Challenge and Opportunity of TSN, the Next-Generation Networking for Industrial IoT and Industry 4.0

Yuan-Yao Shih

Dept. of Comm. Engr., National Chung Cheng University

Challenge and Opportunity of TSN, the Next-Generation Networking for Industrial IoT and Industry 4.0

Internet of things (IoT)

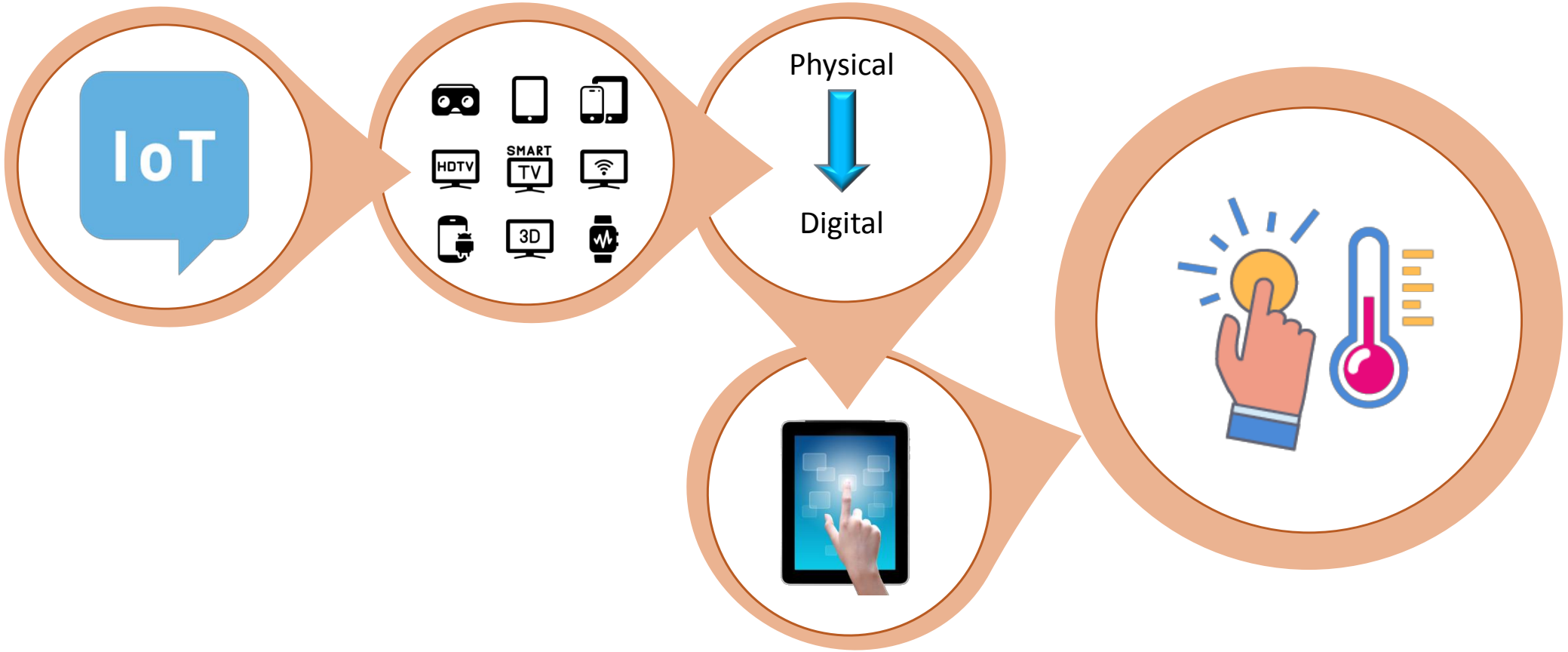


Diagram Source: 3G4G

Industrial IoT (IIoT)

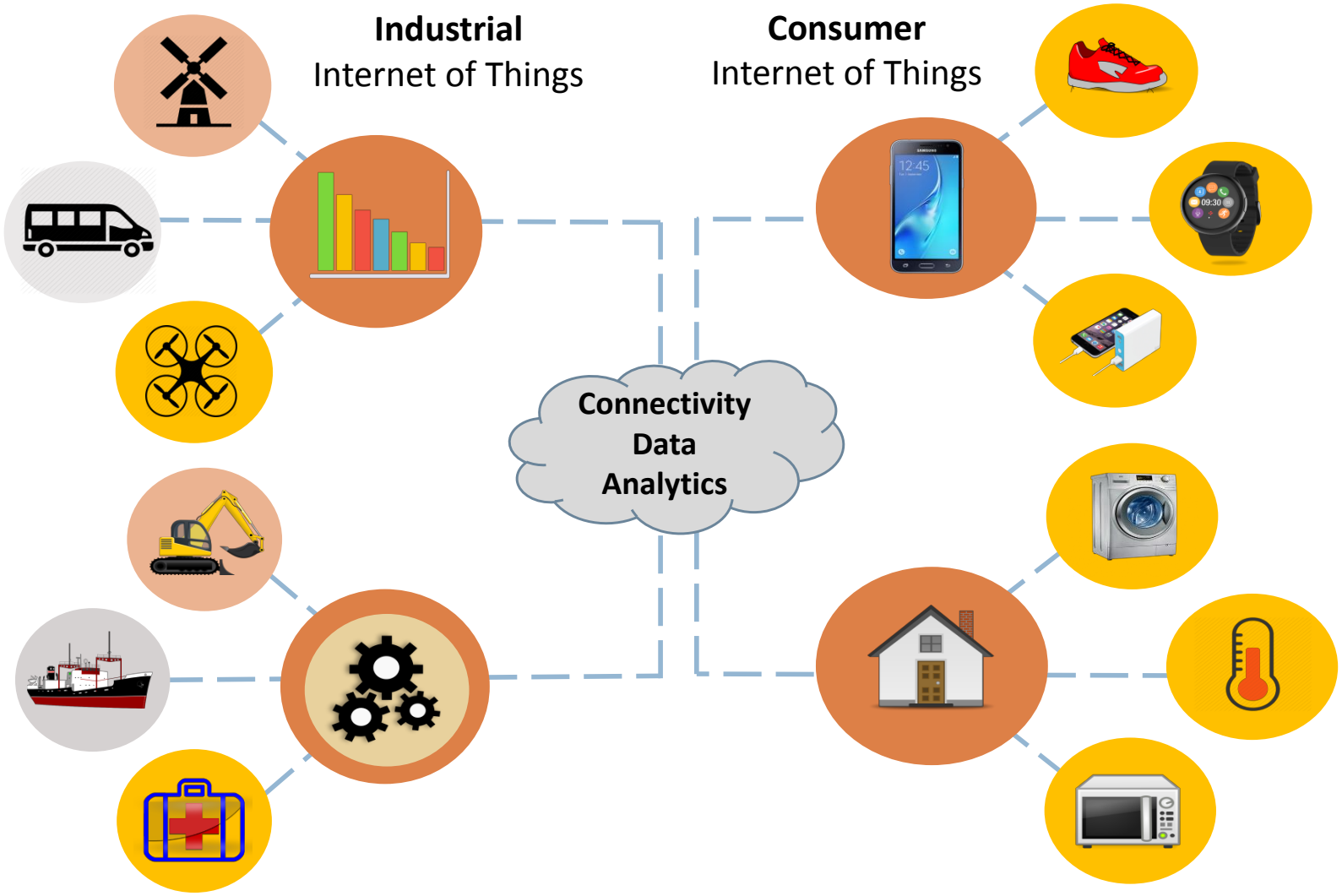


Diagram Source: https://computradetech.com/blog/trends-and-solution/iot-vs-iiot/

Industry 4.0

END OF THE 18TH CENTURY	START OF THE 20TH CENTURY	START OF THE 1970S	PRESENT
			
INDUSTRY 1.0 **Mechanization** Introduced mechanization of production by using water and steam to increase production capacity and productivity, versus manual craft work **1784** First mechanical loom	**INDUSTRY 2.0** **Electrification** Introduced labor-based mass production (assembly lines) powered by electrical energy **1870** First production line, Cincinnati slaughterhouses	**INDUSTRY 3.0** **Automatization** Introduced electronics and computers to replace manual work by stand-alone robotic systems **1969** First programmable logic controller (PLC), Modicon 084	**INDUSTRY 4.0** **Cyber-Physical Systems** The convergence of physical, digital, and virtual environments through **Cyber-Physical Systems (CPS)** and the **Internet of Things (IoT)**

