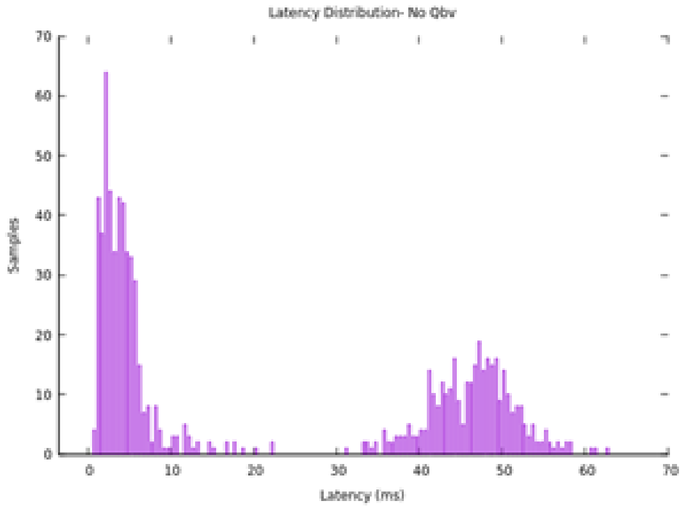


Test Setup for Qbv over 802.11ac/Wi-Fi 5

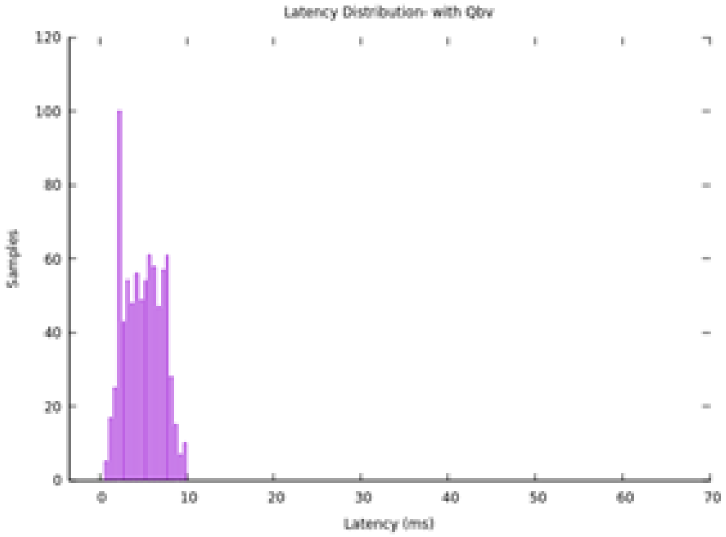
Example Schedule



Priority Traffic: **100 bytes packet every 50 ms** with background BE from 1Mbps to 100 Mbps and **Qbv cycle time of 50 ms**

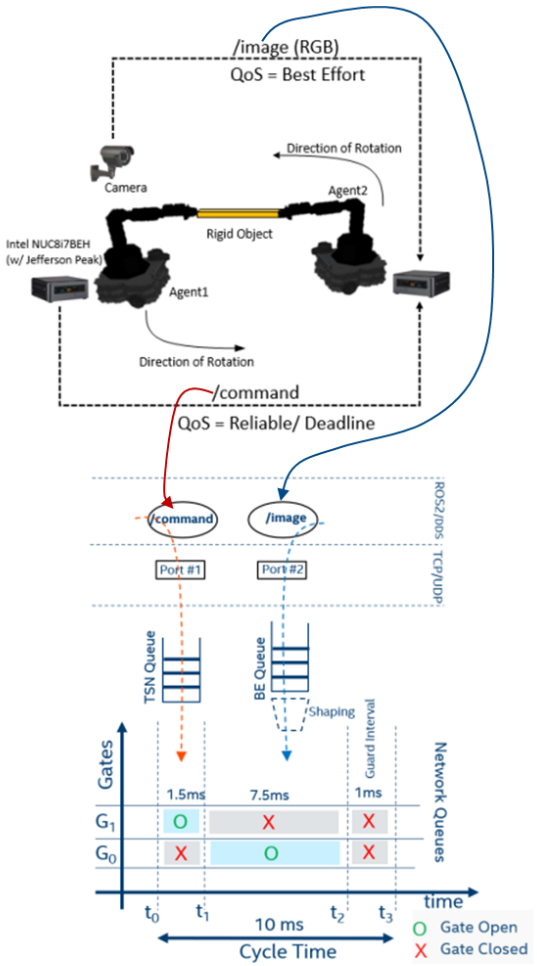


Latencey distribution without Qbv schedules



Latencey distribution with Qbv schedules

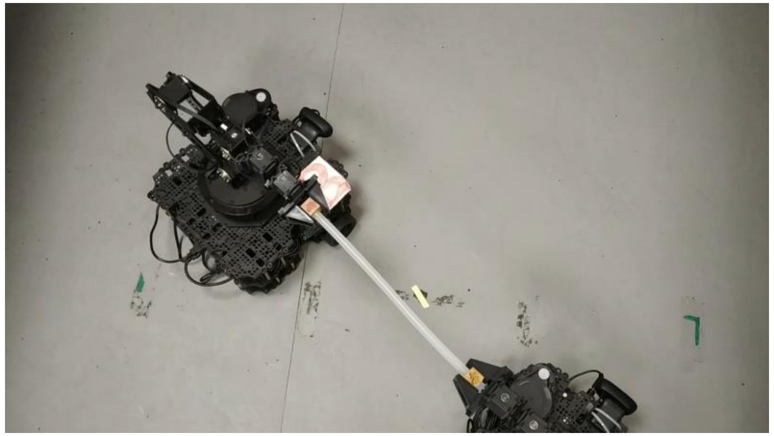
WTSN Enabling Collaborative Robotics



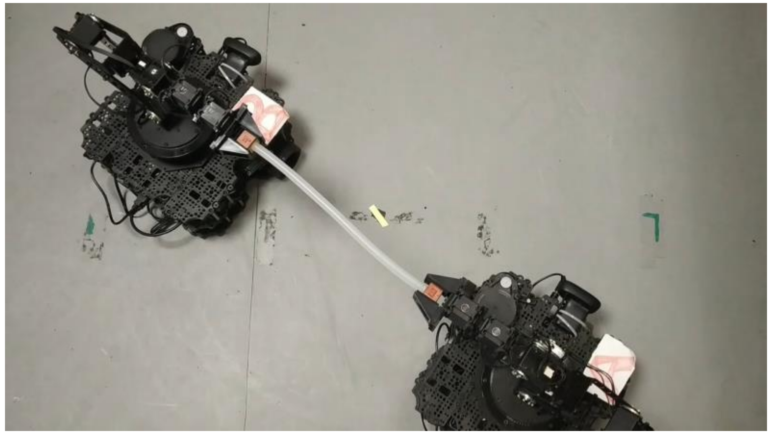
Experimental setup collaborative robotics

