6G Programmable Deterministic Webinar Series

Wireless-aware TSN Configuration and Management

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PREDICT 6G

High demand for strict time & timeliness across many markets


Industrial/Robotics


Automotive


Power and energy


Immersive experiences

Time-Sensitive Networking





STANDARD
EDGE
NETWORKS

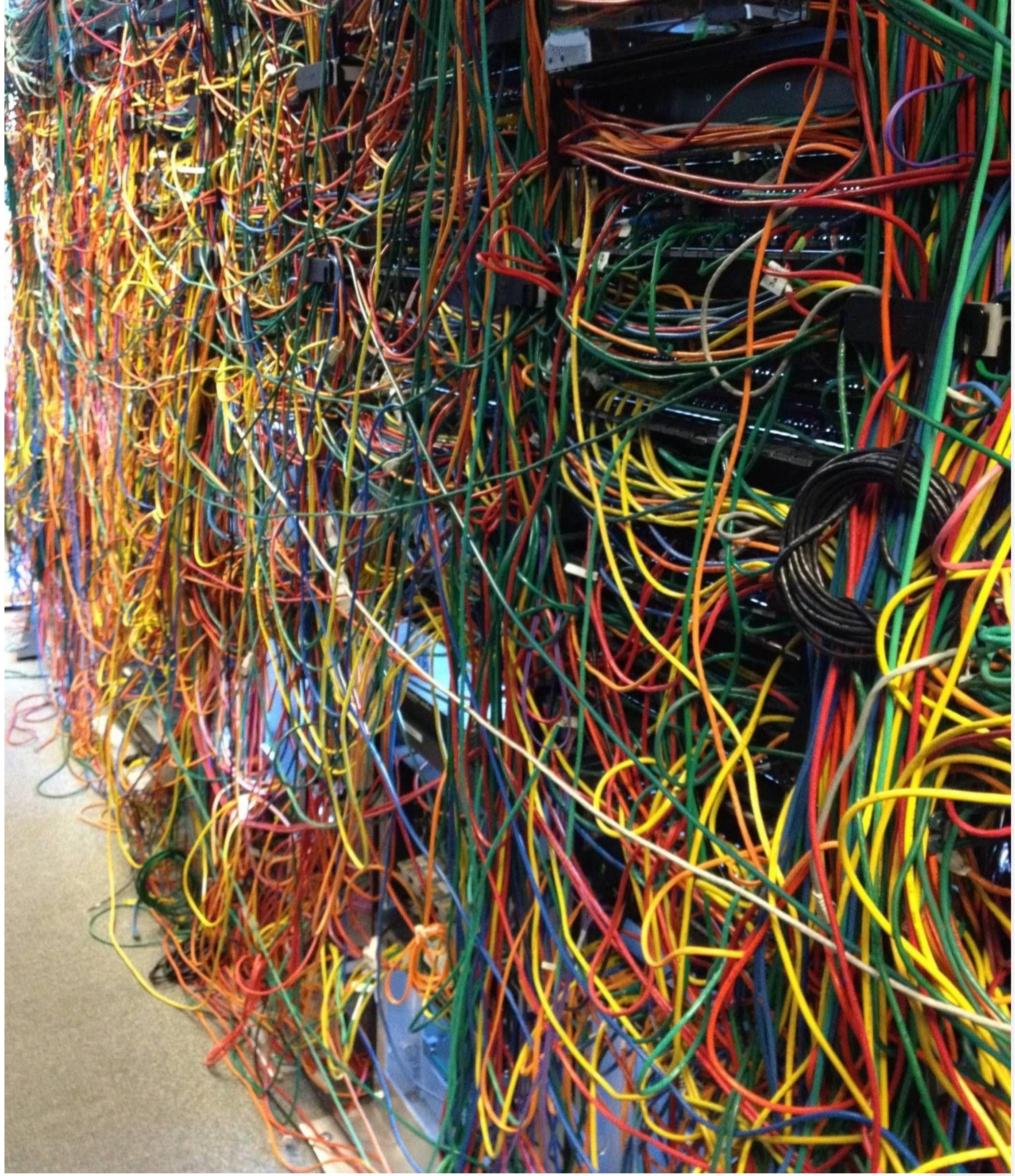
- Time Synchronization
- Latency
- Availability/ Reliability
- Resource Management

Enhancements to ***standard networking*** enabling *deterministic performance on convergence of networks* **supporting *mixed criticality* workloads**

Based on IEEE 802.1 TSN Specifications

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

Wireless has obvious benefits for many time-critical applications



Leading Wireless TSN Use-Cases and KPIs

Robotics & Automation

Extended Reality (XR)

	Mobile Robots	Closed loop Control	AR/VR
Typical area of service	Small/medium/large	Small/medium/large	Small/Medium
End stations per area of service	100	50	<5 devices/group
Traffic Profile	Cyclic and Event	Cyclic and Isochronous	Cyclic (UL), video (DL)
Time Synchronization Accuracy	~1 µsec	1 µsec or better	~1 µsec
Bounded Latency	10 – 1msec (cyclic) 100 – 10 msec (events)	10 – 1 ms (cyclic) 10 – 100 ms (events)	3 to 10 msec
Reliability	99.9 to 99.99%	99.9 to 99.9999%	99.9 to 99.99%
Security	Authentication, integrity and resilience to DOS/Interference	Auth., integrity and resilience to DOS and time/QoS attacks	Auth., integrity and resilience to DOS.

Source: Avnu Alliance White Paper "Wireless TSN: Market Expectations, Capabilities and Certification", https://avnu.org/wirelessTSN/

New Wireless Capabilities

Higher speed, lower latency, higher reliability

Wi-Fi 6/6E/7

Based on IEEE 802.11ax, 802.11be

2.4, 5, 6 GHz band operation (unlicensed)

