# Extending Accurate Time Distribution and Timeliness Capabilities Over the Air to Enable Future Wireless Industrial Automation Systems

http://ieeexplore.ieee.org/document/8672474/

- Proceeding of IEEE.

**tags:** `Paper Study` `Communication` `Wi-Fi`

## Quick Summary

- Industrial Networks:
  - level categories: management level, cell level, field level
    - from (slow, large data) to (fast, small data)
  - realtime requirement categories: non-realtime, soft-realtime, hard-realtime
- Wireless standards in Industrial Networks:
  - 802.15.4 series(ZigBee)
  - Bluetooth
  - 802.11 series (Wi-Fi)
  - LPWAN(SigFox,LoRa)
  - Cellular network.(3G,4G,5G,NB-IOT…)
- IEEE 802.1 TSN:
  - handling time synchronization, control congestion, reliability communication.
  - mechanism:
    - Time synchronization
    - QoS control
    - Traffic identification
    - Network configurations
- TSN Challenge in Wireless communication
  - major different of wireless to wired communication
    - variable capacity, high per.
  - fundamental problem:
    - latency and jitter due to congestion
    - packet loss due to fading and collision
  - Wireless channel variety : capacity is dynamic
  - Large/Unreliable channel access latency:
    - LTE: grant protocol, random access
    - Wi-Fi: LBT protocol
    - Industrial requirements: ultra low latency and reliable communication
  - Interference and coex of different standards.

- New Approach To extend TSN to Wireless
  - Wireless Network Management by a single entity, devices implements a minimal set of features (CUC and CNC)
  - Time Synchronization for Wireless
    - 802.1as PTP over 802.11: TM/FTM(resolution to x00 us)
    - New Area for 5G.
  - Time-Aware Scheduling by synchronize to a common clock, control channel queue globally to control collision.(802.1Qbv)
  - Wireless link reliability:
    - power control to handle interference,
    - time-frequency resource management to optimize overall capacity and provide reliable transmission
    - spatial diversity and Beamforming to enhance link quality.
    - new waveform design: reduce out-band emissions, reduce overhead of short packets(typical in industrial traffic)
    - adaptive MCS selection with feedback csi.
    - redundant channels for better reliability.
- Next Generation Standard capability for TSN enhancement
  - 802.11ax :
    - scheduled access and multi-user ofdma,
    - 2M RU enhance link quality 8dB vs 11ac,
    - OFDMA-MU-diversity,
    - flexible GI(handling outdooor channel),
    - new 6G band to legacy standard interface-free and scheduled channel access.
    - Target wake time(TWT) for power saving and sub-groupping of devices for better resource management.
  - 5G URLLC:
    - low latency frame structure
      - slot time to 0.125ms
      - fast dl/ul switching and HARQ interval
      - self-contained data/ack in a sub-frame.
    - physical enhance: support LDPC and URLLC
    - low latency signaling: DMRS
    - Architecture enhancement: CRAN and SDN, edge comupting
  - Industrial Wireless Network Applications categories:
    - Class A: supports current tech with enhanced features in 11ax/5G
    - Class B: Soft-time-sensitive(AR/VR,HMI,) and selective hard-time-sensitive(controller)
    - Class C: Hard realtime controllers with very low cycle times, ex. 802.11be EHT

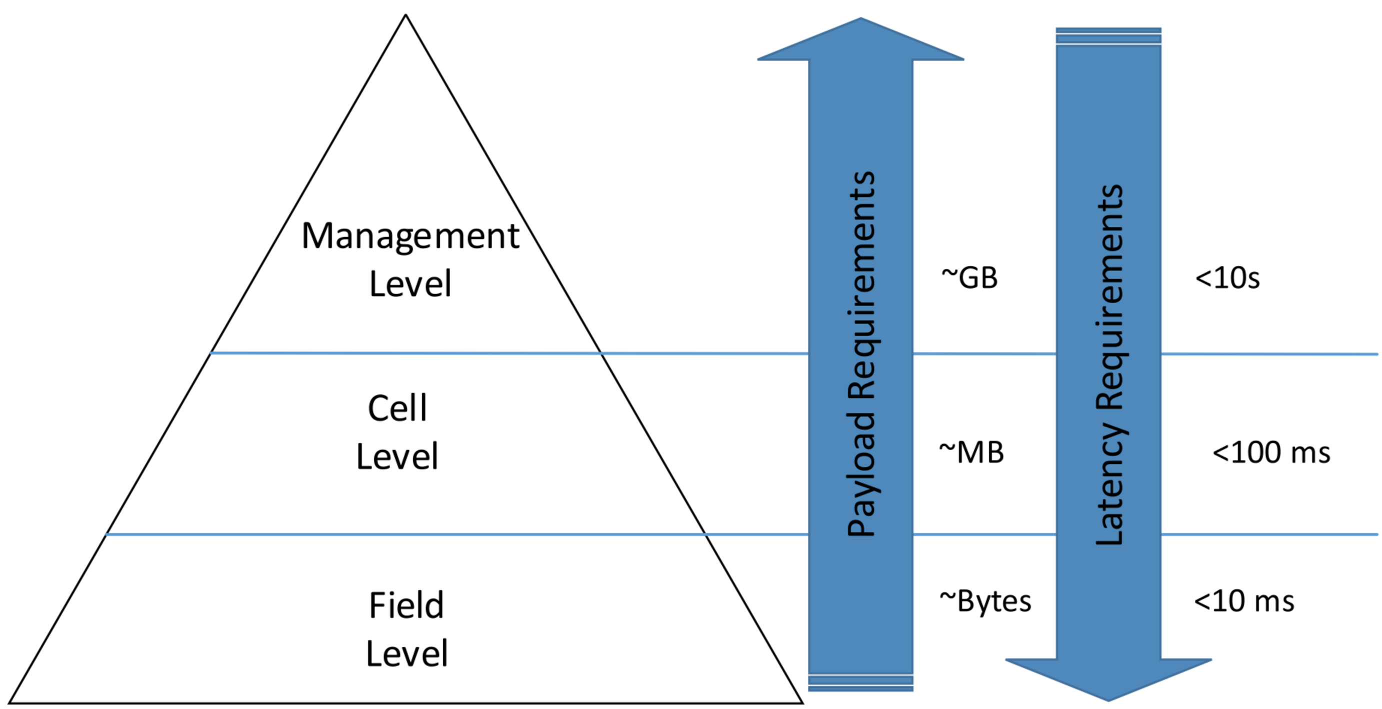
# INTRODUCTION

- New industrial applications require the **time coordinated computing** and **communications** over **wireless** links
  - Ex. AVG/MR
- Some application requires
  - Precise synchronization to a reference time down to **nanoseconds accuracy**

    - Deterministic (bounded) end-to-end latency
        - in us to ms level
    - Extremely low packet loss probability
    - Coverage of time critical and noncritical traffic in the same network.
- IEEE 802.1 TSN Task Group develops standards to enable time synchronization, bounded latency, redundancy, preemption.