DDS QoS Mapping to TSN Qbv Schedule

WTSN enabled

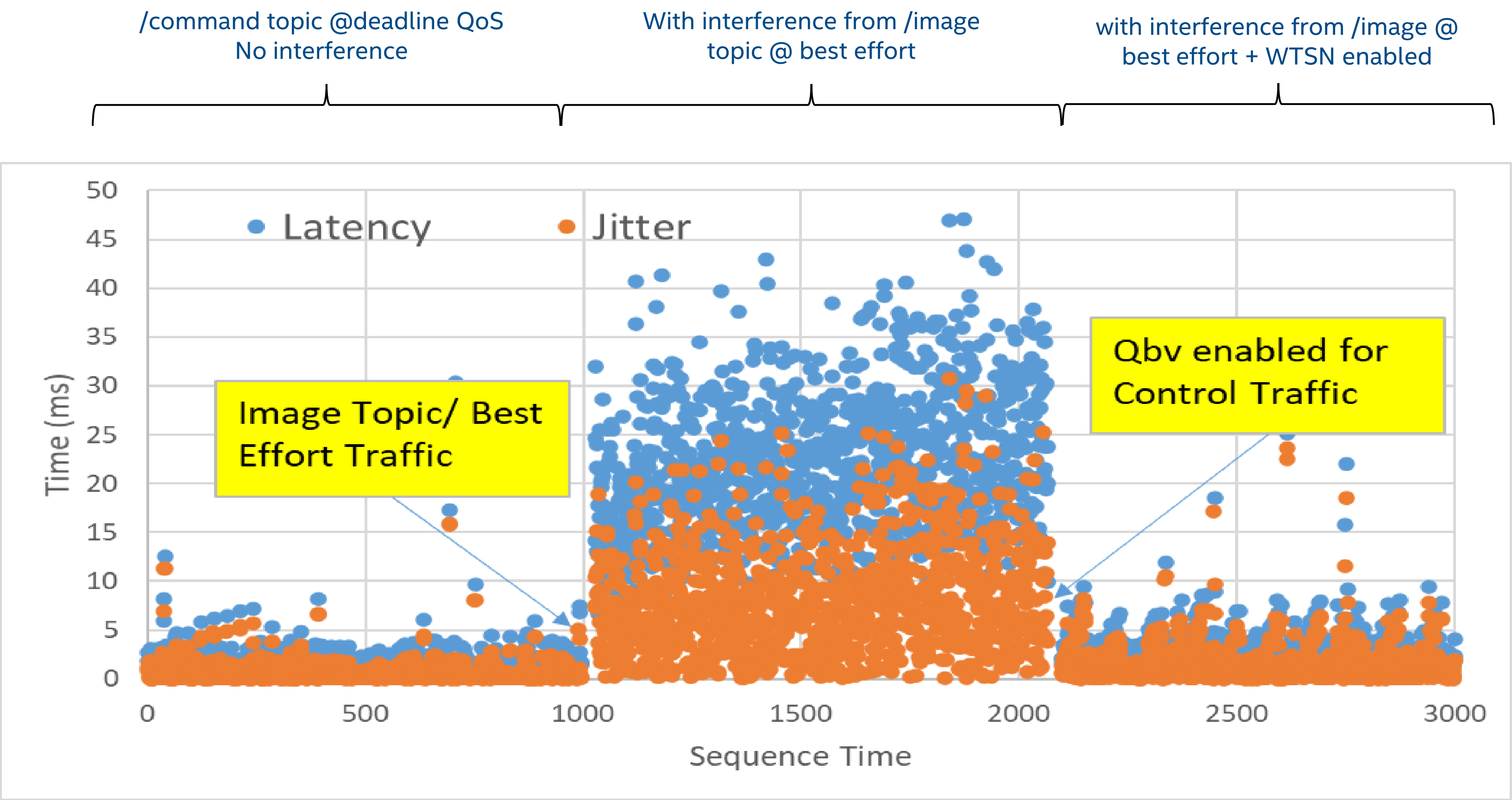


without WTSN



[S. Sudhakaran et. at. Enabling QoS for Collaborative Robotics Applications with Wireless TSN, ICC 2021]

Experiment Results (Wi-Fi 5 TSN)



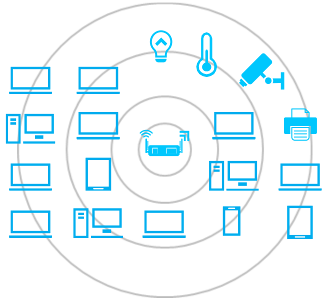
Wireless TSN enables low latency for time-sensitive streams under congestion

NIST – Intel: WTSN enabled Robot work cell

Wi-Fi 6/6E: A Giant Leap Forward

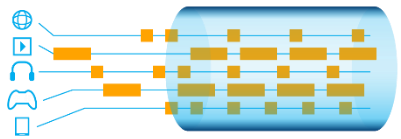
4X GREATER SCALABILITY

OFDMA enables managed, reliable, efficient connectivity across more devices. This means plenty of headroom for future growth or fewer APs required to support existing devices.



REDUCED INTERFERENCE

OBSS enhancements help routers and devices identify local traffic and tune out noise from other networks.



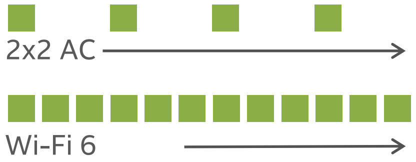
IMPROVED SECURITY

Wi-Fi 6 uses new WPA3 security features, enabling next-generation authentication and best-in-class encryption.