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

MLO (Multi-link Operation) – Wi-Fi 7

5G

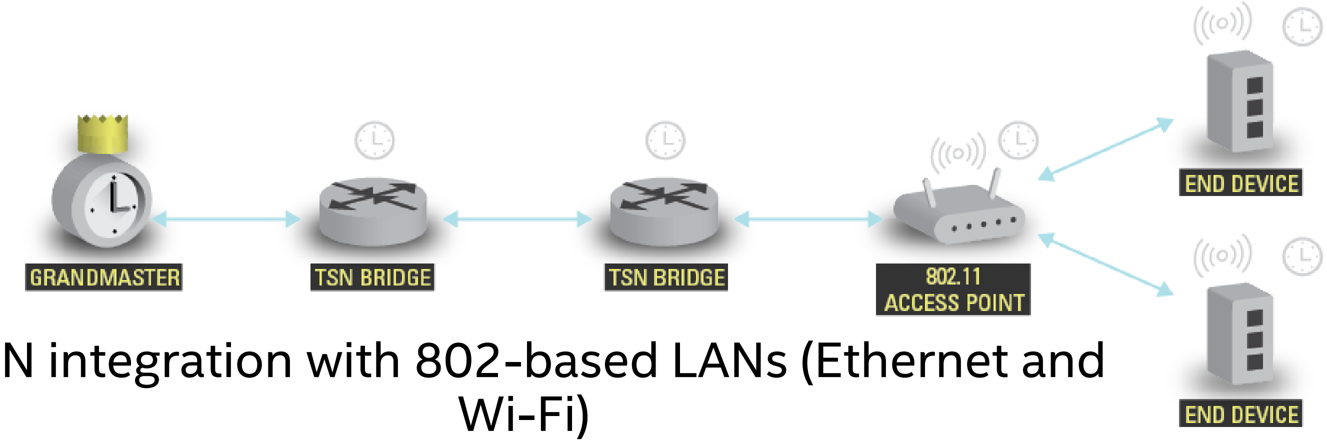
Based on 3GPP Rel 16

mmwave and <7 GHz* (licensed and unlicensed)

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

Ultra-Reliable Low Latency (URLLC)

Wireless TSN enabled by Wi-Fi and 5G

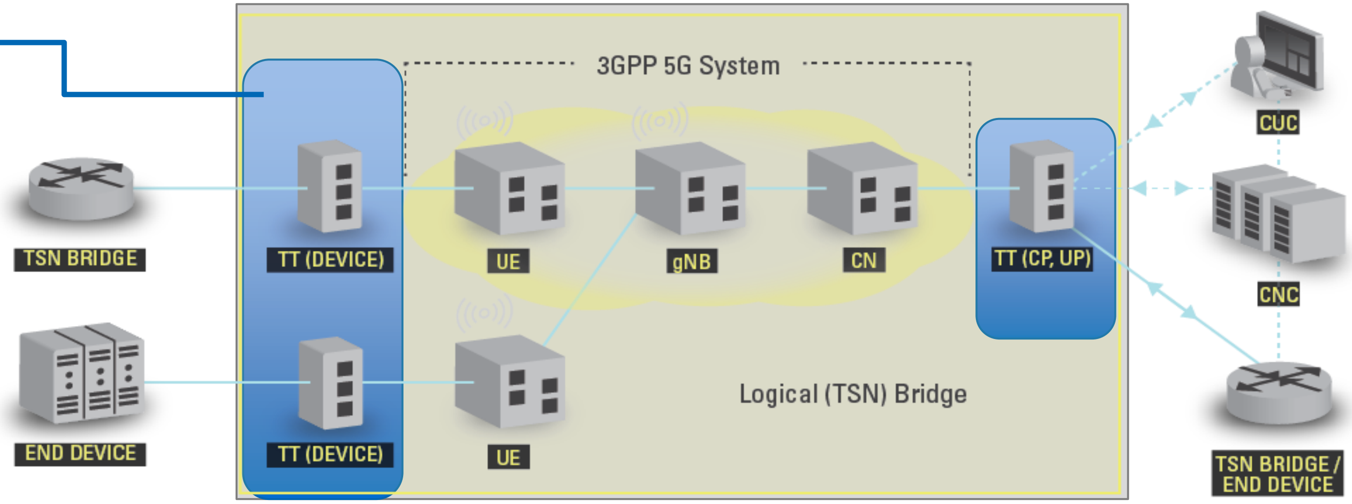


TSN integration with 802-based LANs (Ethernet and Wi-Fi)

- TSN capable 802.11 AP and Clients
- AP operates as a bridge between wired and wireless TSN

- **TSN Translators (TT)**: new 3GPP logical entities to enable TSN across a 5G System
- 5G elements do not implement IEEE 802.1 standards, but 5G leverages URLLC* capabilities to meet TSN QoS requirements

TSN integration via gateways



* Ultra-Reliable Low Latency Communications

Challenges for wireless TSN

Core Elements of TSN

TIME SYNCHRONIZATION

Time Synchronization

A distributed, precise sense of time between different computing systems (e.g., sensors, actuators, and controllers, etc.)

TRAFFIC SCHEDULING

Traffic Shaping

Based on precise timing, network infrastructure handles traffic (e.g., automation, control) in a timely manner