Diagram Credit: International Society of Automation (ISA)

Challenge and Opportunity of TSN, the Next-Generation Networking for Industrial IoT and Industry 4.0

History: The Internet and LANs

Best effort delivery

- According to Wikipedia: *"A network service in which the network does not provide any guarantee that data is delivered or that delivery meets any **quality of service**."*
- *"Under best-effort, network performance characteristics such as network delay and packet loss depend on the current network traffic load, and the network hardware capacity."*

For most Internet applications, "**best effort**" is "**best**".
If not enough -> higher layer services like **TCP**

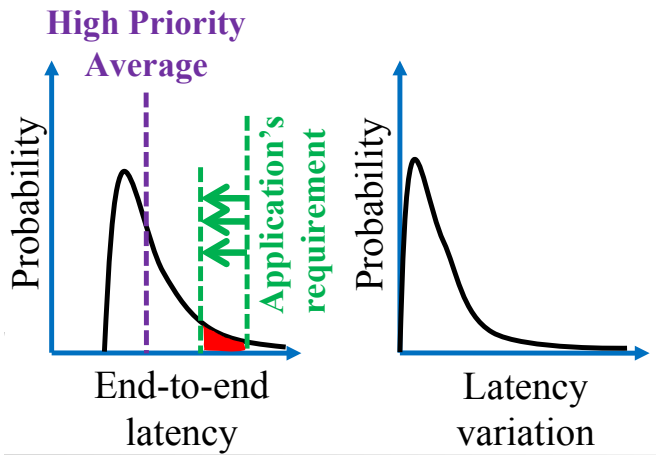
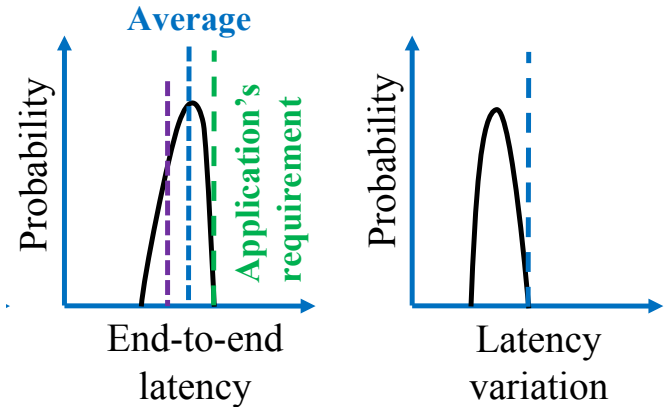


Diagram Credit: doc.: IEEE 802.11-19/1298r1

Industrial Applications Require Deterministic

Deterministic

- != high throughput and low latency
  - -> Depended on applications.
- = definitely and unequivocally characterized
- *"A **deterministic system** is a system in which no **randomness** is involved in the development of future states of the system. A deterministic model will thus always produce the same output from a given starting condition or initial state." ~ Wikipedia*



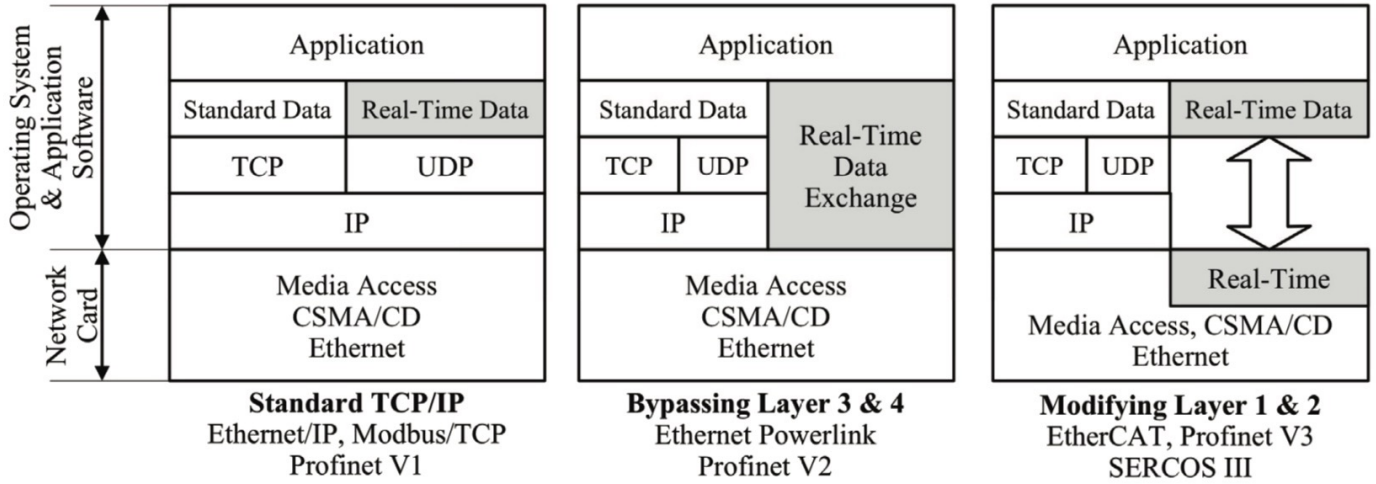
Bounded delay and **a well-known time** are required

Diagram Credit: doc.: IEEE 802.11-19/1298r1

Current/Past-Generation Networking for Industry

Achieve **real-time** on **Ethernet**

- EtherCAT, PROFINET, Ethernet/IP, Modbus, POWERLINK, …

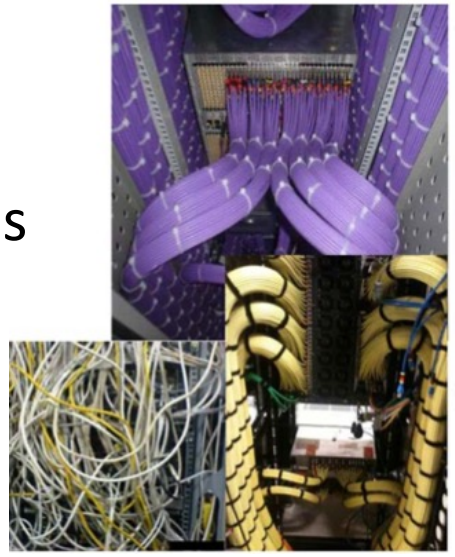


Comparison of Industrial Ethernet Protocols

Diagram Credit: Copperhill

Problem of Current Generation Networking for for Industry

- Specialized or proprietary specifications
  - Vendor Lock-in
- Point-to-point connections
  - Massive cabling
  - Inflexible
  - Dedicated cables