Improved Protection

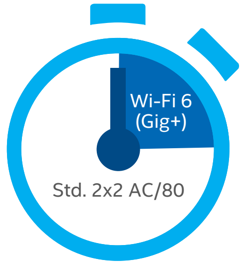
3X FASTER PERFORMANCE

1024 QAM and support for optional 160 MHz channels enable clients and routers to deliver best-in-class Gigabit speeds for the office or home.



RESPONSIVE! ~75% LOWER LATENCY

Wi-Fi 6 helps slash lag times to give you the edge you need to win with OFDMA data management and OBSS interference avoidance features.

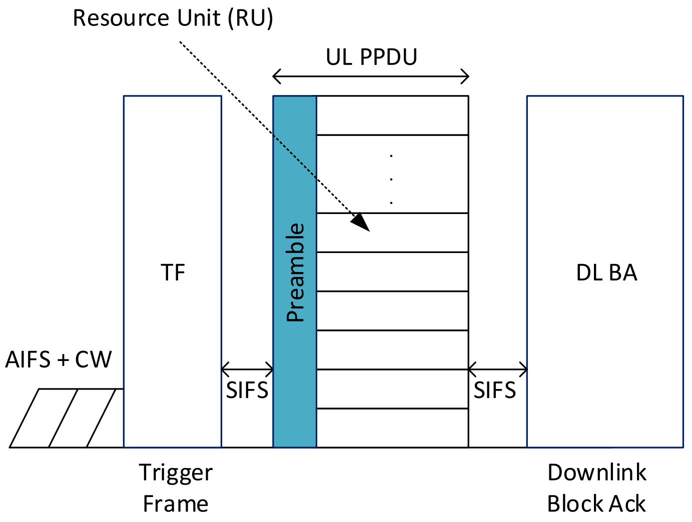


Increasingly stringent usage (e.g., industrial IoT, AR/VR, robotics, cloud gaming) requirements demand continued evolution

Source: https://www.intel.com/content/dam/www/public/us/en/documents/pdf/wi-fi-7-and-beyond.pdf

Time-Aware scheduling with Wi-Fi 6

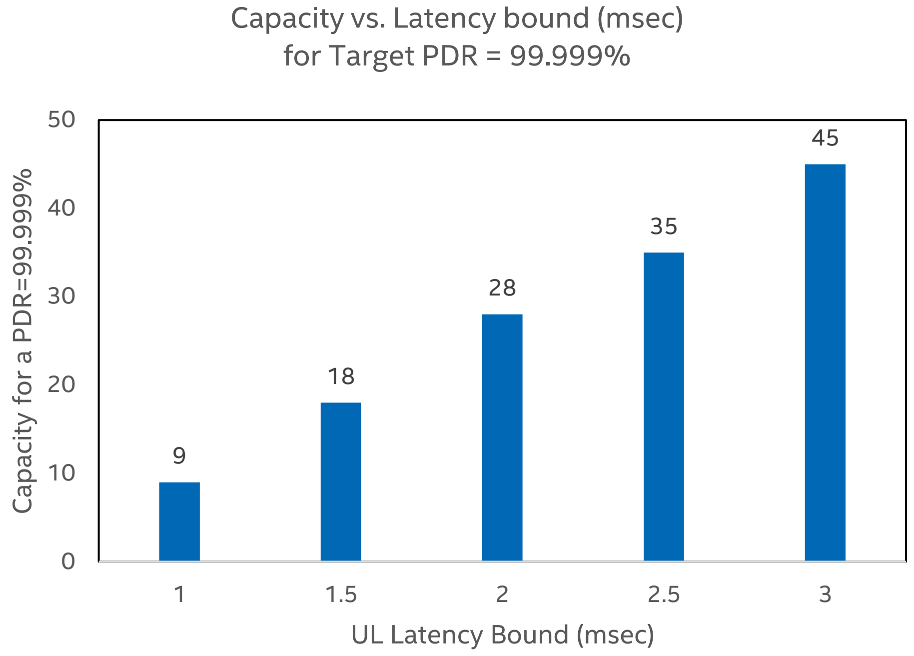
Wi-Fi 6 (802.11ax) defined a new approach to schedule communications
The AP can use the trigger-based scheduling and OFDMA mode to deliver the data according to the worst-case latency and reliability



Simulation Assumptions:

20 MHz channel, SISO, 100 Bytes packets, Channel model E, STAs randomly distributed in a 50 m radio, latency-optimized scheduling strategy, managed network (no OBSS).

Low latency and high reliability can be achieved



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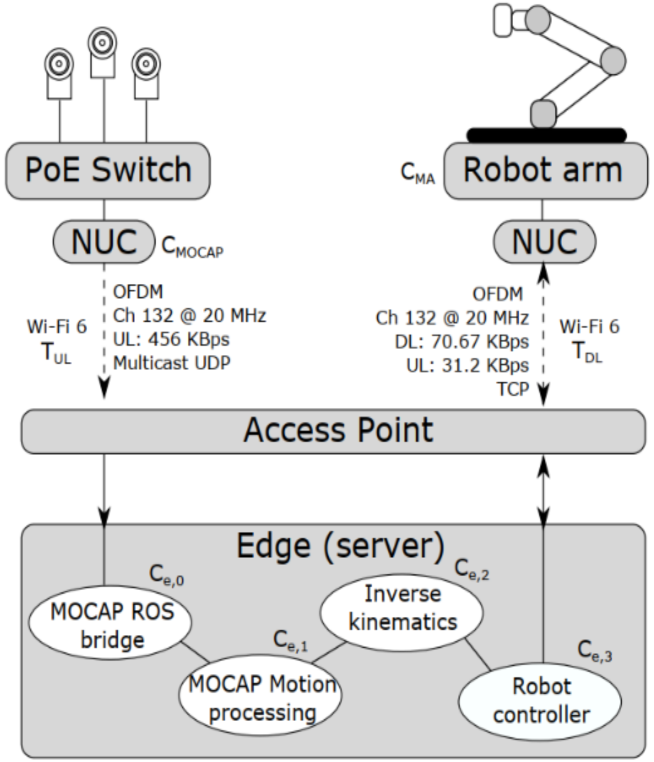
Wi-Fi 6 in Industrial IOT