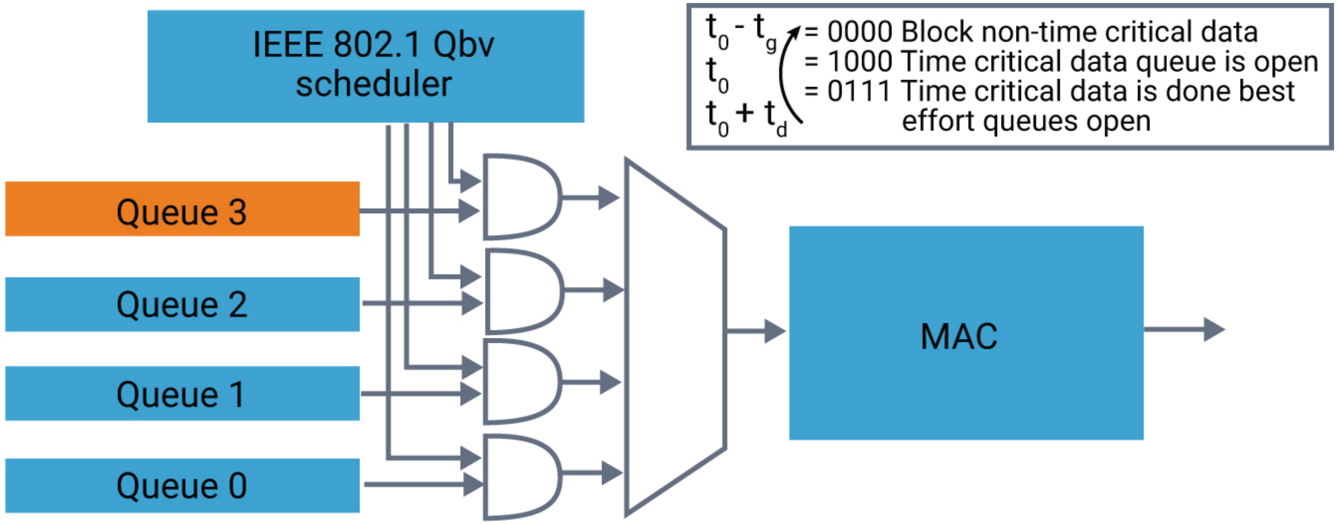
SYSTEM CONFIGURATION

Central Automated System Configuration

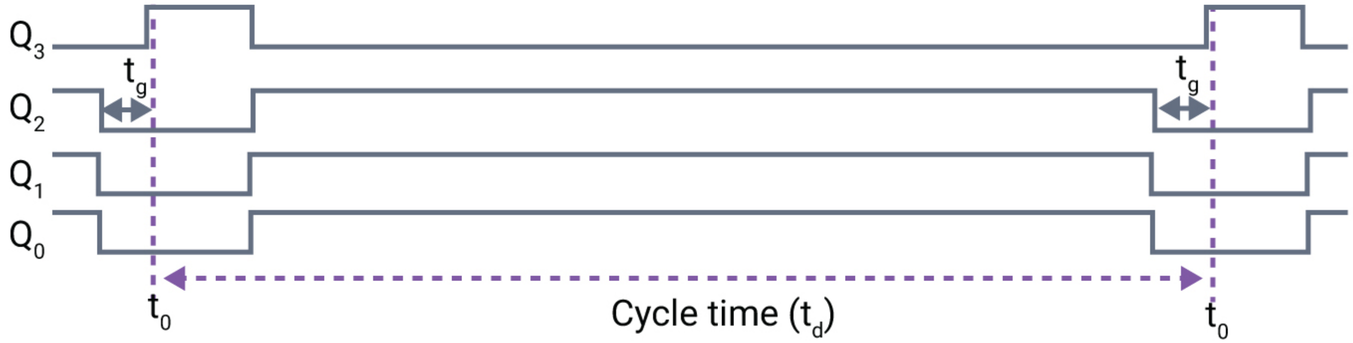
Distribute and configure devices as well as applications using SDN approaches

Enhancements for Scheduled Traffic (802.1Qbv)

- Multiple queues are controlled based on a **repeating schedule** (time, gate open/closed).
- Time reference is provided by 802.1AS

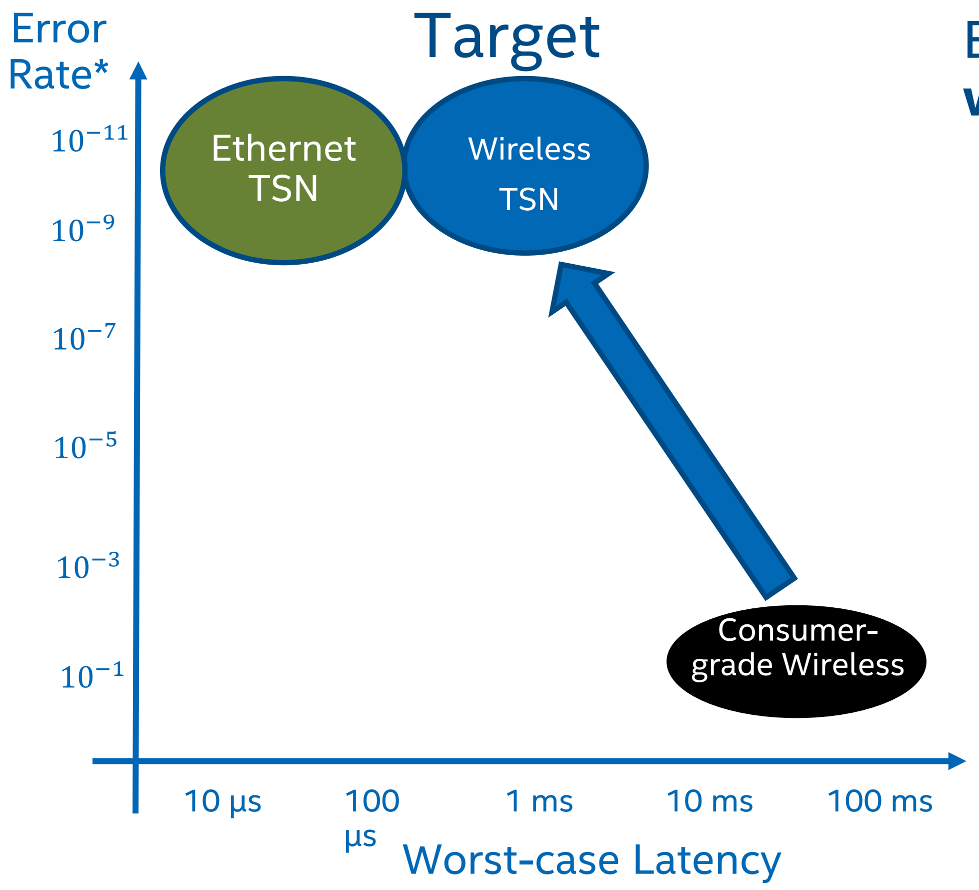


Protecting transmission time for scheduled time-critical traffic



Assumptions: Cycle time, Max data burst and link speed are known by the scheduler

Wired vs. Wireless TSN



* Packets lost or that miss the deadline

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

Wireless requires special considerations

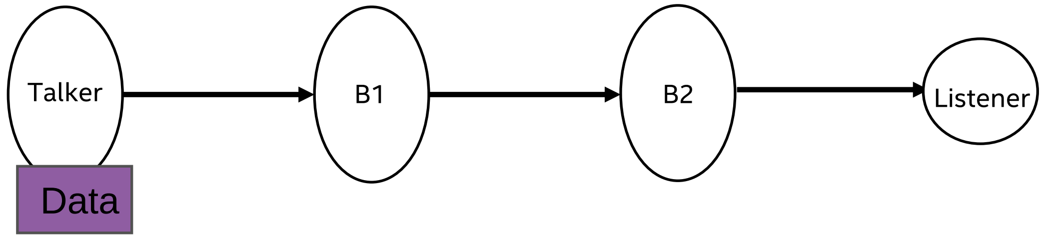
- Stochastic in nature (variable capacity)
- Time/frequency/space varying (shadowing, multipath, …)
- Harsh environment (obstructions, noise, interference)
- Typically, high error rate compared to wires
- Shared medium access can cause variable latency
- Mobility and Roaming overheads

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.