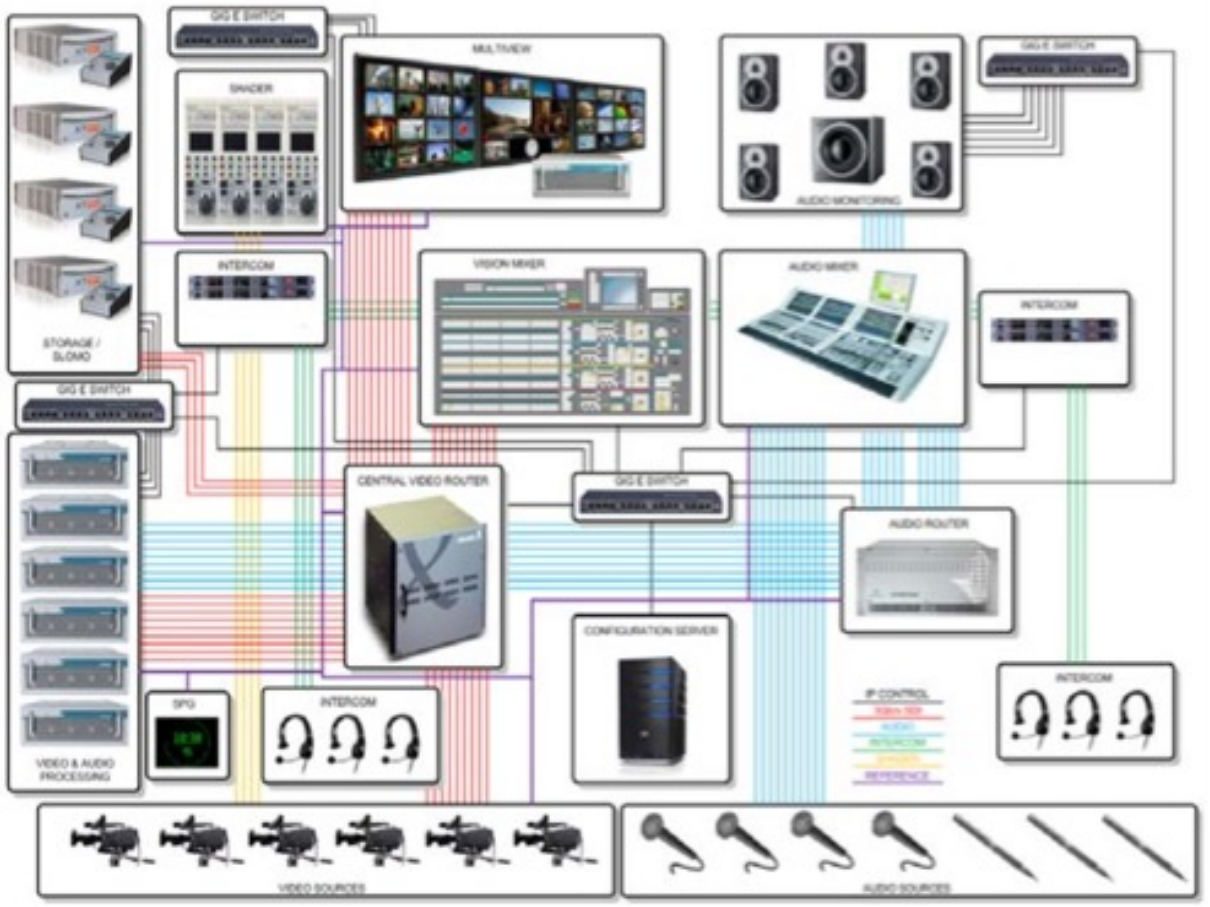


Diagram Source: UNH-IOL_TSN-Overview

Modern Industrial Applications Require More

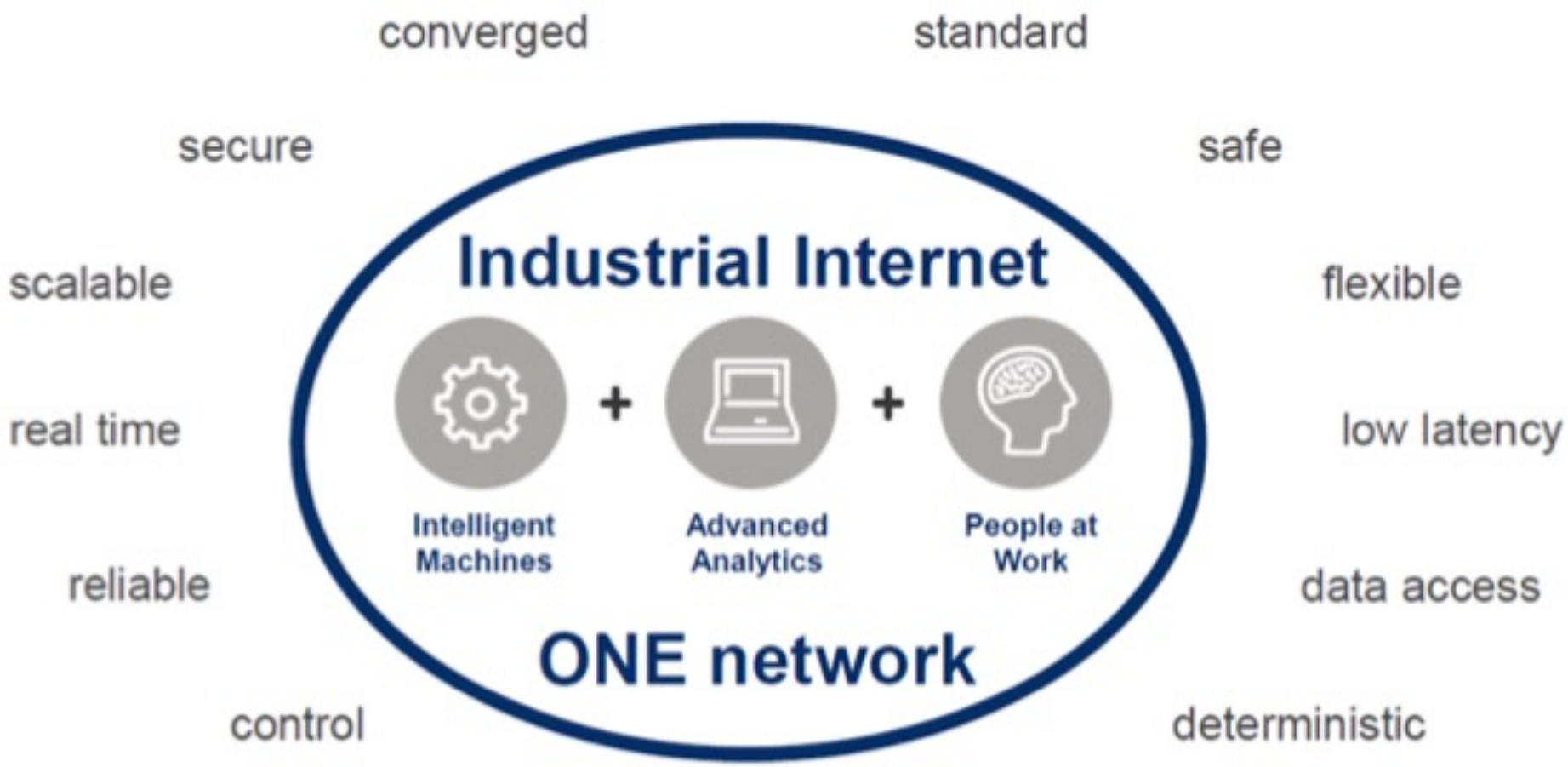
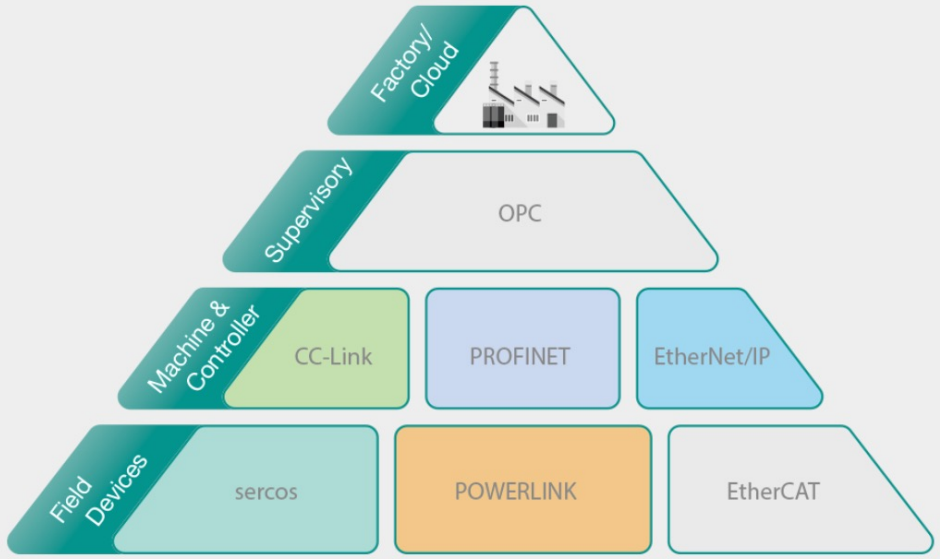