# STATE-OF-THE-ART COMMUNICATIONS AND NETWORKING FOR INDUSTRIAL AUTOMATION

## Industrial Networks




- **Field Level**
    - communication among **sensor**, **actuators**, and **controllers**
    - typically has the most stringent **latency** and **reliability** requirements
    - Throughput requirements relatively low
    - extremely short cycle times (in the order of microseconds) and low jitter
        - PROFINET, EtherCAT, and SERCOS III
    - IEC 61784 International Standard
- **Cell Level**
    - mostly communications between PLCs(Programmable Logic Controller) and between PLCs and industrial PCs
    - require time synchronization and various levels of real-time guarantees
    - relax performance

    - served by IP-based communication over Ethernet
- **Management Level**
    - typical IT infrastructure
    - Flexible data exchange within industrial systems
    - IT/OT(operation process) convergence
    - reuse of IT Technology in operation process
    - cost savings
    - flexibility expected from future industrial networks in supporting a variety of applications
- Category of real-time requirements
    - **Non real-time**:
    - **Soft real-time**: realtime iter-action between devices and/or human
        - require low latency
        - not necessary tight time sync
        - tolerate some missed deadlines
    - **Hard realtime**: require **accurate** synchronization and timeliness (**bounded latency**)
        - isochronous
        - mainly at the field and cell levels.
        - Wireless networks have been used primarily in non-real-time applications and in a few soft real-time applications

## Wireless Netweorks in Industrial Environments

- the deployment of wireless technologies is only at its infancy (無線技術的部署還處於起步階段)
    - **AI** application and movement to ensure **flexible data access** driving deployment of wireless technologies.
- **IEEE 802.15.4**:
    - several PHY modes for operation in the 2.4-GHz and sub-GHz (868/916 MHz) unlicensed bands
    - also several MAC layer modes
    - CSMA-based communication: device sensing channel before transmission, back-off when busy
    - data rate up-to 250Kbps for 2-M BW in 2.4G
    - **ZigBee**
        - ZigBee defines networking and transport protocol of 802.15.4.
        - non-realtime application
    - **802.15.4g**: New PHY for long range and higher data rate.
- **IEEE 802.15.4e**:
    - TSCH(Time-Synchronized Channel Hopping) access
    - High reliability and power-saving
    - Enable **low power consumption** with better control of **latency** compared to CSMA protocols
    - can be used across a mesh network
    - TSCH mode may also be used with the more recent 802.15.4g mode
    - 6TiSCH: define an IPv6 compatible layer to enable configuration and exchange of schedules in a TSCH network

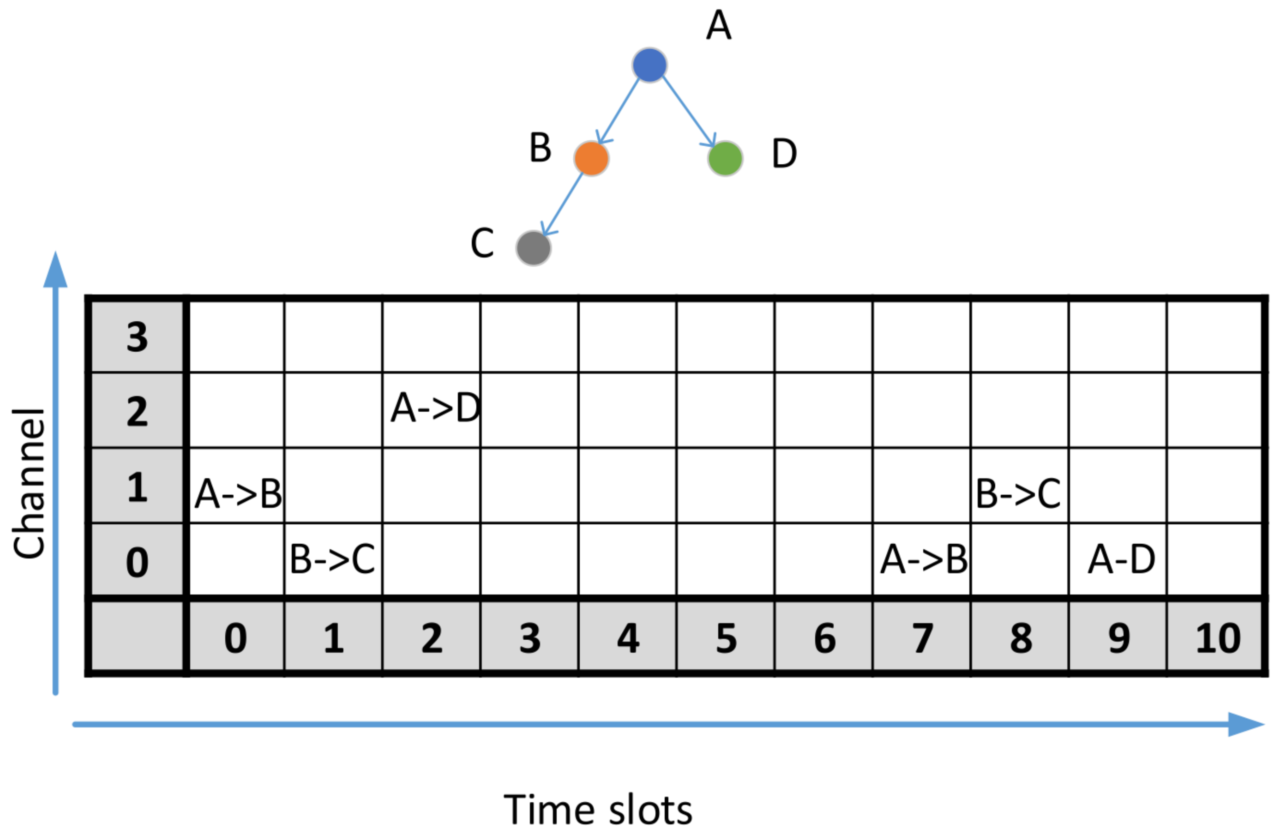



**Fig. 2.** ***TSCH operation and mesh example.***

- **Bluetooth**:
  - local connectivity between phones and other consumer devices operating in the 2.4-GHz band
  - a frequency hopping PHY
  - BT1.2: 1Mbps, BT2.0: EDR, BT3.0: high speed, BT4.0: BLE, for low power
  - Add mesh capability
  - play a role in many HMI(human machine interface) and wearable applications in industrial environments
  - mesh capability enable sensor network application.
- **IEEE 802.11 Wi-Fi**
  - consumer, enterprise, and industrial markets, mainly for general IT connectivity
  - a, b, g, n, and ac from 2007
  - currently mainly 11n/11ac for OFDM and MIMO capability to very high data rate.
  - 11ax next major release: enable multi-user transmission simultaneously.
  - MAC:
    - Based on CSMA
    - Enhanced QoS: enables traffic prioritization through four main access categories(voice, video, best-effort and backgroud)
    - Contention free polling-based options(PCF,HCCA), but not supported in practice for mainstream Wi-Fi provider
  - been used in industrial applications.
  - has great potential to enable fast IT/OT convergence and flexibility in the manufacturing processes.
- **Cellular Technologies**:
  - machine-to-machine communications
  - have been used mainly in industrial systems

    - GPRS, 3G, LTE-m, NB-IOT
    - Goal to reduce power consumption and cost. but not provide realtime performance.
- **LPWAN**:
    - Sub1g communication
    - SigFox/LORA
    - very low throughput over wide areas without hard latency and reliability requirements (mostly normal time)

## IEEE 802.1 TSN

- Enable time synchronization, control congestion, and packet loss due to media or device failure
    - mainly assuming **Ethernet** as layer 2 transport
- subset of TSN standard and capability

**Table 1** IEEE 802.1 TSN Standards

| IEEE Standard | Capability |
|---|---|
| 1588, 802.1AS | Time synchronization |
| 802.1Qca | Path control and reservation |
| 802.1Qbv | Time-aware scheduling |
| 802.1Qbu and 802.3br | Frame preemption |
| 802.1Qcc | Central configuration model |
| 802.1Qci | Filtering and policing |
| 802.1CB | Redundancy (frame replication and elimination) |

- TSN mechanism
    - Time Synchronization:
        - 802.1AS: PTP defined by IEEE 1588 to enable **precise time synchronization** across the network
    - QoS Provisioning(供應):
        - 802.1Qbv: define a global time-aware schedule to control congestion and provide deterministic latency.
        - 802.1Qbu and 802.3br: to reduce latency for high priority frames.
        - 802.1CB: introduce redundancy through frame duplication and elimination to reduce impact of packet loss
          frame duplication and elimination
    - Traffic Identification: TSN devices must differentiate **time-sensitive** streams from other flows
        - 802.1Q: identify and differentiate time-sensitive types from other types of traffic,
            - VLAN tag field
            - traffic classes: eight traffic classes per Ethernet port, each associated to a dedicate queue
    - Network Configuration:

    - 802.1Qcc and 802.1Qca: CNC model and stream reservation capabilities
    - 802.1Qci: policing and filtering mechanisms to ensure nodes follow the configured schedules and avoid malicious behavior.

# CHALLENGES FOR WIRELESS TSN

- Two fundamental problems:
  - latency and jitter caused by network congestion
  - packet losses
- Wired link
  - constant capacity and
  - extremely low packet error rate
  - bandwidth reservation can guarantees latency/jitter
  - preemption avoid interference from best effort traffic
  - redundancy path reduce loss from HW.
- Two fundamental different of Wireless media to Wired
  - Variable capability
  - Typically high per
  - Make challenges in providing deterministic latency and reliability guarantees expected by time-sensitive applications.