Challenges of dynamic Wireless links speed

Wired TSN

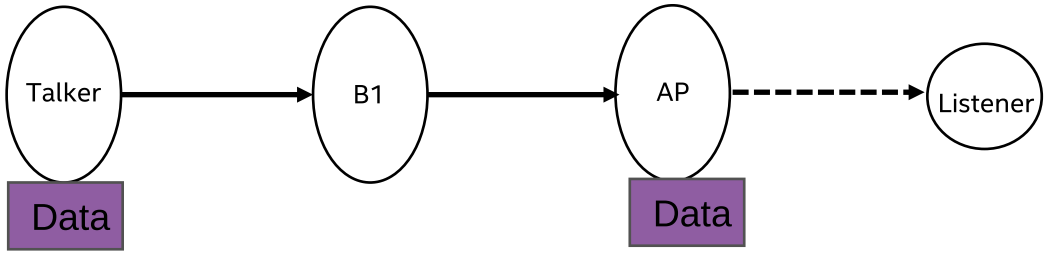
Wired – Constant Link Speed (e.g., 100 Mbps, 1 Gbps, …)



- Link speeds/bridge capabilities are static
- Schedule only changes when due to new flows/topology updates

Wired + Wireless TSN

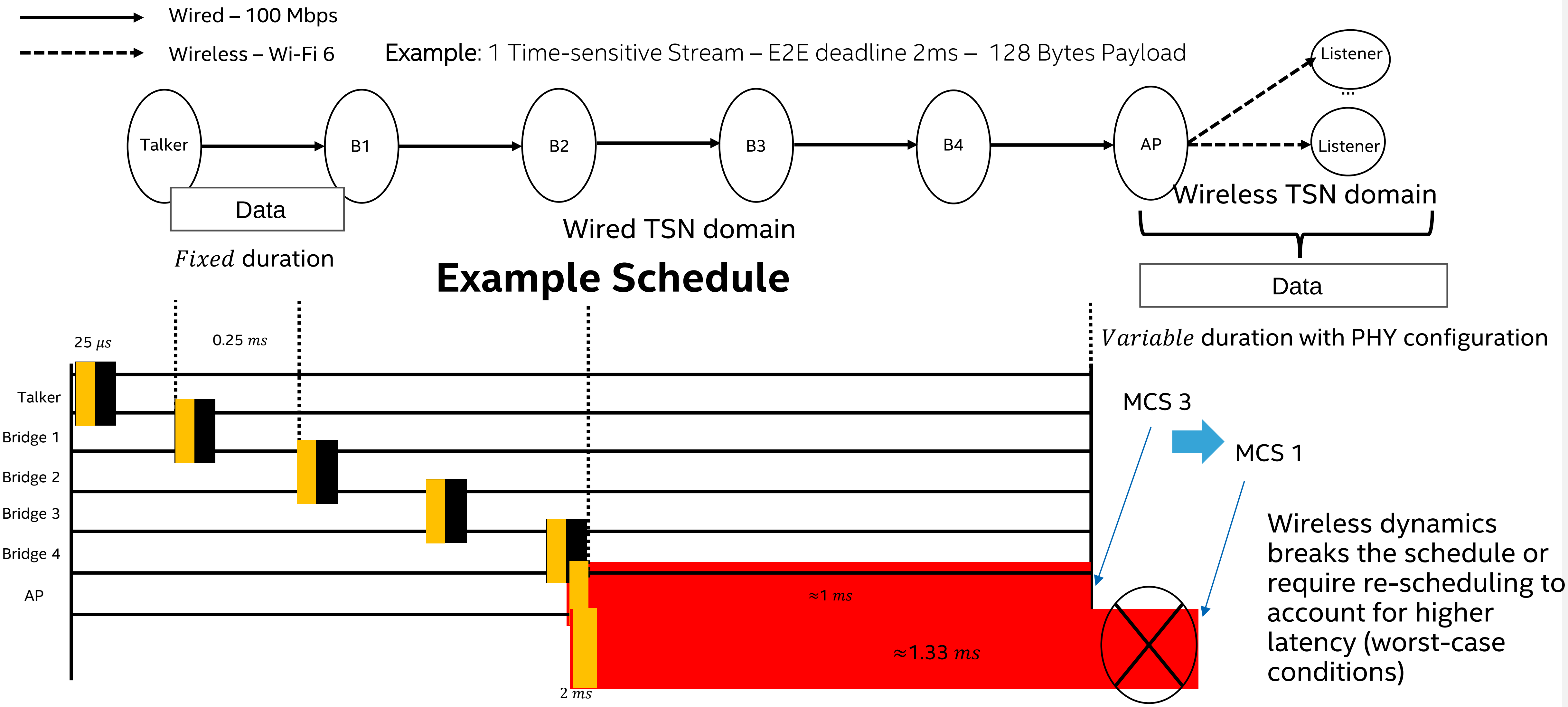
Wireless – Variable Ling Speed (e.g., function of power, noise, bandwidth, coding …)



- Link speeds and (wireless) bridge capabilities are **dynamic**

Variable and typically slower wireless speed can lead to longer end-to-end latencies or violations of KPIs

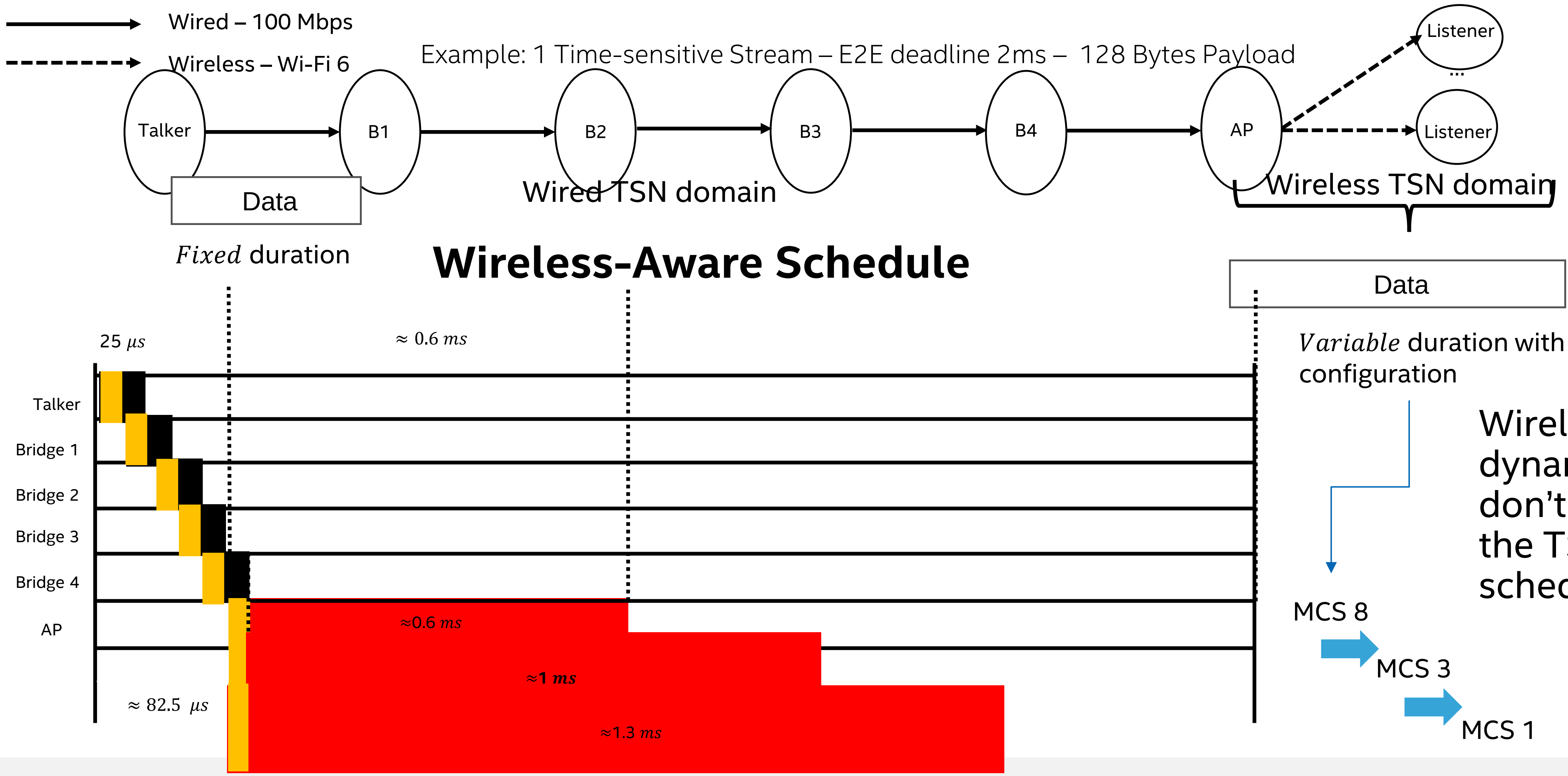
802.1Qbv Scheduling across wired and wireless TSN