Diagram Source: UNH-IOL_TSN-Overview

The Road Toward IIoT and Industry 4.0

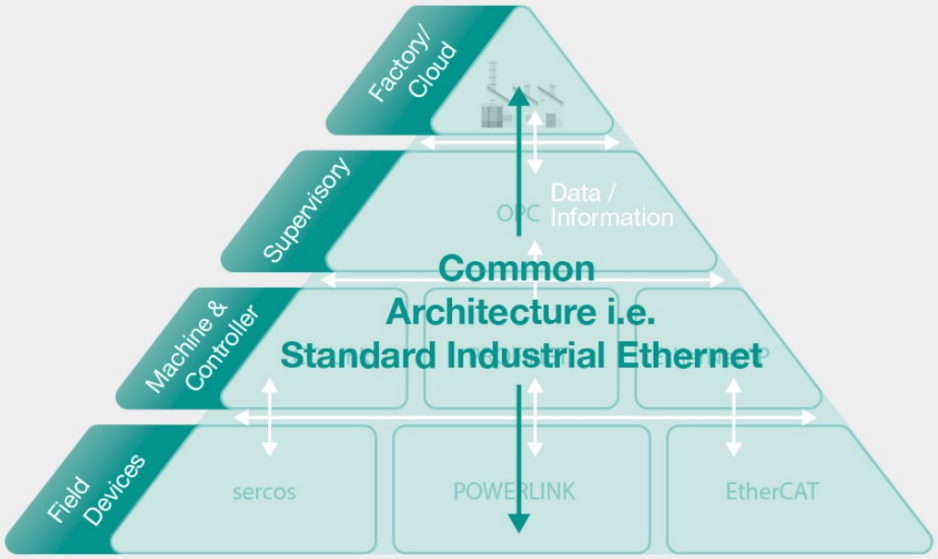
Today



Automation Pyramid

- Multiple protocols and standards
- Few topologies result in limited applications
- It is hard to access data
- Higher integration and maintenance costs

Tomorrow



Autonomous Pyramid

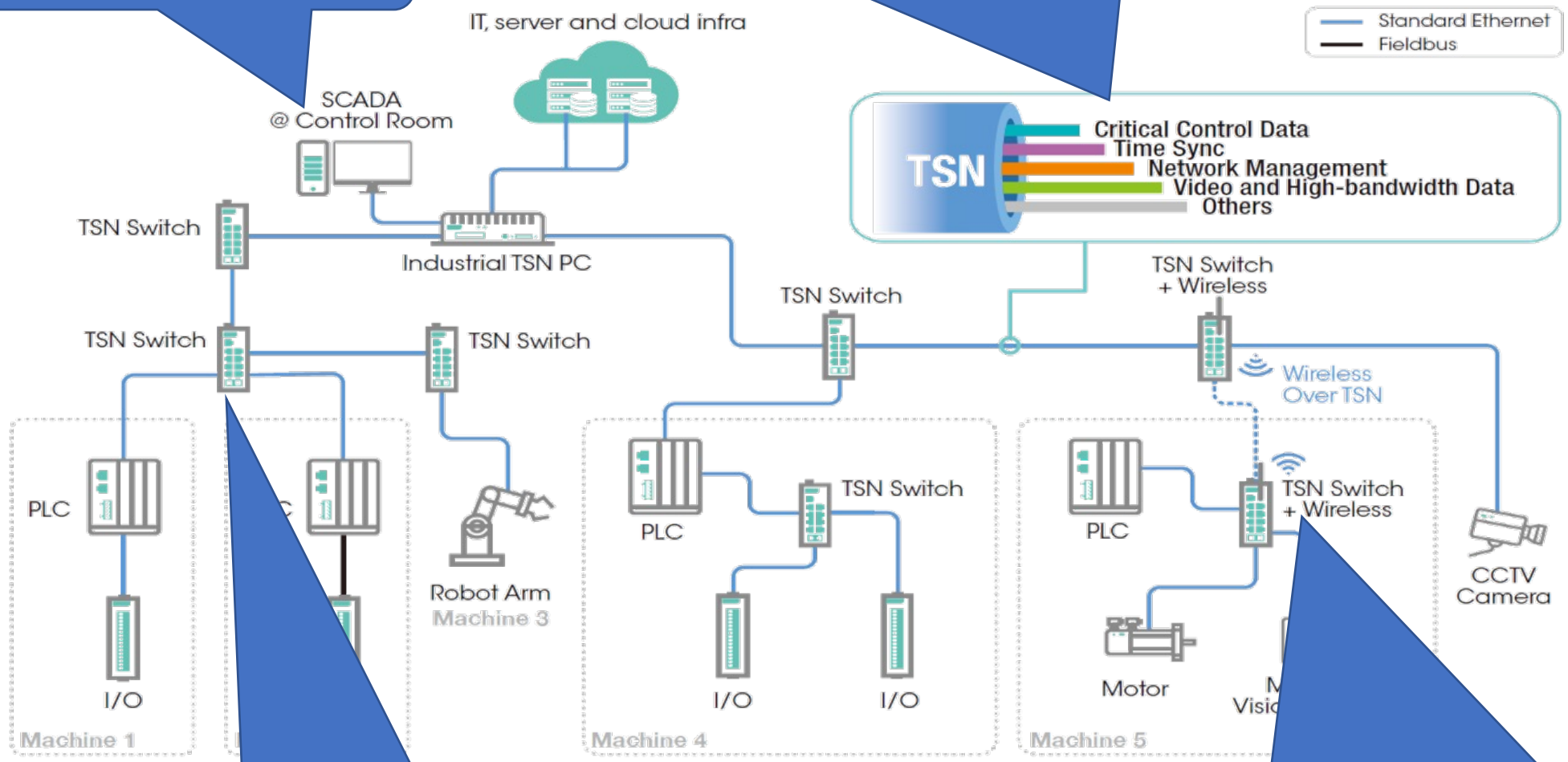
- Vendor independent but can communicate with each other (same language)
- A flexible topology allows for more new applications
- Data can be directly accessed from the cloud or the field
- Easy to maintain and can achieve plug-and-produce manufacturing

Diagram & Text Source: MOXA Inc.