## Wireless Channel Variations

- Wireless channel capability is dynamic.(from fading, interference, ranges…)
- high capacity and bounded latency is not always possible.
- Understand Channel behavior is key to access achievable latency, reliability and capability
- 11n/11ac: TGN-channel model for indoor and statistic outdoor
- 11ax: ITU-R channel and Doppler fading.
- Channel models are generic enough to statistically represent a plethora of propagation environments
- Ray-tracing tool for analysis of the well-defined environments,
  - providing coverage maps
  - fading statistic
  - power-delay profiles
  - rms delay
  - coherence bandwidth…

## Channel Access Latency

- major source of latency in LTE:
  - grant acquisition
  - random access procedures
- major latency source in WiFi:
  - listen-before-talk (LBT) channel
  - increasing access delay when increasing of devices.

    - randomness of LBT protocol is the key issue for hard realtime application.
- Need to support ultra-low-latency service with deterministic access to medium and low-jitter
- Multiple-access technologies:
    - FDMA,TDMA,CDMA,OFDMA,SDMA,NOVA
        - OFDMA + SDMA has been adopted in current cellular and Wi-Fi
        - NOMA: non-orthogonal multiple access
            - new approach, but receiver need to perform successive cancellation.
            - not been adopted in major wireless standards
    - Multichannel access strategies
        - the device to access multiple channels and initiate multiple data transmissions independently
        - need multiple radios to sense and contend for access simultaneously in multiple channels

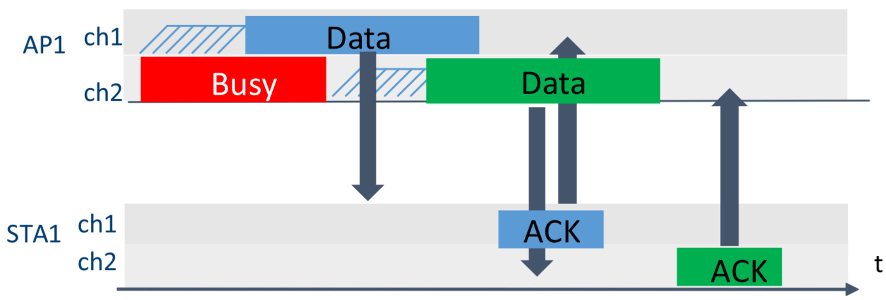



**Fig. 4.** ***Multichannel access.***

    - Latency-specific optimizations should consider the unique and dynamic characteristics of wireless channels and links.

## Centralized Coordination and Scheduling

- hard to control latency through distributed random access, especially under congestion
- Need centralized coordination of medium access
    - 3GPP: NodeB/eNodeB/gNodeB
    - Wi-Fi: traffics is scheduled by AP, scheduling becomes important in 11ax OFDMA.
- (New) scheduling algorithm need to consider
    - throughput, fairness, and plus stringent **latency** and **reliability**.
- Distribute schedule information to devices
    - 3GPP: devices are assigned deterministic access opportunities once admitted
    - Wi-Fi: transmitted by the AP before every transmission opportunity

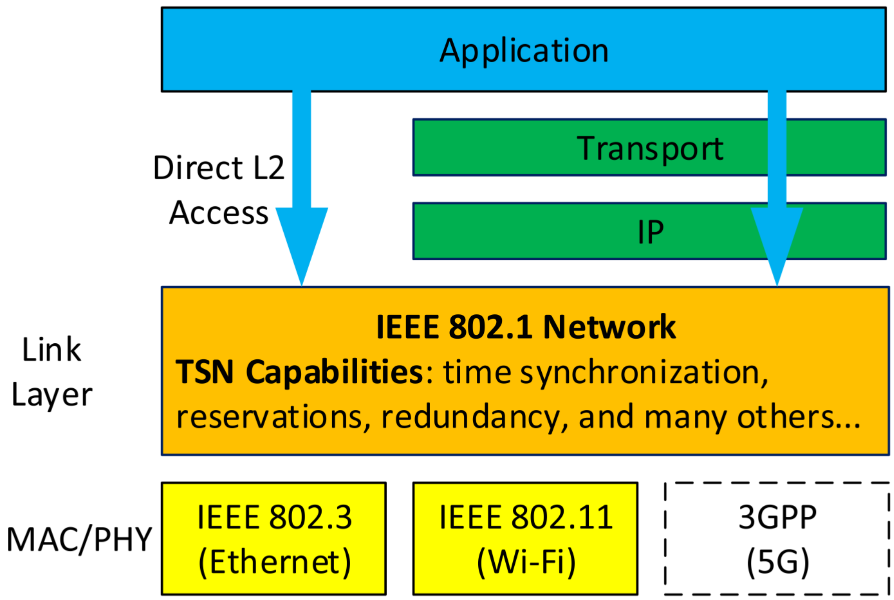
## Interference and Coexistence

- Not problem in Wired communication.
- More challenge in requirements of both TSN and non-TSN traffic in a converged network.
- Non-time-sensitive traffic: multiple retransmission to ensure payload delivery
- Opportunity retransmission is limited in hard-real-time traffic.
- Interference sources:
    - other kind devices(protocol) in the same channel band.
    - self-interference due to schedule conflict

    - RF emissions: microwave ovens, electrical machinery, welding arches, power plants, callings
        - dominantly contained in the sub1G band, and may have little or no effect in higher bands (2.4G,5G)
        - RelCovAir project: Real experiments in industrial environments

# NEW APPROACHES TO EXTEND TSN CONCEPTS TO WIRELESS

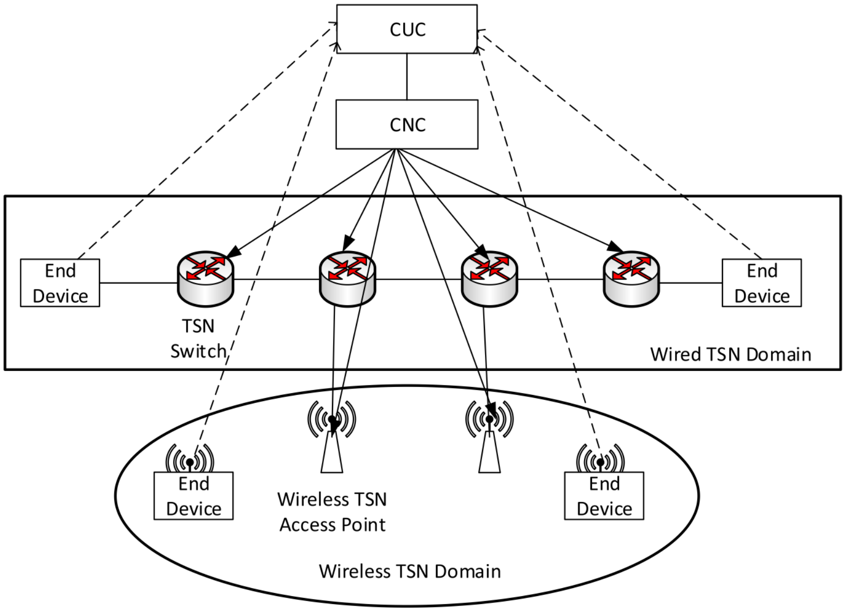
- Reference protocol stack




- 802.3 major supported
- 802.11 supports some capability: time synchronization
- ongoing standards
    - 802.11 extends TSN capability
    - 3GPP to introduce TSN on next generation standards

## Wireless Network Management Model

- wireless network should be managed by a single entity
- All devices can implement a minimal set of required features (CUC and CNC)
    - CUC: collects information about the critical traffic streams
    - CNC: uses this information to perform admission control, define/deployment resource allocation strategies to meet time-sensitive applications
    - Wireless devices and APs should be configured by the same CUC and CNC entities
- Infrastructure and end devices support interoperable methods and protocols