Enabling E2E QoS and Determinism



Under 3 msec communication latency with Wi-Fi 6

(msec)	C_{MOCAP}	T_{UL}	C_e	T_{DL}	C_{MA}
Average	8.85	**2.17**	0.83	**2.43**	37.6
Std. Dev.	4.66	**0.20**	0.20	**0.33**	1.79
99 Perc.	16.0	**2.50**	1.20	**2.98**	40.0

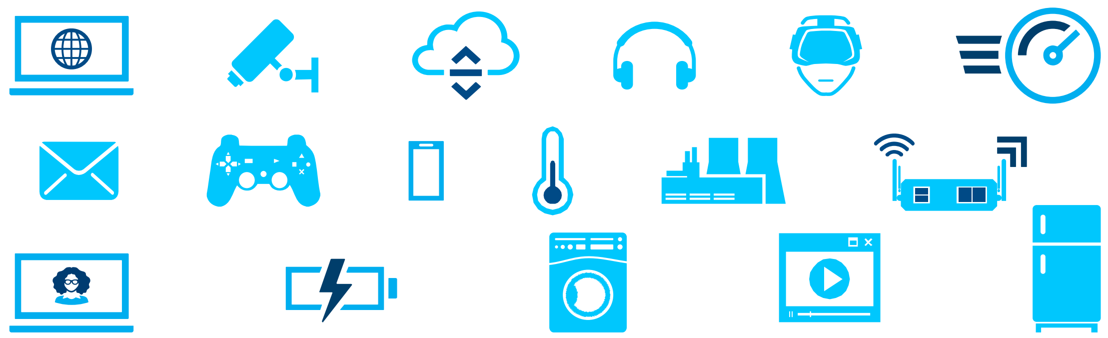
Up Next: Wi-Fi 7

Based on IEEE P802.11be

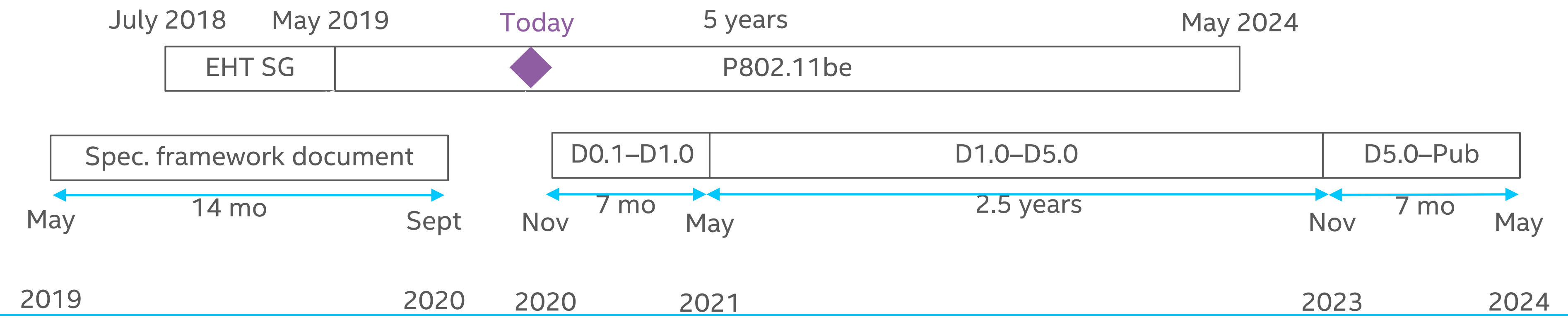
P802.11be project goals*

- Amendment to 802.11, building on 11ax
- Maximum throughput of at least 30 Gbps
- Frequency range: between 1 & 7.250 GHz
- Improvements to worst-case latency & jitter

Targeted usages



Target timeline



* http://www.ieee802.org/11/PARs/P802_11be_PAR_Detail.pdf

Source: https://www.intel.com/content/dam/www/public/us/en/documents/pdf/wi-fi-7-and-beyond.pdf

Key Wi-Fi 7 Features*

User Experience Data Rate

Spectrum Efficiency

Network Energy Efficiency

Connection Density

Key Enhancements

320 MHz channels
4096-QAM
16 spatial streams

Multi-link operation
Multi-AP operation
Deterministic low latency

Peak Data Rate

Cost Effective

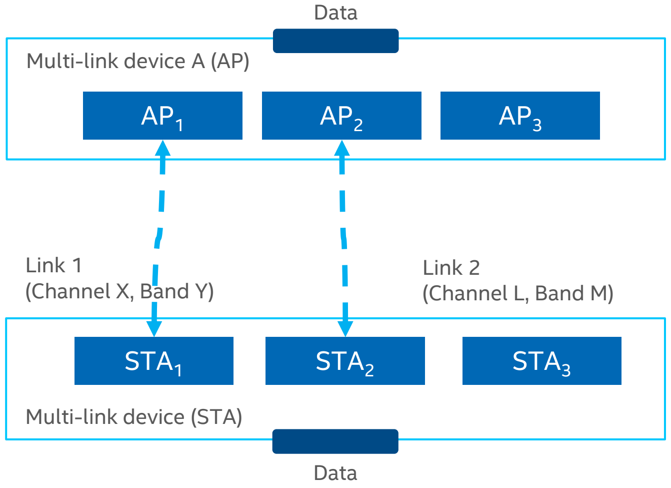
Area Capacity

Low Latency

* Accurate as of Dec/2020. Feature set and their specification are subject to change. Source: https://www.intel.com/content/dam/www/public/us/en/documents/pdf/wi-fi-7-and-beyond.pdf

Wi-Fi 7 enhancements for low latency & TSN

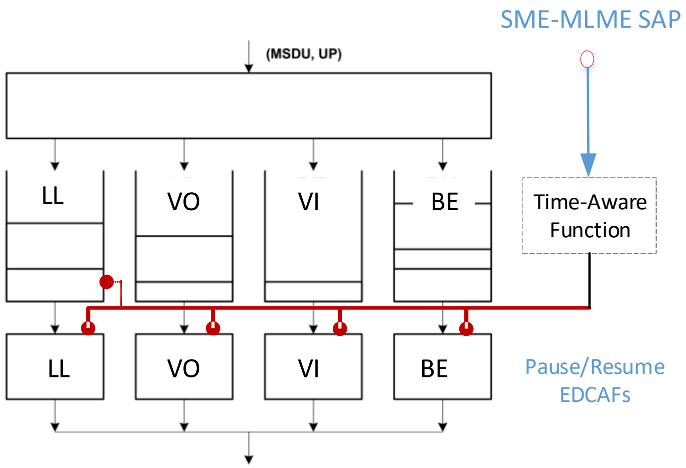
MLO (Multi-Link Operation)



Enables redundancy at the 802.11 MAC
New tools to avoid congestion delay

Potential features for deterministic low latency

- QoS provisioning for low latency reliable traffic streams
- Restricted TWT service periods for low latency traffic
- Time-Aware (Qbv) scheduled access integrated in the MAC with protected service periods



Wi-Fi and TSN Evolution

... 2019 2021 2023 ...