Benefits of Time-Sensitive Networking

Open Standards: No vendor lock-in, lower cost

Sharing the Wire: Higher network resource utilization



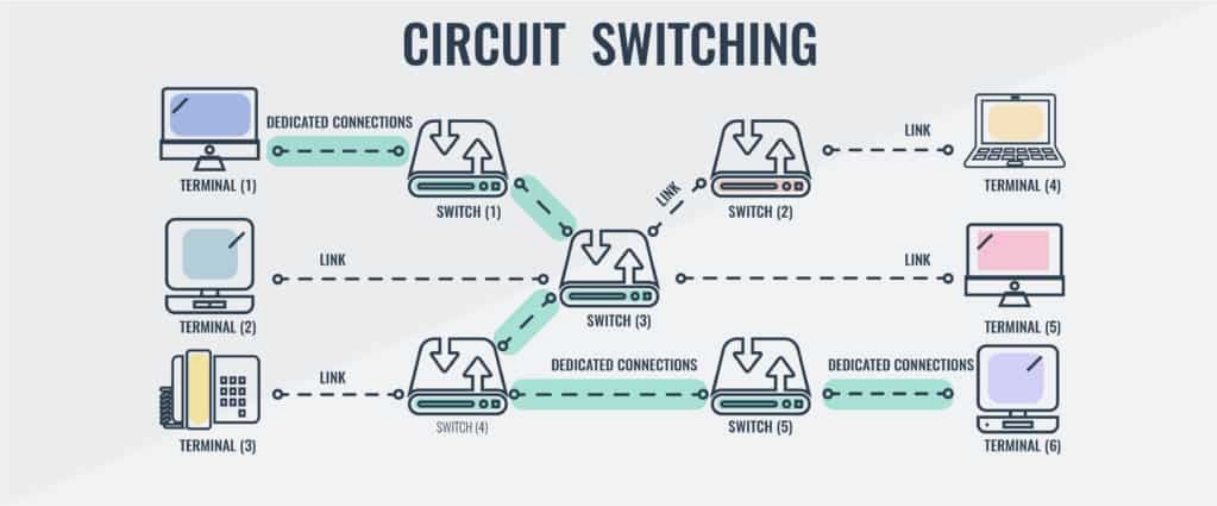
Timeliness and Reliability Guarantee

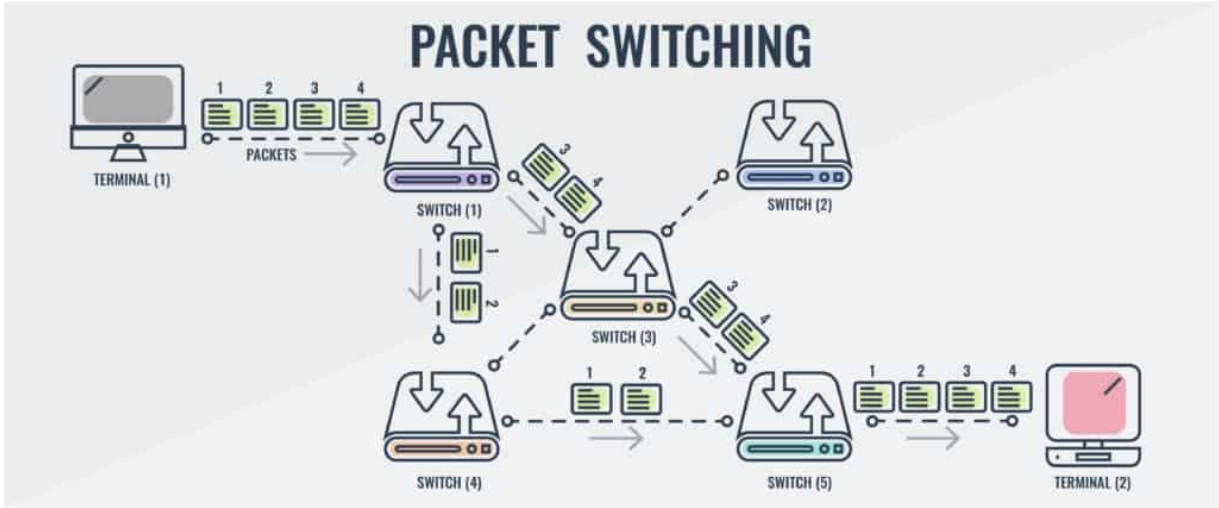
Compatible with Various Network Communication Standards

Diagram Credit: MOXA Inc.

Challenge and Opportunity of TSN, the Next-Generation Networking for Industrial IoT and Industry 4.0

How to Ensure Timeliness (1/2)





Old days: land-line **circuit-switched** telecom networks

- Provide almost flawless streaming QoS

Internet: **packet-switched** connections

- “best effort”

How to Ensure Timeliness (2/2)

TSN: back to the concept of "**circuit**"

- **Flow (stream)** as the circuit
- Also need interoperation with existing models of "the internet"

To achieve those goals, TSN needs to:

1. Provide a network-wide precision **clock** reference
2. Limit network **delays** to a well-known (and hopefully small) value
3. Keep **non-time-sensitive** traffic from messing things up

History: AVB and TSN

AVB = Audio-Video Bridging

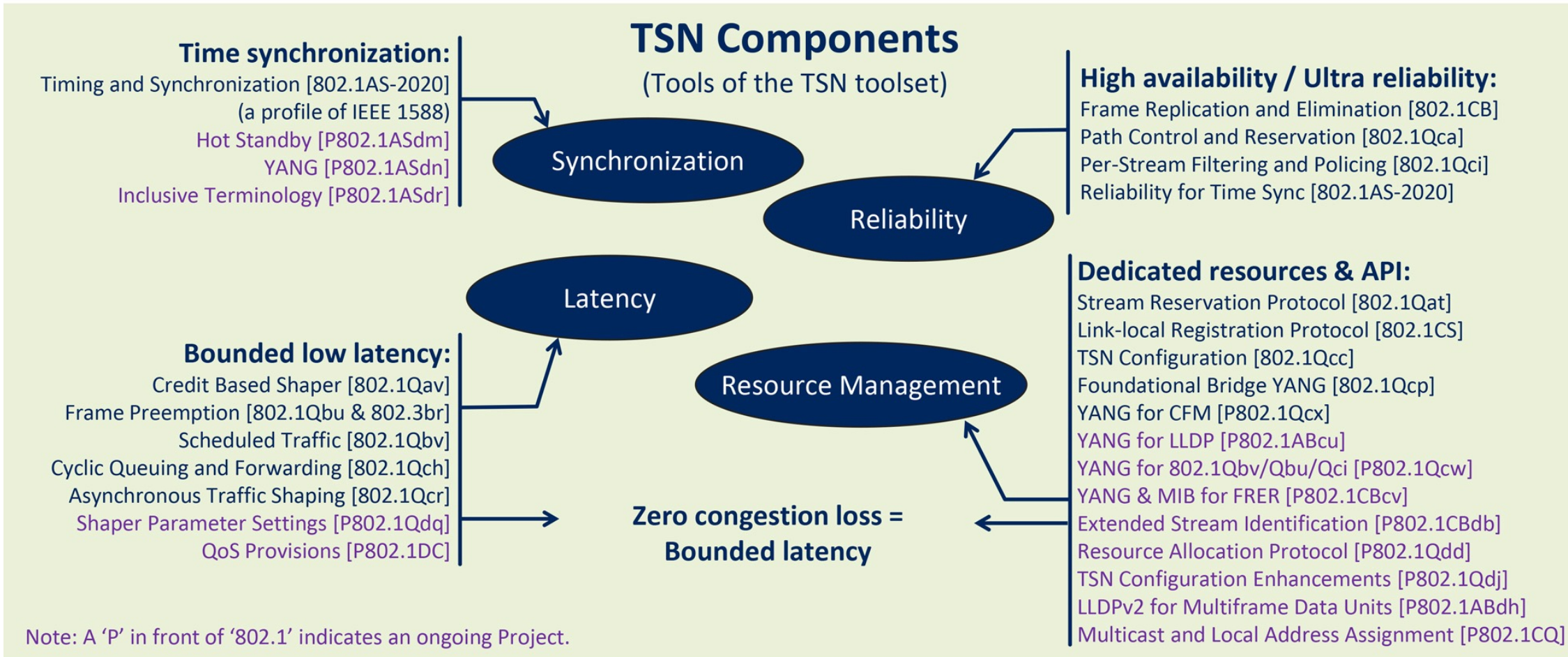
- IEEE 802.1 project started in 2005 largely to address the needs of the professional audio market –"*IEEE 802.1 Audio Video Bridging Task Group*"
- Can also be useful for consumer electronics, professional video, and automotive "infotainment"