Wireless dynamics breaks the schedule or require re-scheduling to account for higher latency (worst-case conditions)

MCS: Modulation and Coding Scheme

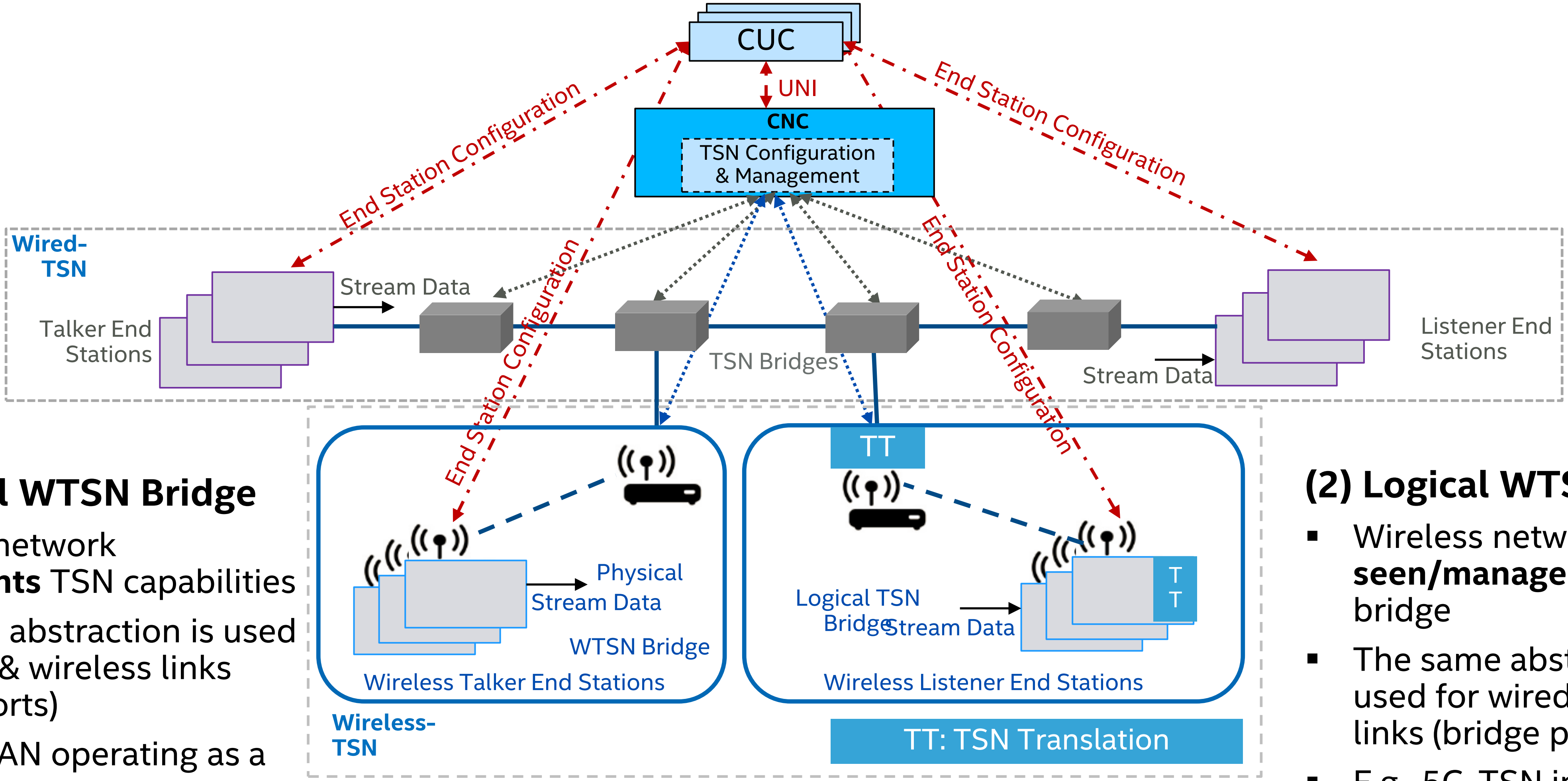
Wireless-Aware 802.1Qbv Scheduling



Wireless dynamics don't change the TSN schedule

Adapted from: Seewald et al, 802.1 TSN contribution

Typical TSN Configuration & Management Models



(1) Physical WTSN Bridge

- Wireless network **implements** TSN capabilities
- The same abstraction is used for wired & wireless links (bridge ports)
- E.g., a WLAN operating as a TSN bridge