...

Wi-Fi 5 TSN

Wi-Fi 6/6E TSN

Wi-Fi 7 TSN

...

TSN Capabilities

Time Synchronization

Traffic shaping over EDCA

Traffic shaping and bounded latency with scheduled OFDMA operation

Deterministic low latency enhancements

Redundancy over multi-NiC

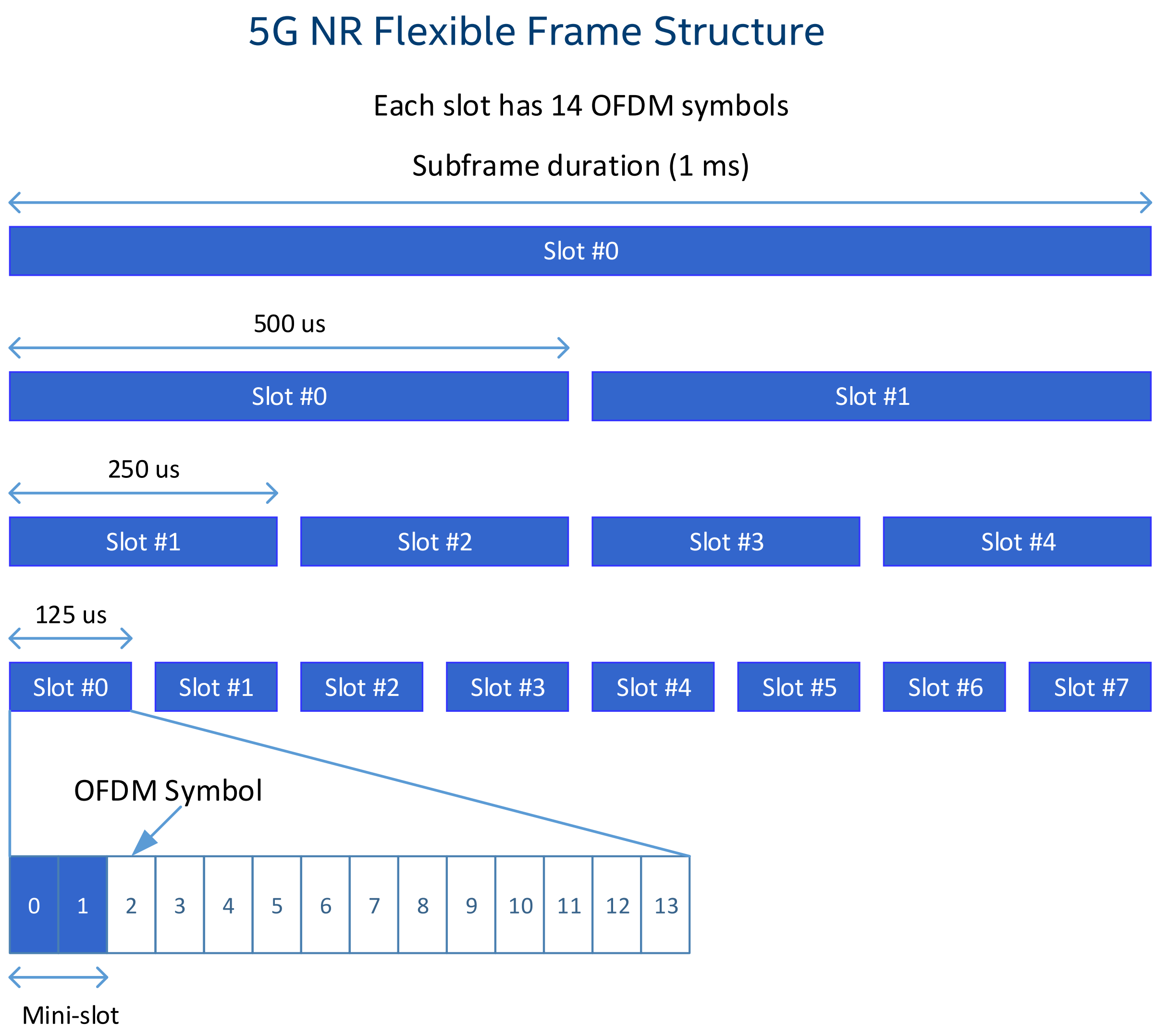
Redundancy over MLO

TSN Configuration and management

Wi-Fi and TSN will continue to evolve and introduce new TSN tools

TSN – 5G Integration