TSN = Time-Sensitive Networking

- Capabilities of AVB-capable network were also very interesting to other groups (e.g., Industrial and automotive control and sensing)
- Wider spectrum of requirements
- -> The Audio/Video Bridging Task Group was renamed the "*Time-Sensitive Networking Task Group*" in November 2012.

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

Audio Video Bridging [802.1BA/Revision]	Fronthaul [802.1CM/de]	Industrial Automation [IEC/IEEE 60802]	Automotive In-Vehicle [P802.1DG]	Service Provider [P802.1DF]	Aerospace Onboard [IEEE P802.1DP / SAE AS6675]



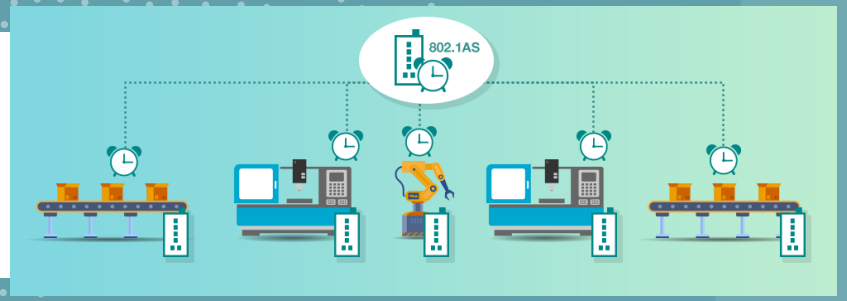
More on TSN standards and ongoing projects at: https://www.ieee802.org/1/tsn

July 14, 2021

Diagram Credit: IEEE SA

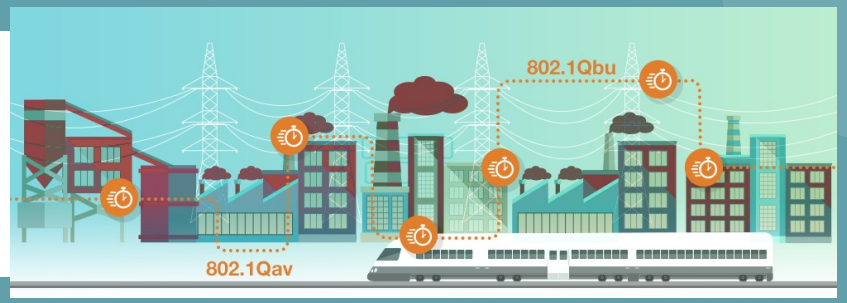
Time Synchronization

As the name suggests, time-sensitive networking focuses on establishing a common time reference between all devices within a unified and interoperable infrastructure, which forms the foundation of its entire operations.



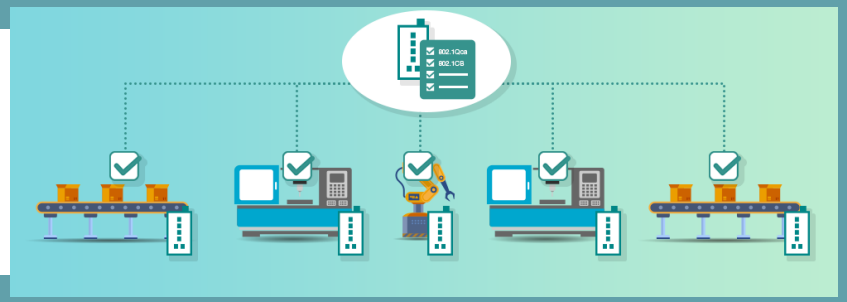
Bounded Low Latency

By adopting the concept of non-negotiable time period allocation for end-to-end transmissions, these components ensure deterministic data transmission over the network.



Reliability

To implement and maintain all aspects of a deterministic networking environment, a set of components has been defined to ensure optimal reliability and security.



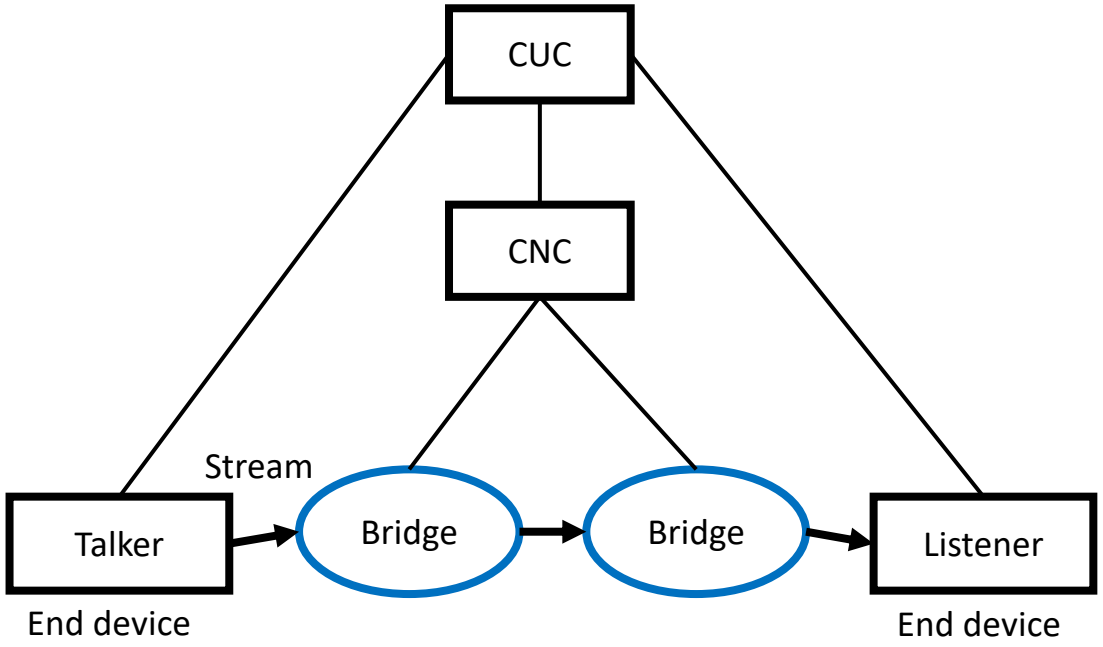
Resource Management

When the network and applications become more converged and larger in scale, additional tools are required to provide better manageability and visibility.