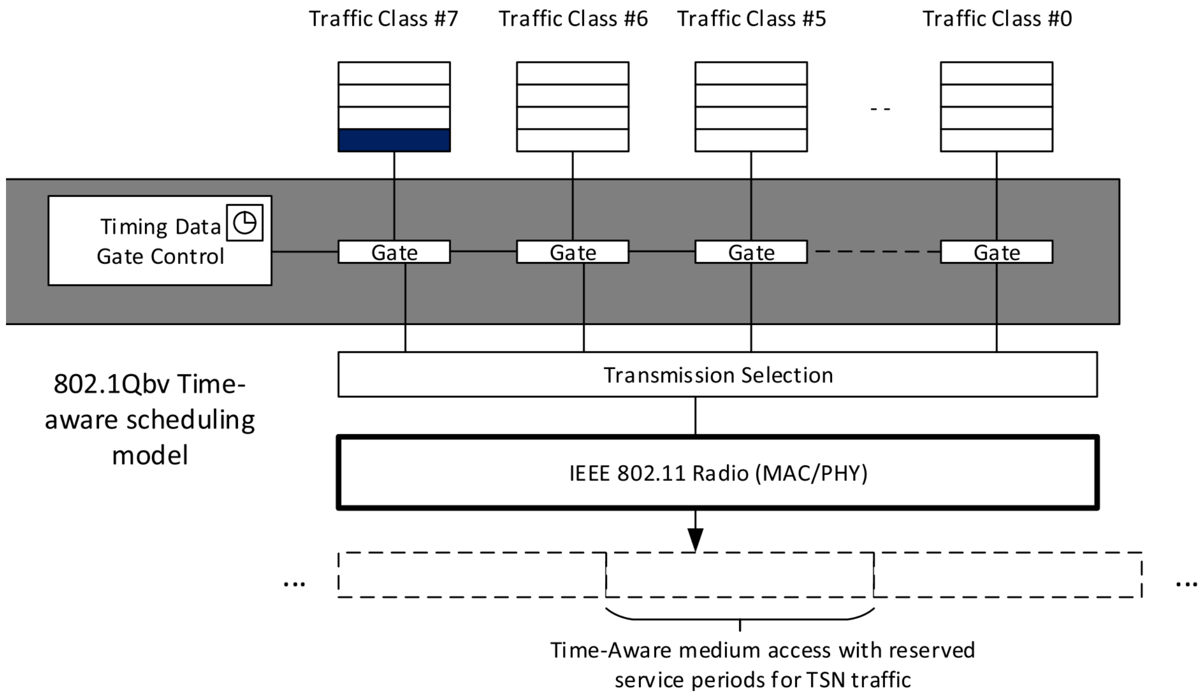



## Wireless Time Synchronization

- 802.1as define PTP over 802.11
  - time measurement capability in 802.11-2012
  - Fine time measurement capabilities (~ x00ns)
- 3GPP: no synchronizing the radio and applications to the same clock
  - new area in 5G URLLC

## Time-Aware Scheduling

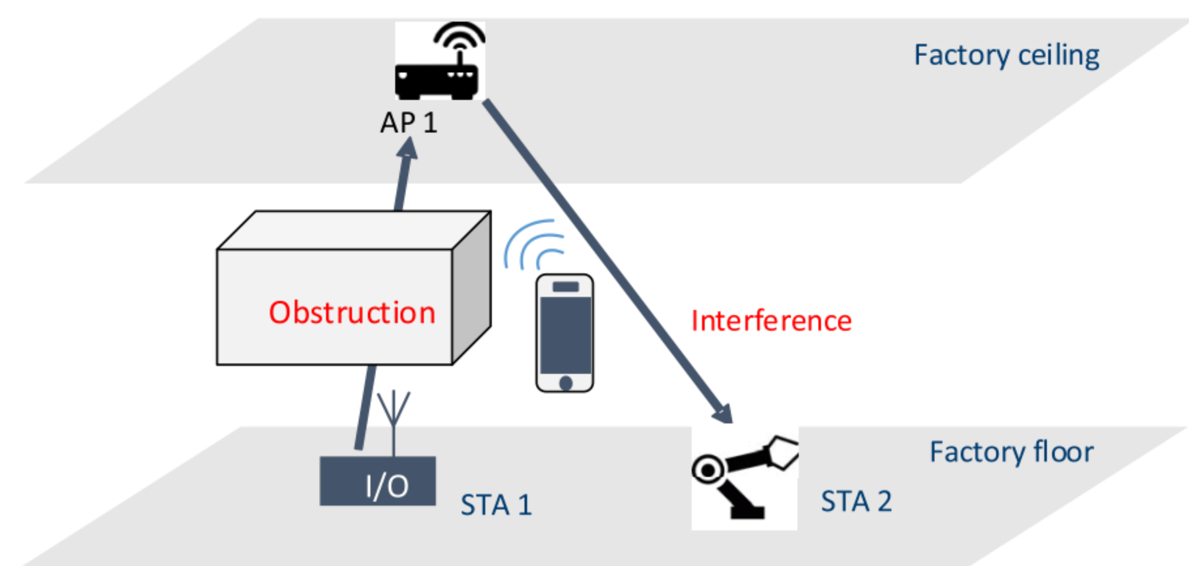
- 802.1Qbv time-aware scheduling: gates synchronized to a common reference clock
  - control queue process (opening/closing) by sharing a common egress(出口) port within an Ethernet switch
  - global scheduler define time to open/close the queue to eliminate congestions and make time-bounded latency
- Example model of 802.1Qbv
  - when queue open, transmission selection selects a data frame to send and delivers it to the 802.11 MAC layer.
  - MAC follows a random access procedure, and could introduce random delays to transmission




- Potential solution of challenge to reduce the random delay
  - TDM to control the wireless medium access refer to the global reference time between wireless devices.
  - The scheduler assign time slots to devices aligned with the end-to-end latency of each data frame.
  - Scheduler need to ensure the end of the traffic within associated time slot due to the variety of channel capacity
- Extends 802.1Qbv in 802.11 need to modify MAC layer to enable distribution control by Qbv server.

## Wireless Link Reliability

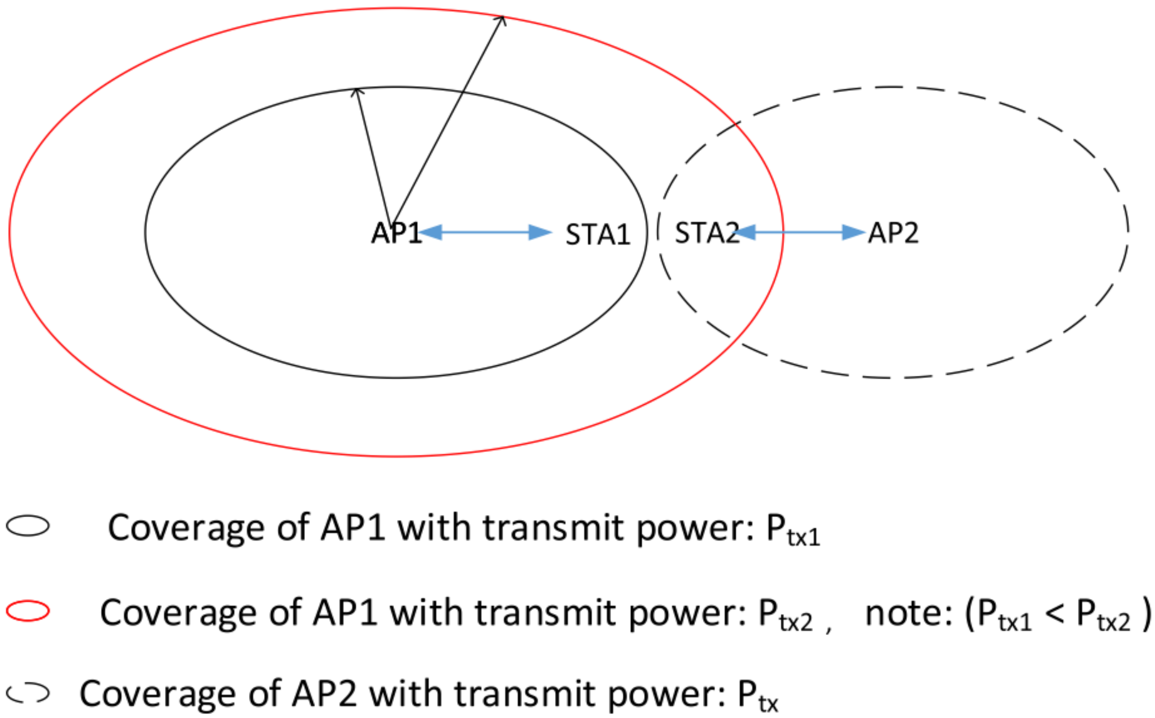
- Reliable transmission challenge due to fading, interference of other device and inter-emission from other system.