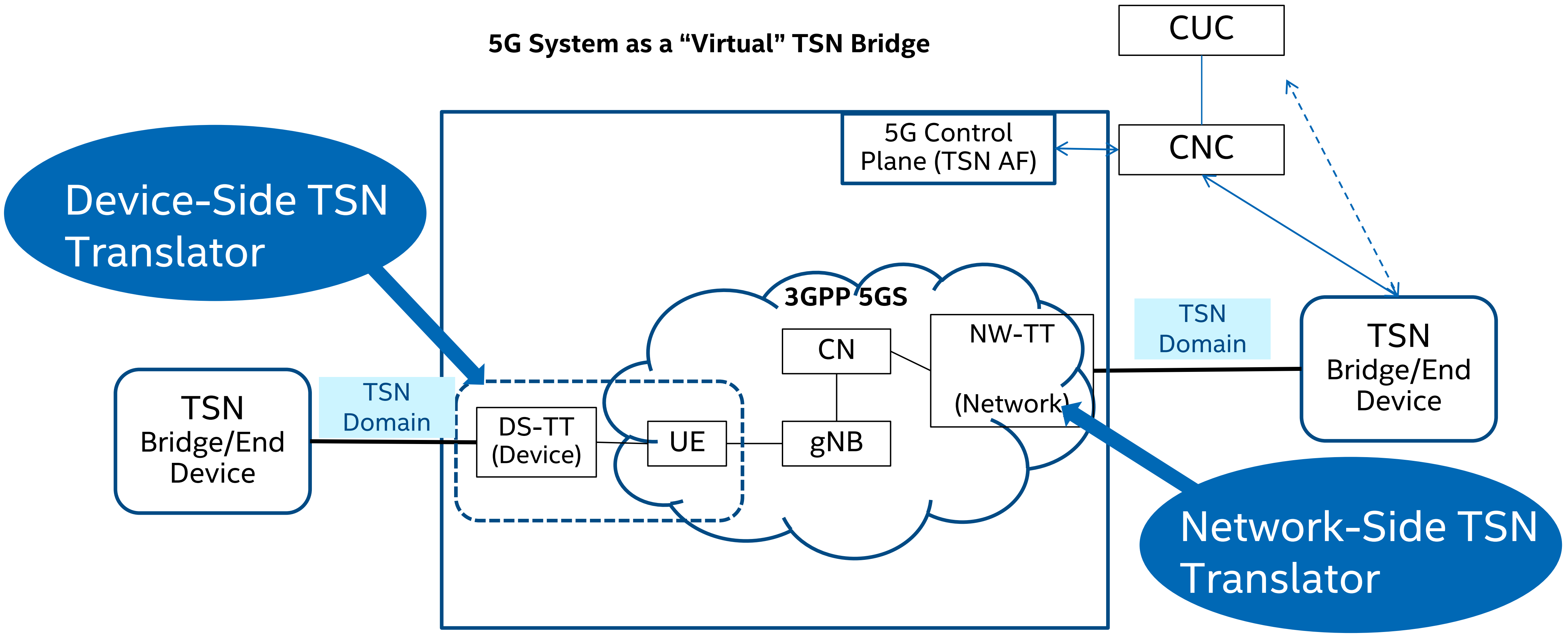
5G NR & URLLC capabilities



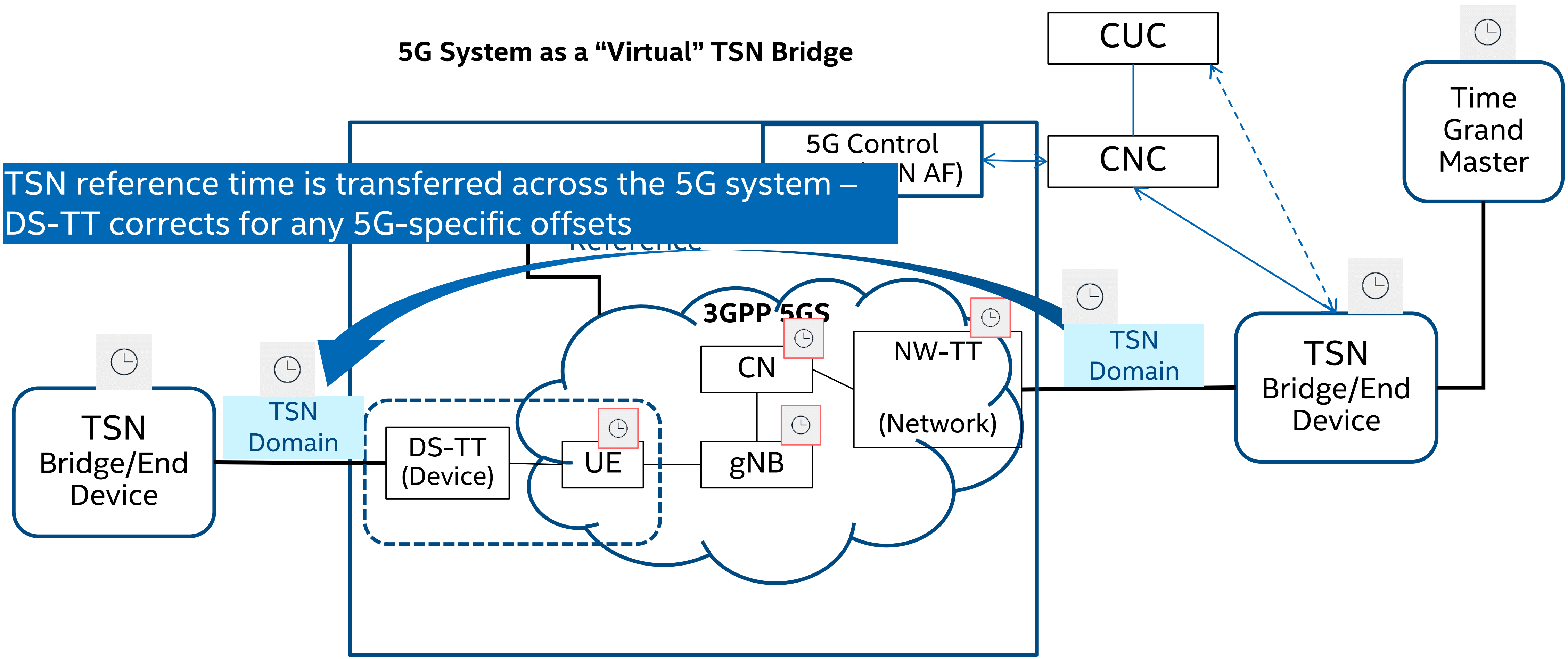
Features to support low latency and high reliability:

- Shorter TTIs (down to 125 us)
- Self-contained subframe (control signaling, data and ACK/NACK in a single subframe)
- Polar codes (enhanced performance for short packets)
- Grant free UL access (less overhead and faster access)
- Integrations with TSN (Rel. 16)