Diagram & Text Credit: MOXA Inc

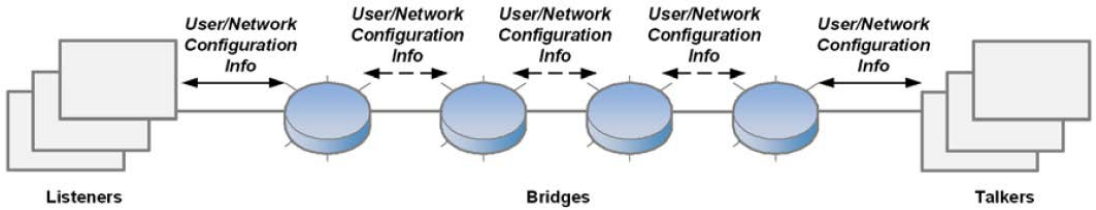
TSN: Basic Unit Components

- **Centralized User Configuration (CUC):** An application that communicates with the CNC and the end devices. The CUC represents the control applications and the end devices.
- **Central Network Controller (CNC):** A proxy for the network and the control applications that require deterministic communication.
- **End device (Station)**
  - **Talker**: The source or producer of a stream
  - **Listener**: The destination, receiver, or consumer of a stream
- **Stream (Flow)**: A unidirectional flow of data from a Talker to one or more Listeners
- **Bridge**: Like switch

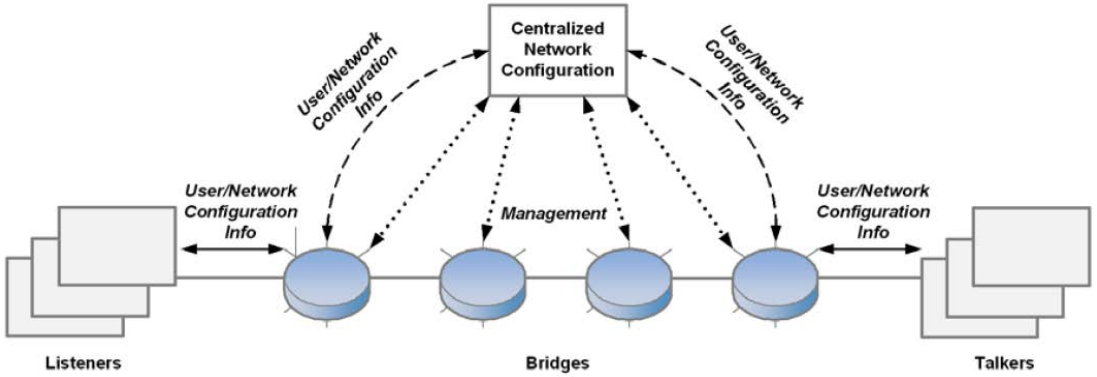


TSN Management Configurations

Fully distributed



Centralized network & distributed user



Fully centralized

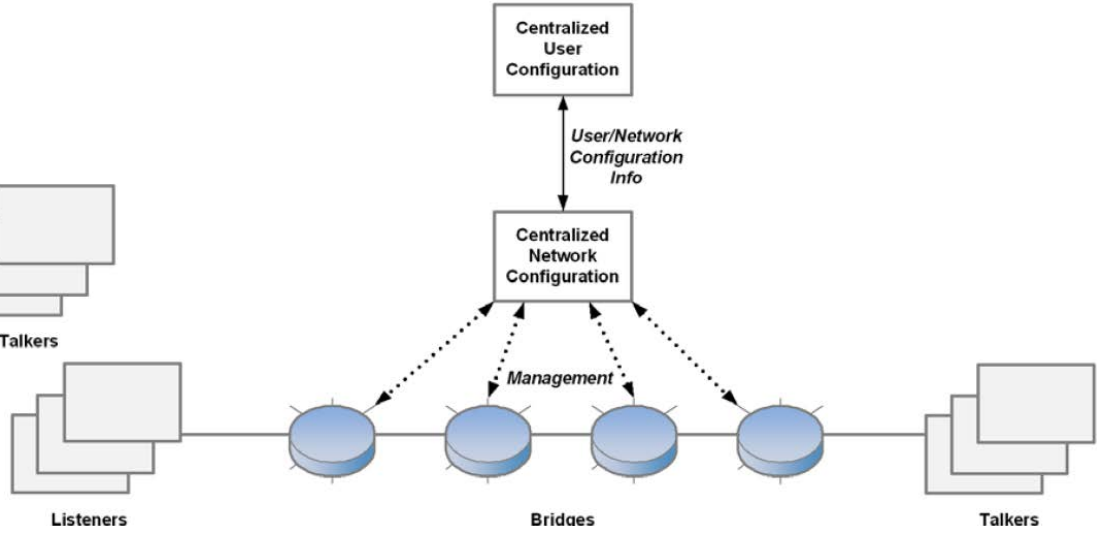


Diagram Credit: doc.: IEEE 802.11-19/1298r1

TSN Flow (Stream) Identification

- Providing QoS for a flow first requires some way to identify the flow
- **Priority code point (PCP)** field and **VLAN ID (VID)** within the 802.1Q VLAN tag are used to define a TSN flow.

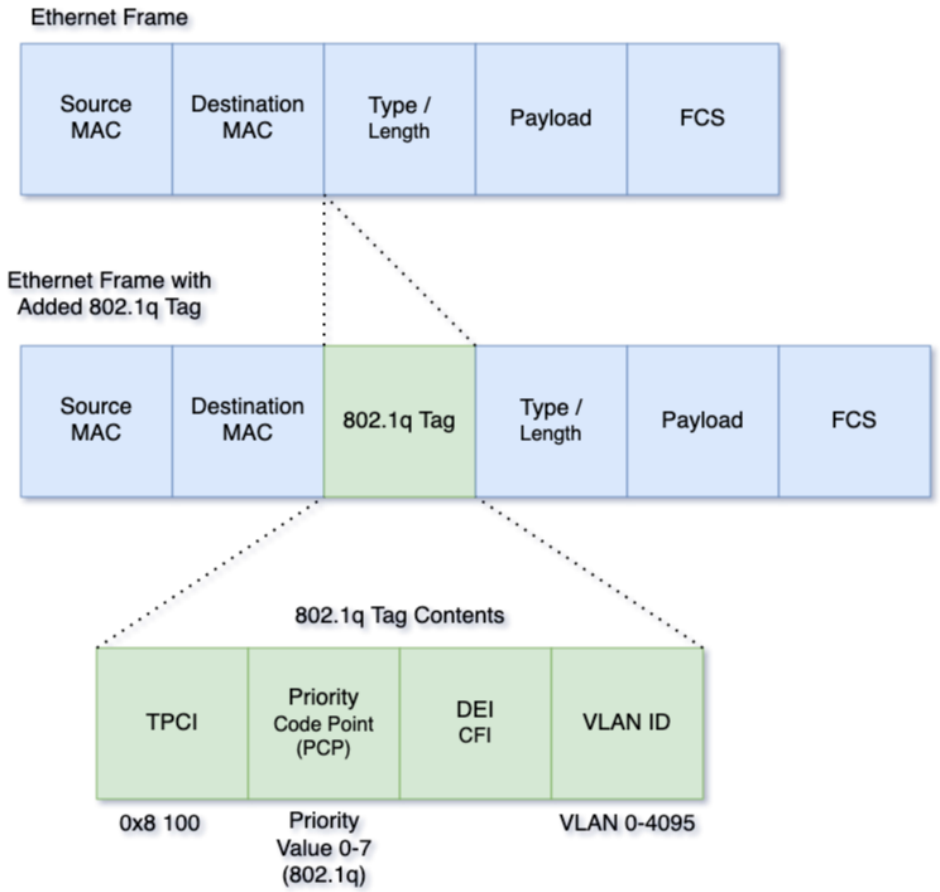


Diagram Credit: [PDF] Performance analysis of a non-synchronized heterogeneous TSN network