- Several techniques can be used to improve reliability: power control, resource scheduling, spatial diversity/BF, waveform design.

### Transmit Power Control

- increase power can get better reliable but will interference other devices.
- To control each device power to ensure the guarantees of the reception with limited power
- Unlicensed band need to follow transmit power spectrum mask spec.




### Optimal Time–Frequency Resource Scheduling

- Reliability enhancement by scheduling transmit in good time-frequency resources
- Example in LTE and 11ax OFDMA downlink OFDMA.
  - AP get CSI of each device and select good for each one to optimize the transmission efficiency and quality.
  - CSI is the overhead of the system capacity.

### Spatial Diversity or Beamforming

- Spatial diversity and BF enhance power efficiency and reliability.
- still need CSI feedback.

### PHY Waveform Design

- OFDM has better spectrum efficiency and good enough fading channel performance.
- But poor out of band emission and generate interference to other band.
  - Mitigation of the out-of-band emission
    - windowing, filtering, subcarrier weighting, carrier cancellation, mapping antipodal symbol pair onto adjacent subcarrier, precoding.
- Short packet is common in industrial communication. current 802.11/LTE packet format suffer efficiency issue for short packet.
  - Luvisotto et al. propose a new design approach for supporting small packets with lower latency by reducing some of the overheads in the 802.11 OFDM PHY.
    - (https://ieeexplore.ieee.org/abstract/document/7924385)

### Adaptation of Modulation and Coding Scheme

- MCS adaptation to make transmission rate meets channel capacity according to CSI feedback.
- Ref:(https://ieeexplore.ieee.org/abstract/document/7588154/)

### Redundancy

- Frame Replication and Eliminations is introduced in the IEEE 802.1CB to improve reliability.
- Multiple-link aggregation is already supported in both the LTE and 802.11 standards
  - focus only on increasing the throughput and not for hard real-time and reliability requirements

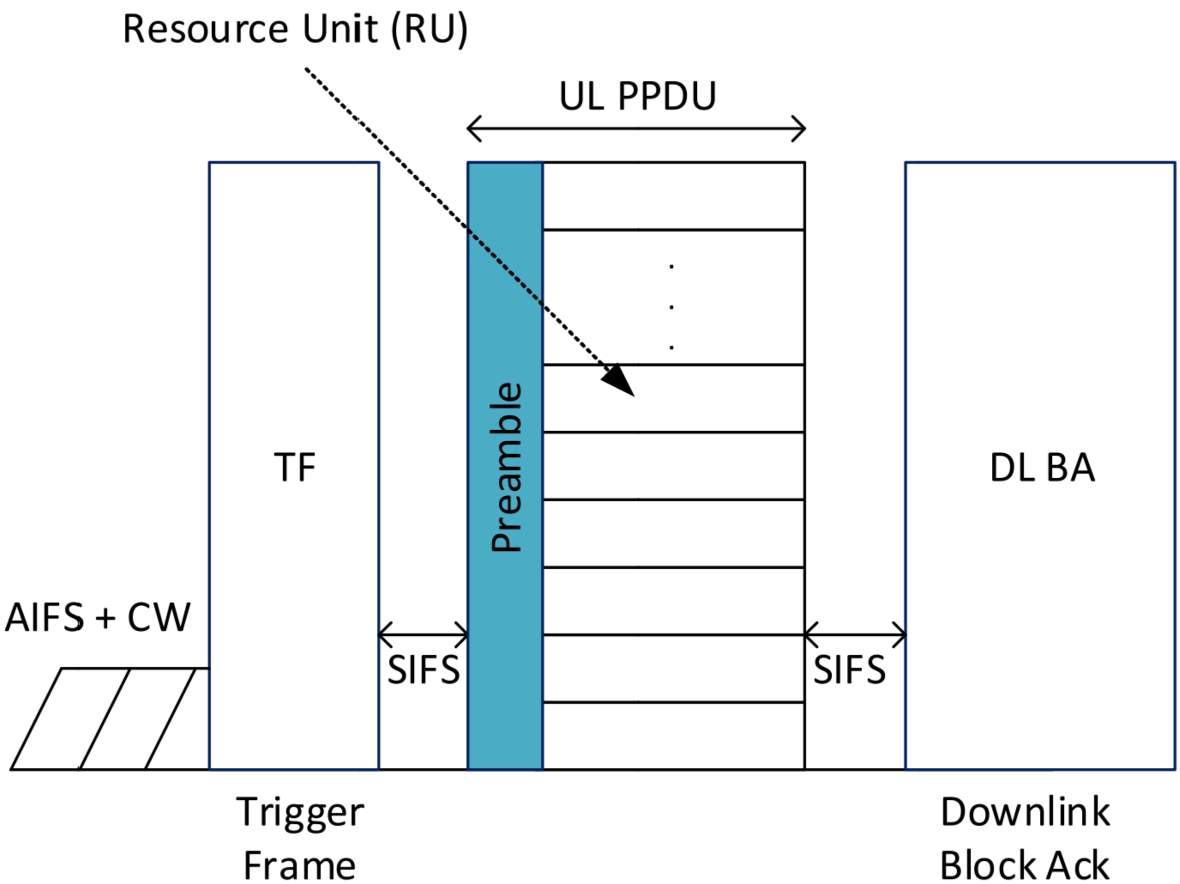
# NEXT-GENERATION WIRELESS CAPABILITIES FOR TSN

## 820.11ax

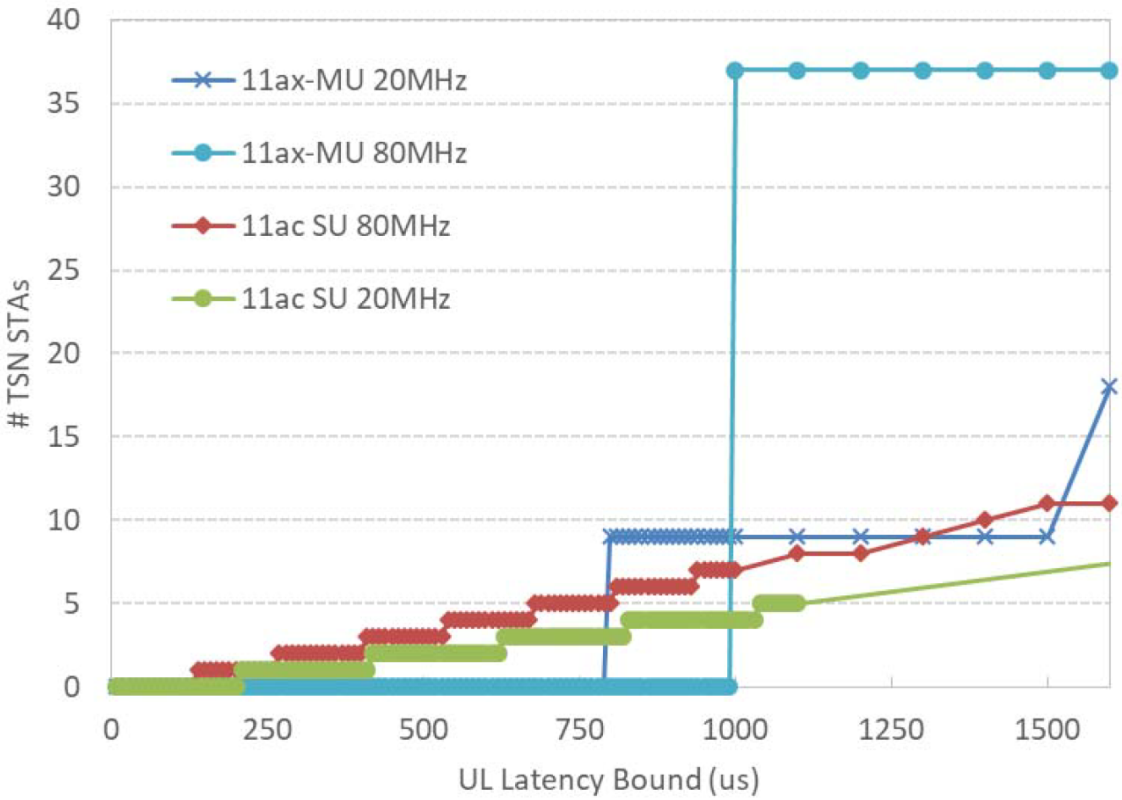
- Enhancements in 802.11ax

### Scheduled Access and Multi-user OFDMA

- AP schedule devices connection access the wireless channel on the traditional contention-based channel access
  - more control and deterministic behavior of the traffic
- MU-OFDMA: multiple user can be scheduled across frequency and spatial domain.
- Trigger-based communication
  - Trigger frame initializes multiple user in the same UL PPDU