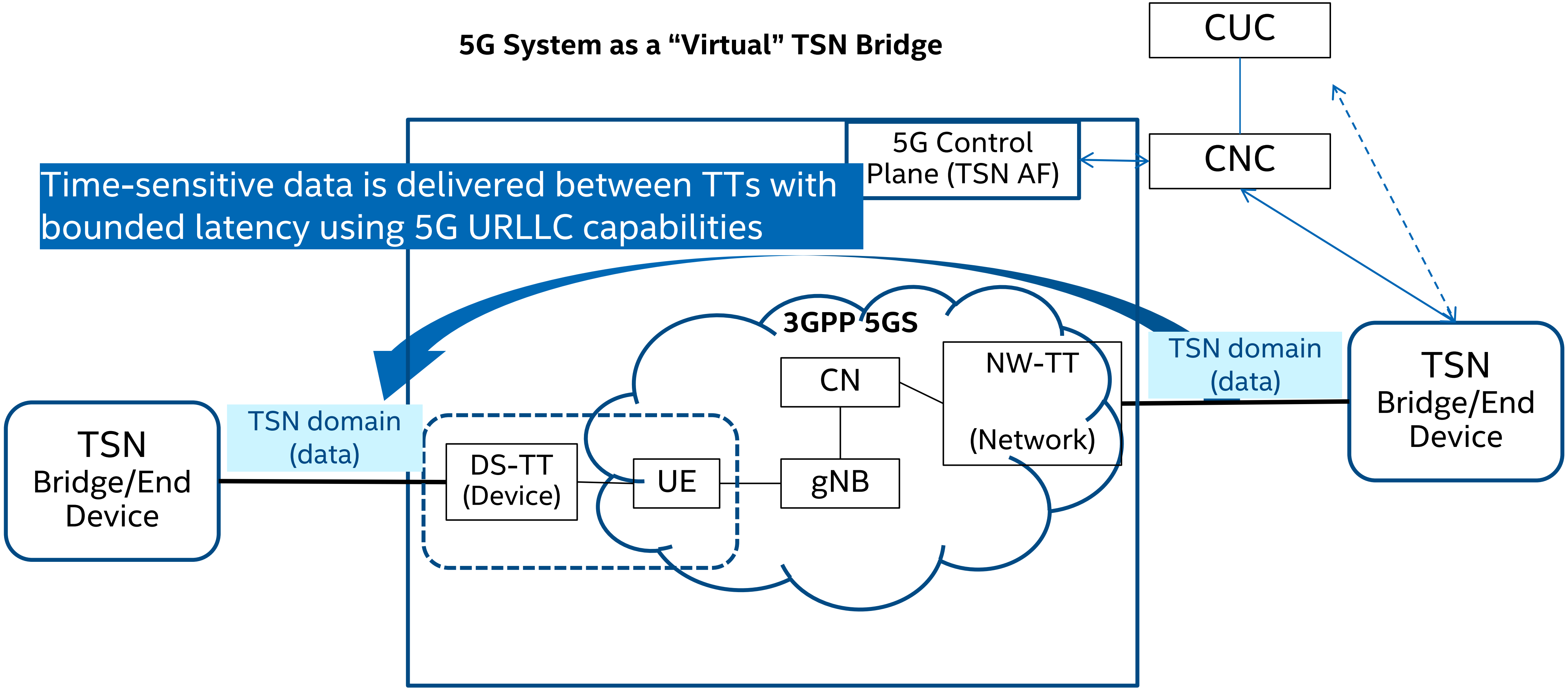
5G Integration with TSN (Rel. 16)



TSN time synchronization across a 5G system



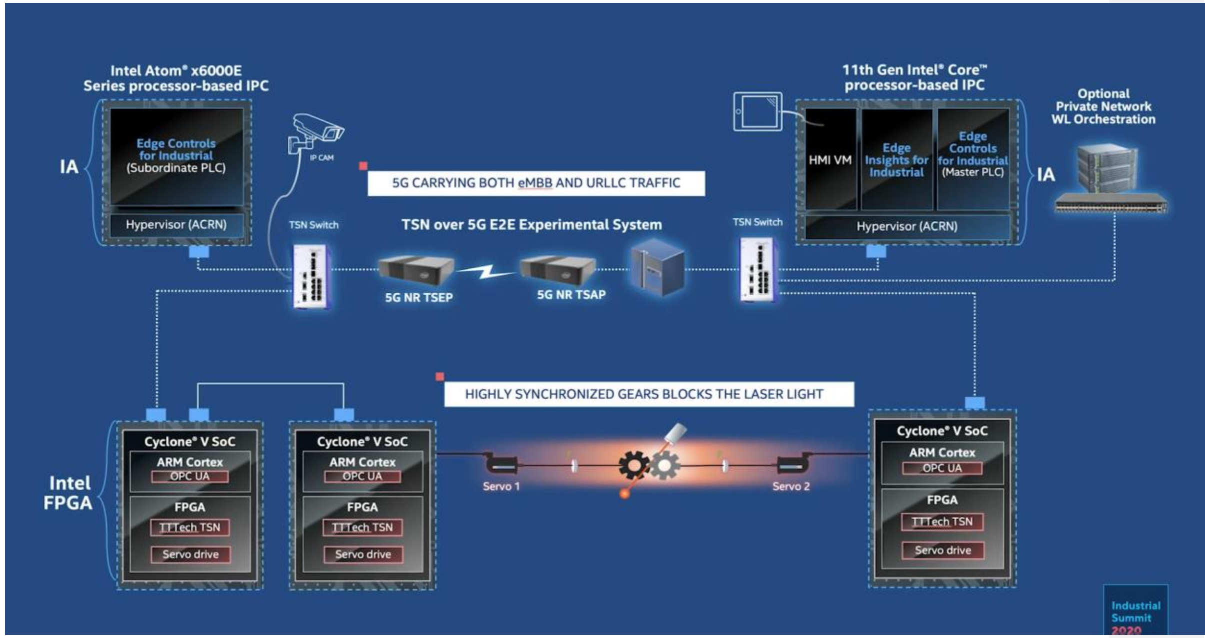
Time-aware scheduling across a 5G system



TSN over 5G Testbed

- 5G - Rel16: **NR SA, URLLC**
  - **5G + industrial application integration** with TSN bridges (802.1AS, 802.1Qbv)
- E2E KPIs achieved:

E2E KPIs		Max	Min	Avg	Reliability
TSN synchronization accuracy (ns)		300	2	13	N/A
TSN traffic latency (ms)	UL	3.57	3.40	3.53	99.999%
	DL	3.56	3.36	3.55	99.999%



Source: https://blogs.intel.com/iot/2020/07/22/shaping-the-future-of-the-industrial-iot-with-tsn-over-5g/#gs.u02a36

intel.