(2) Logical WTSN Bridge

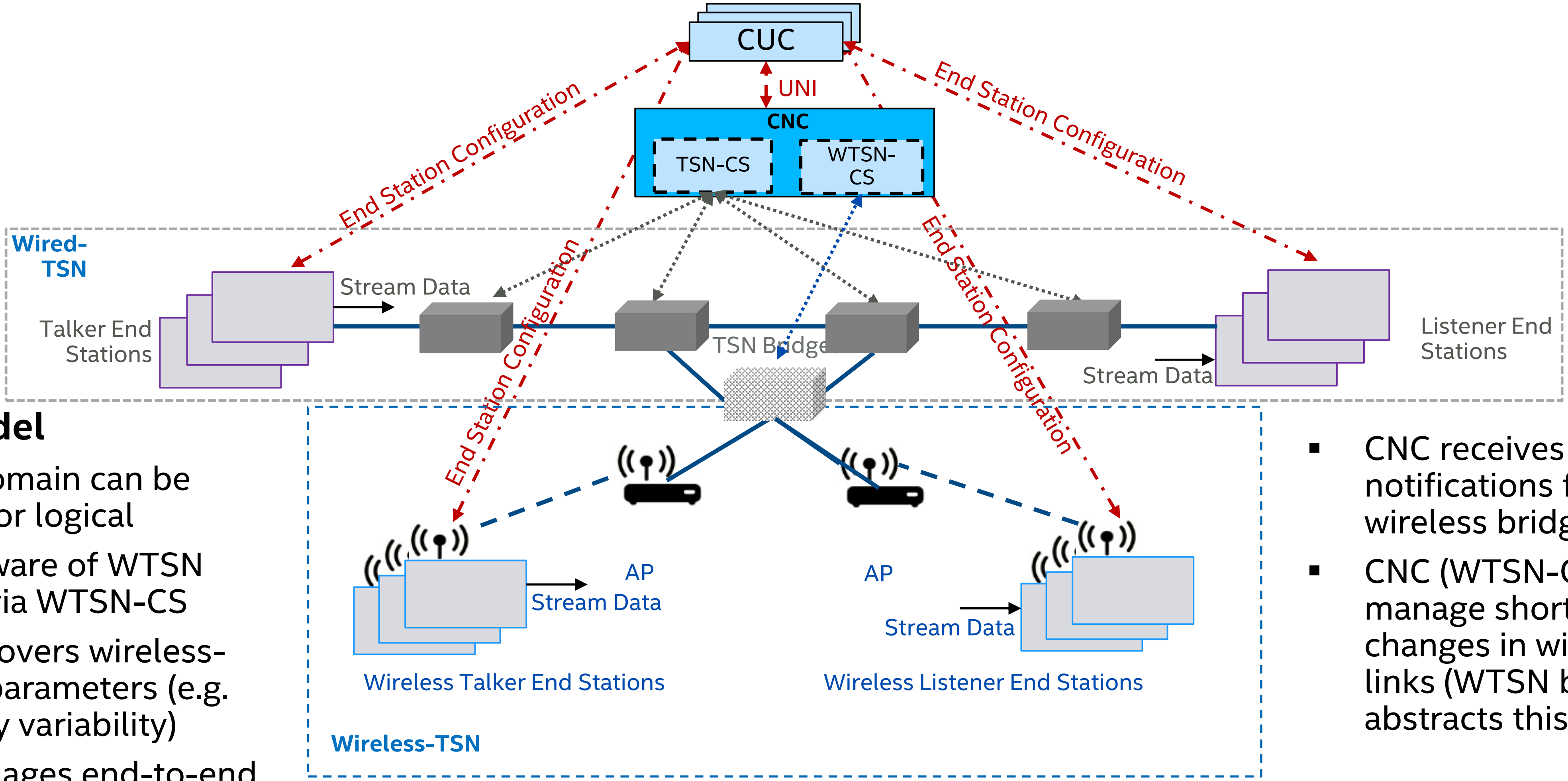
- Wireless network is **seen/managed** as a TSN bridge
- The same abstraction is used for wired & wireless links (bridge ports)
- E.g., 5G-TSN integration in Rel. 16

How to deal with wireless dynamics in 802.1Qbv scheduling?

- Do nothing (assume worst case always) – efficiency/capacity tradeoffs
- Enable E2E TSN configuration tools to be aware of the variability of (wireless) bridges/links

See proposals in IEEE 802.1 TSN Contribution:
Configuration Enhancements for Wireless TSN
- Maik G. Seewald, Malcolm Smith - Cisco
- Dave Cavalcanti, Juan Fang, Javier Perez-Ramirez – Intel
IEEE 802.1 Plenary Session, July 2021
https://www.ieee802.org/1/files/public/docs2021/dj-seewald-wireless-tsn-0721-v01.pdf

Wireless-aware TSN Configuration & Management



Hybrid Model

- WTSN domain can be physical or logical
- CNC is aware of WTSN domain via WTSN-CS
- CNC discovers wireless-specific parameters (e.g. LinkDelay variability)
- CNC manages end-to-end TSN resources

- CNC receives notifications from wireless bridge
- CNC (WTSN-CS) doesn't manage short-term changes in wireless links (WTSN bridge abstracts this aspect)

Adapted from: Seewald et al, 802.1 TSN contribution

LinkDelayVariability Descriptor

B0 B7	B8 B15	B16 B23	B24 B31	B32 B39	B40 B47	B48 B53		B54 B63
UpdateInterval	Delay0	Perc.0	Delay1	Perc.1	Delay2	Perc.2	…	Reserved

Field	Description
UpdateInterval	Minimal interval in msec for which the reported delay values are valid. If not updated, the descriptor is valid for another interval.
Delay0	Delay in msec
Perc0	Percentile for Delay0
Delay1	Delay in msec
Perc1	Percentile for Delay1
Delay2	Delay in msec
Perc2	Percentile for Delay2
…	…
Delay5	Delay in msec
Perc5	Percentile for Delay5