- provides better controls of channel
- Remove contention between devices for UL transmission
- Enhance uplink efficiency in short packet
  - Example 9-users 256 byte in 256QAM(mcs9) in BW20
  - 11ac needs 1.3 ms (including overheads of channel access gap)
  - 11ax needs 0.758 ms reduce 70%



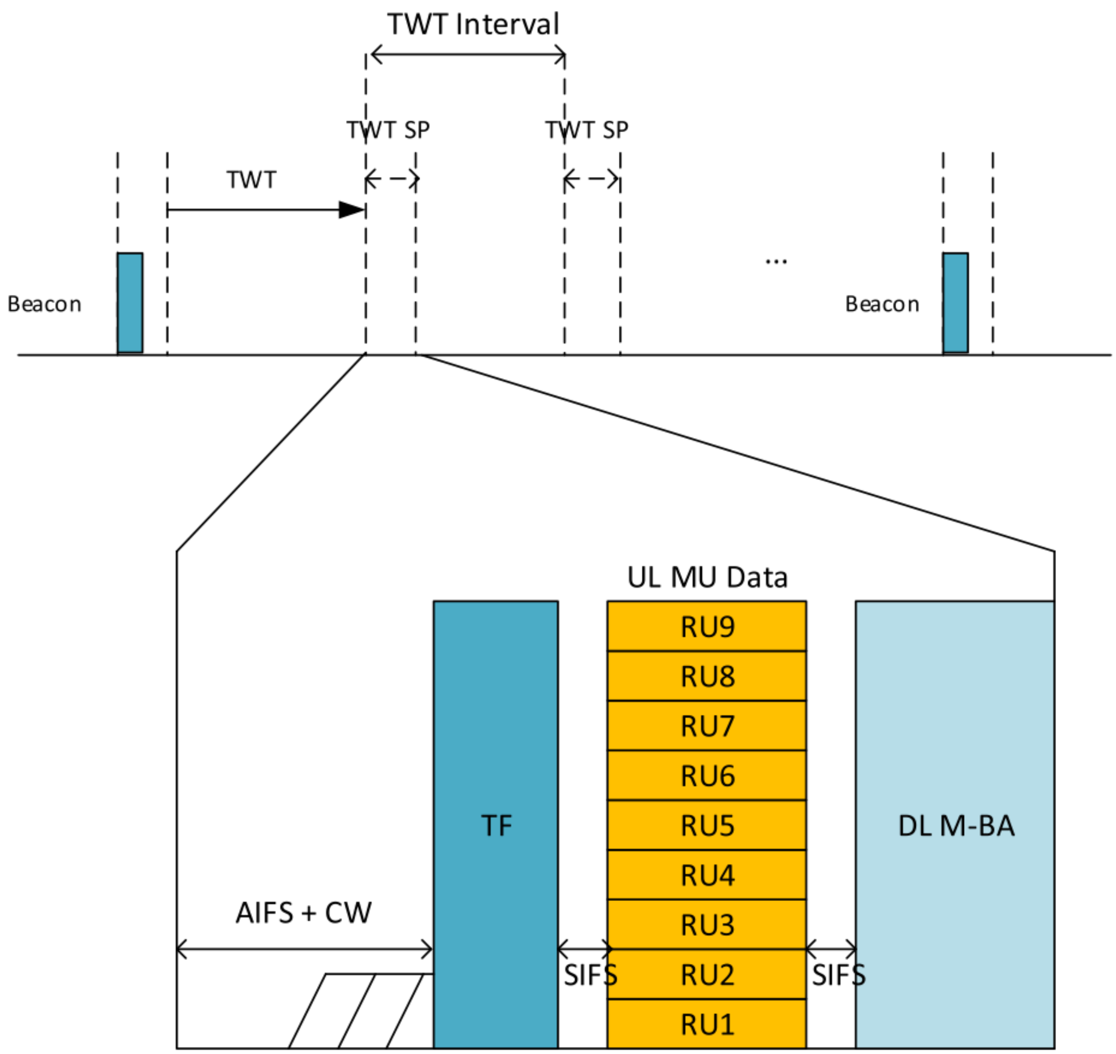

- MCS selection is tradeoff between latency and reliability
  - small mcs => better reliability
  - large mcs => shorter transmission time
  - depends on channel condition(capacity)

## Improved Reliability in the Physical Layer

- Minimal 2MHz RU
  - boosting 8dB SNR in the same transmit power.
  - extend transmission time.(and increasing latency)
- OFDMA MU-diversity leads better throughput and reduce latency.
  - each user can be assigned in good enough RU and make overall throughput enhanced.
- Flexible GI to compact inter-symbol-interference.
- Enable new 6G band, legacy standards not operates in the band.

## Target Wake Time

- New power saving mechanism that enables devices and the AP to agree on a schedule defining when the devices would be awake to communicate.
- Power management: devices expect sleeps outside the TWT windows.
- Control collision: by define devices in different TWT service interval.
- Cowork with OFDMA:
  - AP separates devices into multiple groups of TWT service periods.
  - Transmission in each group using trigger-based control.