Looking beyond 5G

Growing need for determinism and TSN

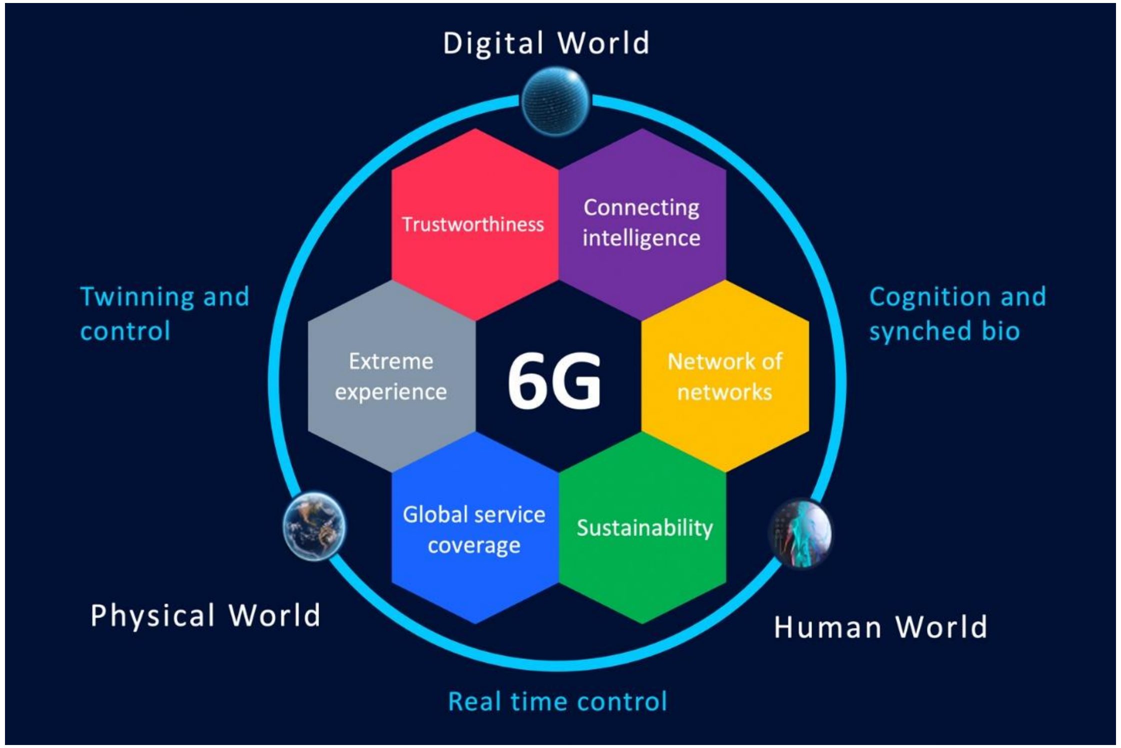
Digital – Physical experiences

Exponential growth for connected computing

Deterministic QoS

Autonomy

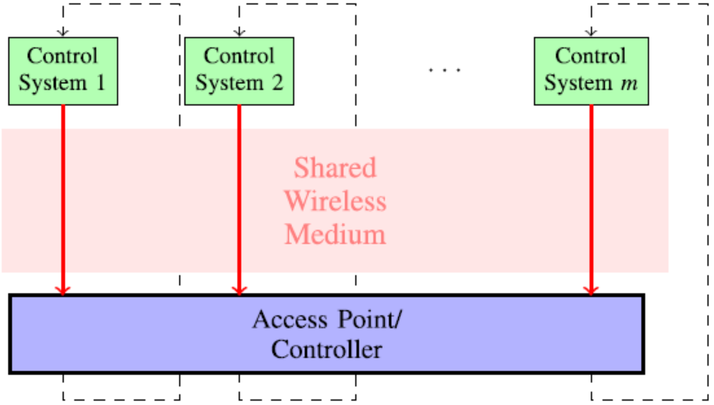
Sustainability and efficient

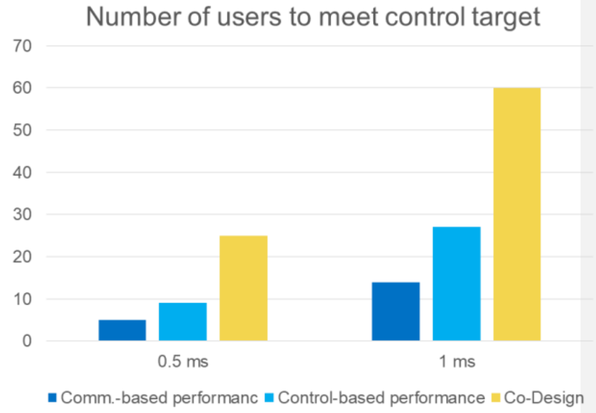


Source: https://hexa-x.eu/about/

Increasing Efficiency with Compute+Comms Co-design

- Control systems treat the "network" as ultra-reliable (wired) pipe
  - Thus, the expectation for "**wire-equivalent**" performance from wireless technologies
- What if, rather than trying to meet "wire-equivalent" latency and reliability, we look at **meeting control, or task specific goals** (e.g., stability, minimal drift, etc.)?
  - **Co-design: Optimize the resources utilization** in the wireless network **based on the state of the control system**
  - This enables the wireless network to support many more control loops compared to the traditional black box approach





[M. Eisen et al, Control Aware Radio Resource Allocation in Low Latency Wireless Control Systems, IEEE IOT Journal, Vol. 6, No. 5, Oct 2019]

Conclusions

- Advances in Wi-Fi and 5G are enabling the extension of TSN to wireless
- Deployment of wireless TSN technologies will be gradual (time synchronization and time-aware scheduling are the first step)
- It is important to enable wired-wireless TSN integration across multiple transport technologies (Ethernet, Wi-Fi and 5G)
- The need for determinism and TSN will grow in many application domains
- Wireless networks and TSN capabilities will evolve
- Complexity of the TSN toolbox is increasing and automation capabilities will be needed to address a more diverse set of applications