Adapted from: Seewald et al, 802.1 TSN contribution

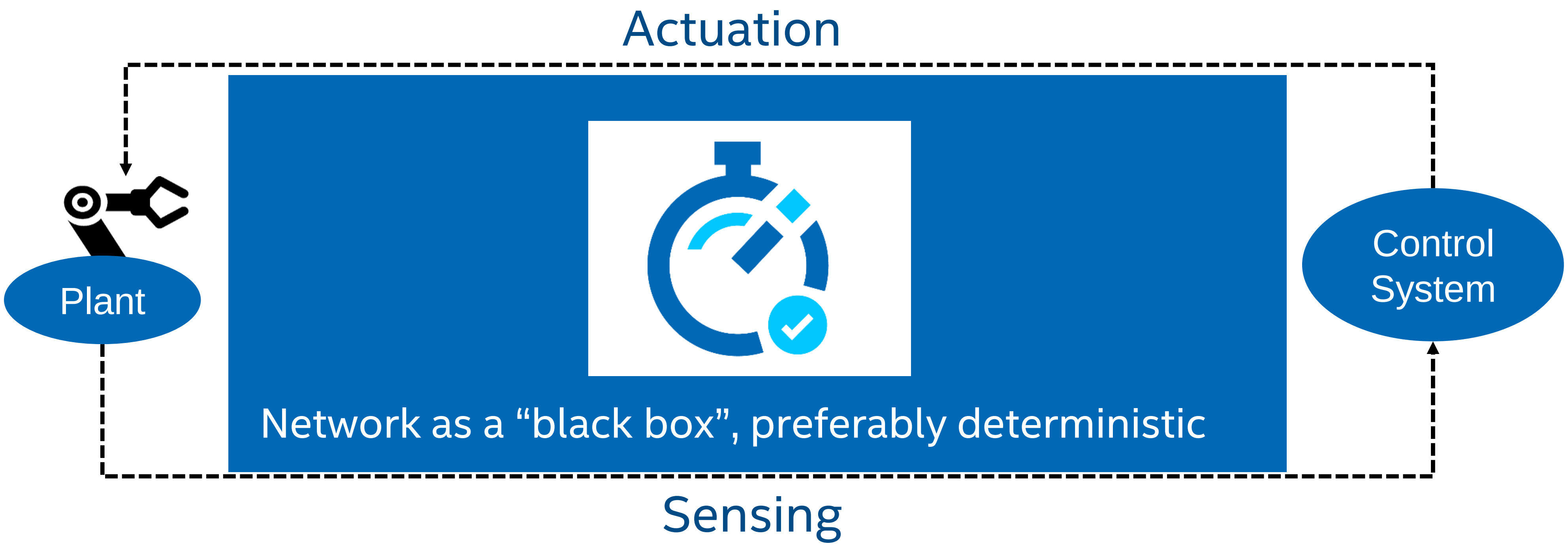
Benefits of being wireless-aware

CNC knows the WTSN dynamic range	Flexibility	Key E2E TSN Benefits
• Realistic range of MCS/data-rates can be used to report reasonable delay bounds to CNC • CNC scheduling can account for wireless variability (e.g., 99.9%-ile, 99.99% vs. 100%-ile worst-case)	• Designers can determine trade-off between necessity for gate re-computation vs. efficiency • Systemic degradation can still be accommodated (i.e. by exception)	• Gate over-runs (e.g. due to low speeds) mitigated via aggressive scheduling of upstream nodes • Overall latency can be reduced by using high-confidence 99%-ile delay bounds

Adapted from: Seewald et al, 802.1 TSN contribution

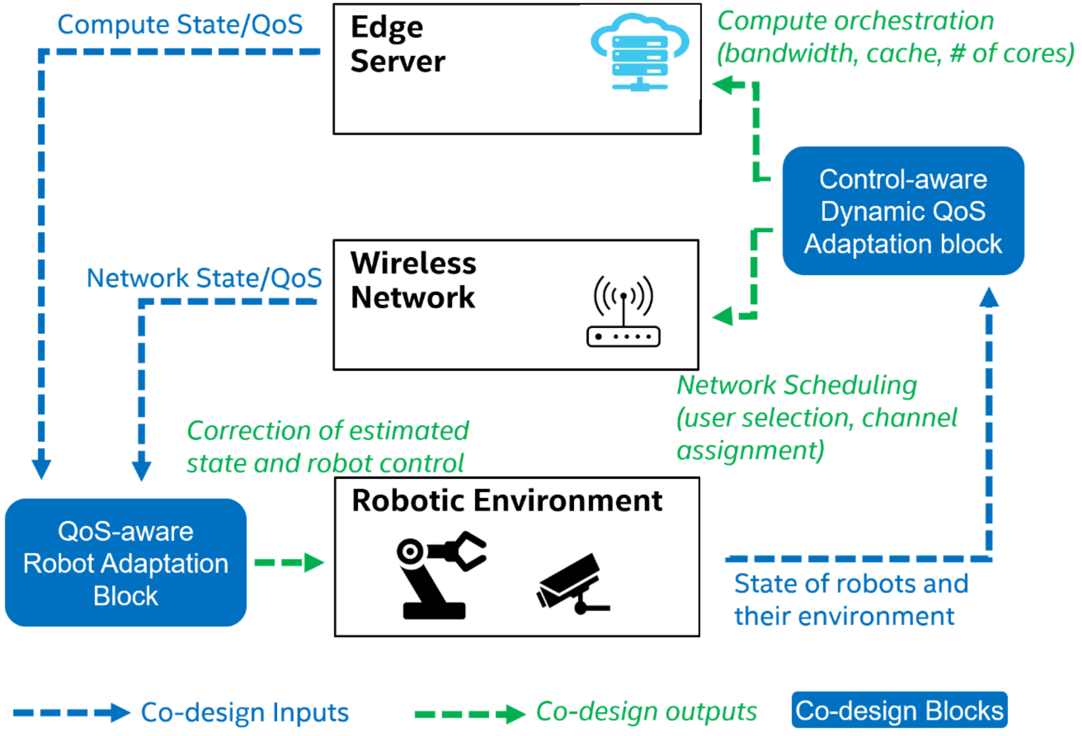
Control-Aware Network Management

Control systems treat the “network” as a (wired) pipe



What if, rather than trying to design a “deterministic” pipe, we look at **meeting control, or task/application specific goals** (e.g., stability, minimal drift, etc.)?