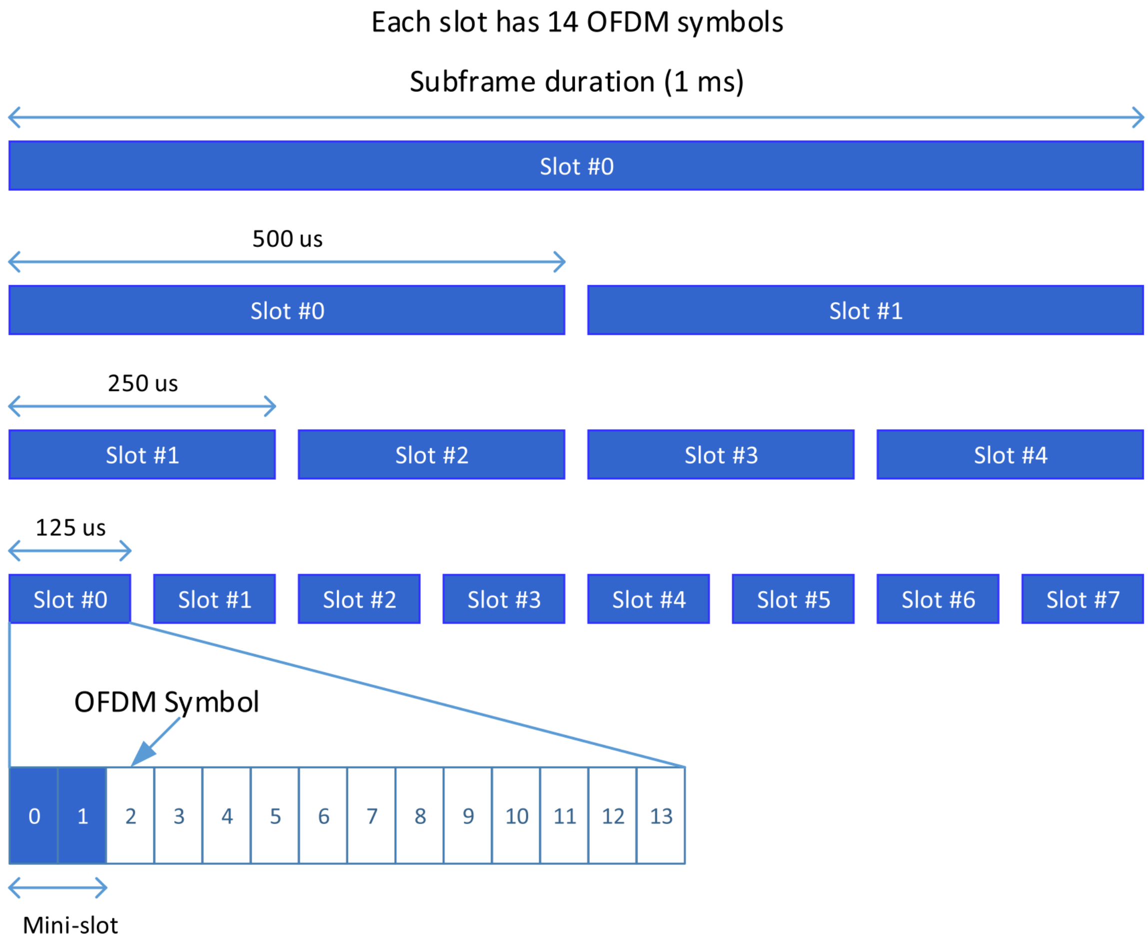



## 5G Ultra-reliable Low-Latency Communications

- URLLC: wide range applications, extremely low latency and ultra-high reliability

### Low-Latency Frame Structure and Numerology

- Flexible slot duration, slot duration is low to 0.125ms for data transmission




- Enhanced OFDM numerology with wider subcarrier spacing leads to smaller OFDM symbol duration.
- allows mini-slots to be allocated for short transmissions: 2/4/7 OFDM symbols
- allow faster uplink/downlink switching and HARQ timing interval for TDD to reduce latency in potential retransmissions for time-critical data.
- a self-contained sub-frame structure:
  - data transmission, associated control signaling, ACK/NACK feedback can all take place within a single subframe
  - useful for very short turnaround time low-latency applications.

## PHY Enhancements for High Reliability and Low Latency

- support for Polar codes and LDPC.
- Polar code
  - significant performance improvements in short packets over turbo-code and convolutional code.
  - have no noticeable error floor: important to reach extremely high level of error tolerance.
  - massive MIMO: spatial diversity from **more than 32 antennas** to massively increase the transmission reliability
  - mmWave communication @ 28 GHz: very high reliability as well as low latency in industrial automation and factory deployment use cases of light-of-sight communication.

## Low-Latency Signaling and Protocol

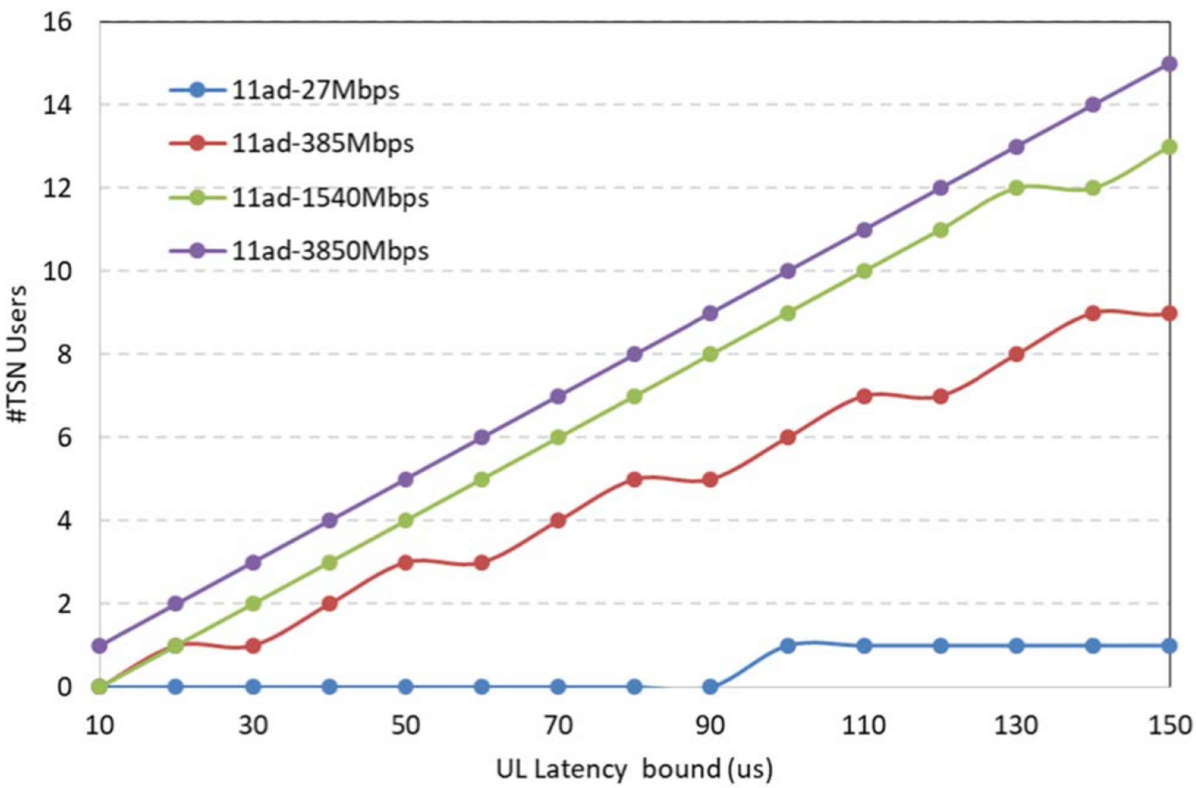
- grant-free access in the UL by which devices: avoid time-consuming UL resource request and grant mechanism for hard real-time data.
- Front-loaded DMRS(Demodulation Reference Signal) enables lower data decoding latency in low-mobility scenarios
  - DMRS is specific for specific UE,
    - Used to estimate the radio channel.
    - The system can beamform the DMRS, keep it within a scheduled resource
    - Multiple orthogonal DMRSs can be allocated to support MIMO transmission
    - The network presents users with DMRS information early on for the initial decoding requirement that low-latency applications need.
    - For for low-speed(mobility) scenarios since channel change slow.
      - In high-mobility scenarios to track fast changes in channel, increase the rate of transmission of DMRS signal(called “additional DMRS”).
  - DMRS refers to demodulation reference signal:
    - used by a receiver for radio channel estimation for demodulation of associated physical channel DMRS design
    - mapping is specific to each Downlink and Uplink NR channels
- Omitting HARQ, removing cipher and header compression, and prioritization for mission-critical data

### Architectural Enhancements

- introduce both RAN and core network.
- CRAN-based design introduces flexibility in dynamically assigning computing and communication resources necessary continuously.
  - traffic mix, network load, and wireless channel conditions evolve over time
- Core network: SDN-based partitioning of control and data plane allows for lower latency in both the control and data planes
- Support NFV and network slicing: consistently provisioning required network resources for hard realtime applications during network congestions and load fluctuations
- MEC and caching at network edges: reduce the latency by bringing the computing power and content near the client devices

## mmWave Communications in WiGig

- 11ad/ay makes bounded latency possible
  - mmWave provides high bandwidth and make low latency transmission possible.
  - 9 user case: 90us(3850 Gbps) to finish the transmission vs 750us in 11ax.
- mmWave short range and directional bring additional challenges. Overhead of beam-tracking and blocking issue impacts the both reliability and latency.

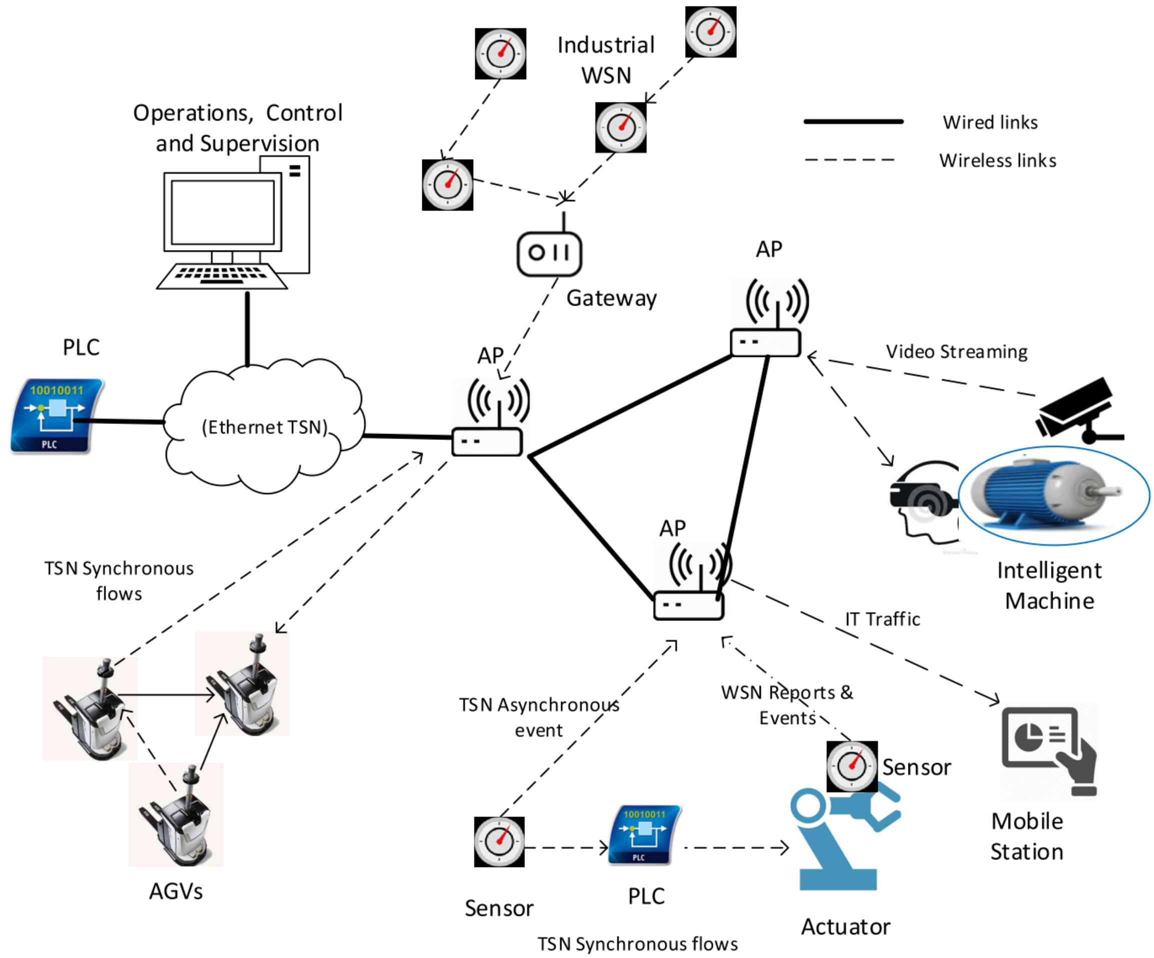



## Integration With Wired TSN Infrastructure

- 802.11 seamless integrated to 802.3 ethernet protocol since natively 802 series standard.
    - 802.11 already been as part of 802.1 TSN protocol.(defined by 802.11ak amendment)
    - The next step is the support for additional TSN capabilities, such as time-aware haping, redundancy, and preemption.
- 3GPP 4G and 5G networks are not native 802 technologies at the link layer
    - one work item to enable transmission of 802-base link layer frames (Ethernet frames) over 5G links
    - Support for 802.1AS-based time synchronization across 5G links

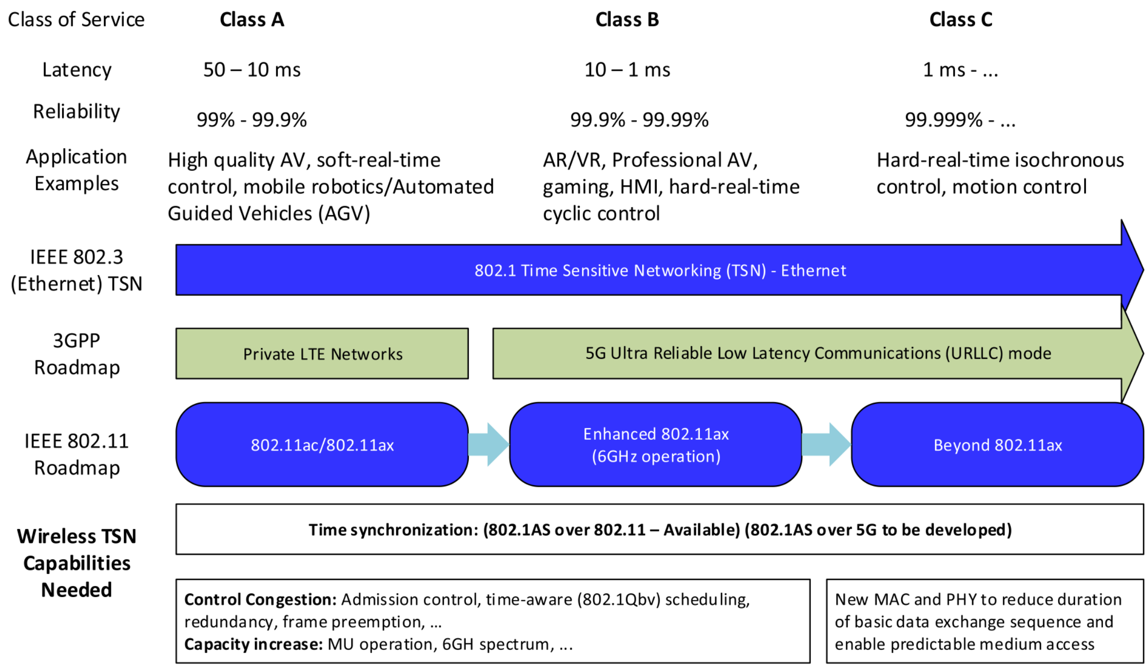
# INDUSTRIAL WIRELESS INFRASTRUCTURE AND APPLICATIONS

- **Wireless** TSN would extend the infrastructure to mobile and portable devices (controllers, sensors, actuators, and AGVs)
- Combination of 802.11 and 5G can address wide range of deployment scenarios.
- need for **time-aware networking** protocols to manage access control, resource reservation, routing, and coexistence across the envisioned **industrial wireless infrastructure**




# Time-Sensitive Applications Classification and Wireless Roadmap

- Applications that involve moving parts and mobile devices(robots, AGVs, and AR/VR) be the first to take advantage of new wireless TSN capabilities
- A classification of industrial applications
  - Class A: supported by current wireless technologies (LTE and 802.11ac and ax) with proper enhancements for admission control, latency-optimized scheduling, and introduction of time-aware (802.1Qbv) concepts
  - Class B: Soft-time-sensitive(AR/VR,HMI,) and selective hard-time-sensitive applications(controllers) require higher reliability than class A in single-digit milliseconds (以數毫秒為單位).
    - required network planning and optimizations in 802.11ax and 5G URLLC
  - Class C: hard realtime controllers with very low cycle times, such as motor control. The 802.11 EHT(distributed MIMO, multi-AP, and low latency enhancements) could enable class C.




# Wireless Experimental Platforms

- Experimentation with 802.11/Wi-Fi is relatively easier than with 3GPP technologies.
- The experiments in synchronization need to fundamentally access low-level MAC and PHY. But current vendors will not open the FW.
- SDR platform have been to enable research and development with MAC and PHY.
  - USRP, WARP, GNU Radio
  - Architecturally, an SDR platform consists of a **front-end module** and a **signal processing module** implemented in FPGA or a combination of FPGA and system on chip(SoC)
  - could be found in markets, very common chips offer 100MHz in 6GHz band.
  - Software toolchains: NI instrument and MathWorks
- A low-latency SDR system(Tick) provides programmable and ensure low-latency throughput accelerator-rich architecture, and HW/SW co-design.
- SDR hardware and software tools will need to be enhanced to enable new wireless capabilities as well as implementation optimizations that can address the strict TSN requirements.

# CONCLUSION