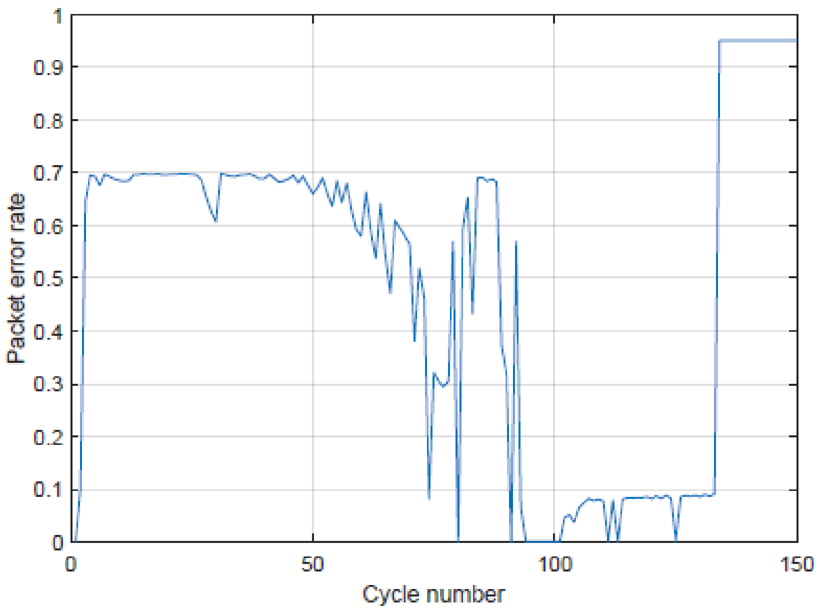
Communications-Control Co-design



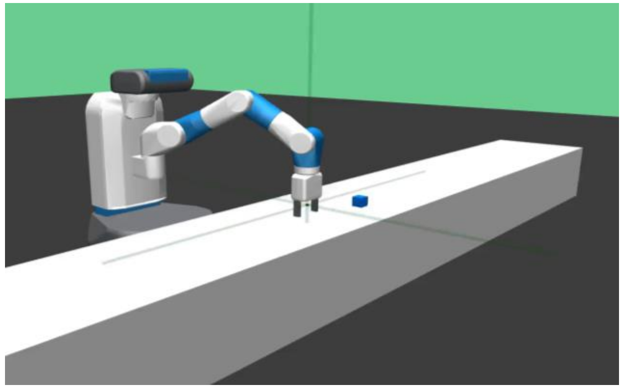
M. Eisen, et al, " Communication-Control Co-design in Wireless Edge Industrial Systems" , 2022 IEEE 18th International Conference on Factory Communication Systems (WFCS), pp. 1-8.

Dynamic Reliability in Wi-Fi 6 Scheduling

- Learned codesign policy for robotic pick and place task



Reliability over time in episode

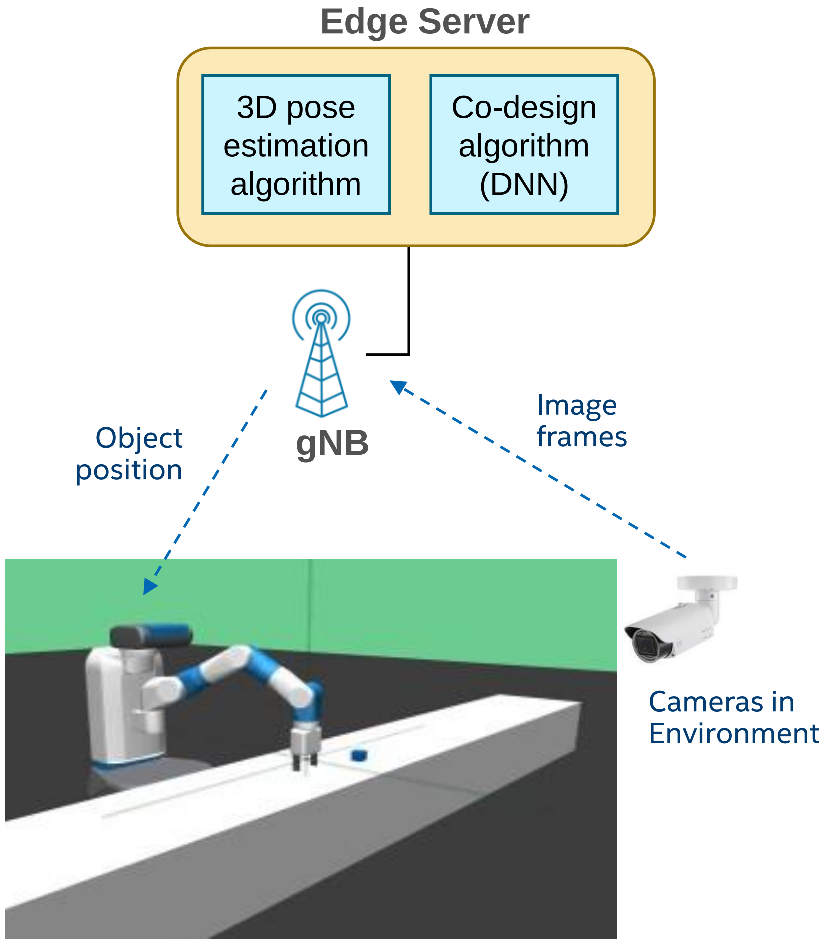


Conveyor belt robot

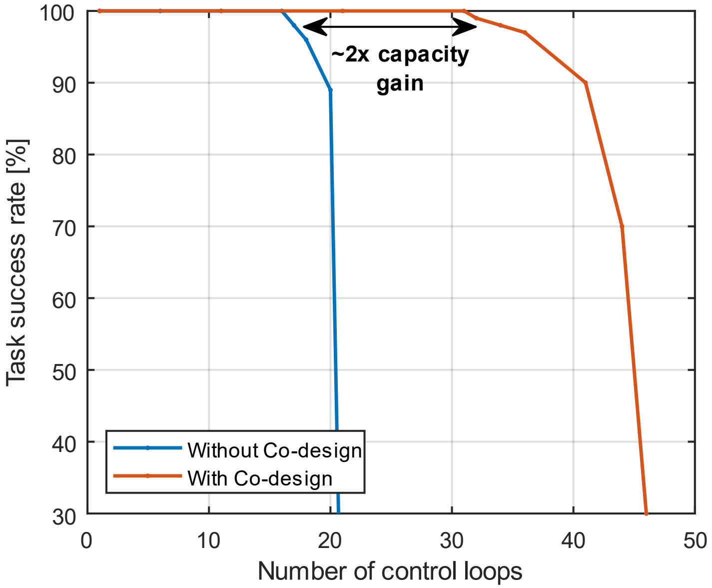
# systems	Dynamic reliability	Fixed reliability
8	97%	100%
10	95%	93%
12	95%	83%
14	88%	72%

[M. Eisen et al, Reliability Adaptation in Wireless Control with Reinforcement Learning, 54th Asilomar Conference on Signal, Systems, and Computers, Feb. 2020]

Dynamic Reliability (Co-design) for 5G



- In robotic manipulation use-case, a closed loop control system is formed over the 5G network.
- Co-design can improve the efficiency of 5G network by adapting the QoS in accordance with dynamics of the robotic control system.
- Co-design principle: adapt QoS depending on object's position



[A. Merwaday et al, Communication-Control Co-design for Robotic Manipulation in 5G Industrial IoT, IEEE INDIN 2023

Wireless-aware TSN configuration and management considerations

- Network planning and access control policies
- Spectrum
- Interference
- Variable link performance
- Consider Application & Network Co-design

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