Time Synchronization

- **Precise time synchronization** is required to:
  - allow multiple streams to be synchronized
  - provide a common time base for sampling data streams at a source device and presenting those streams at the destination device with the same relative timing
- **IEEE 802.1AS:** Time Synchronization for Time-Sensitive Applications
  - Based on IEEE 1588-2008 (1588v2), the generic Precision Time Protocol (gPTP).

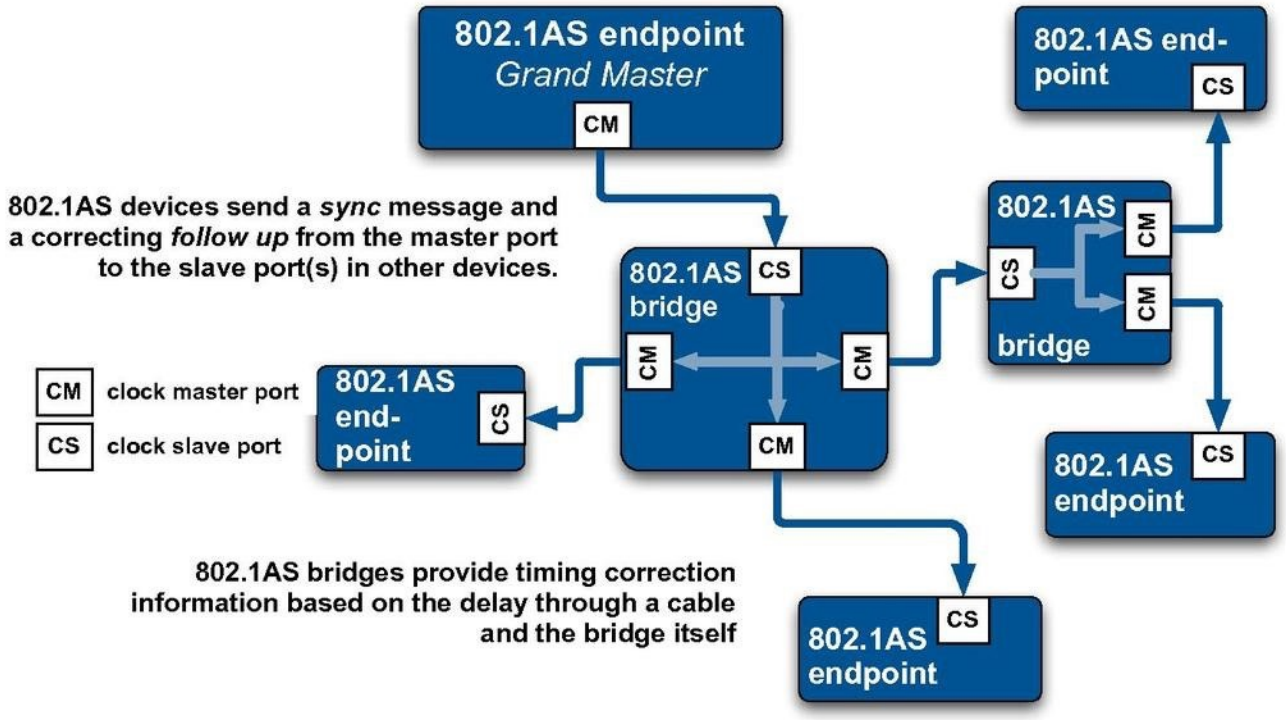


Diagram Source: https://en.wikipedia.org/wiki/File:Clock-Master.pdf

Flow Control - IEEE 802.1Qav

- We do NOT care about average delay, nor fastest delivery -> **“worst case” delay** is the important metric
- We need to **shape the traffic**
- **IEEE 802.1Qav** Forwarding and Queuing of Time-Sensitive Streams (FQTSS)
  - Schedule transmission of packets to **prevent bunching**, which causes overloading of network resources (limit the amount of traffic buffering) via **credit-based shaper**.

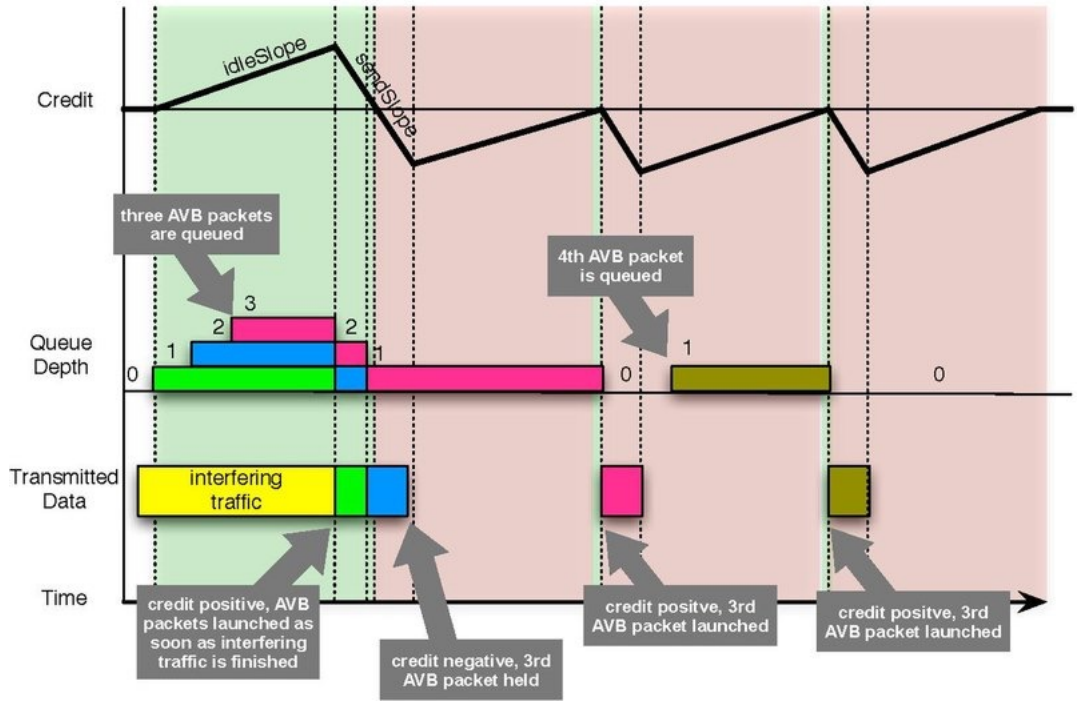


Diagram Source: https://en.wikipedia.org/wiki/File:Traffic-shaping.pdf

Flow Control - IEEE 802.1Qch

- Cons of the FQTSS
  - Large topologies can result in increased delay
  - Worst case delays are topology dependent
- **IEEE 802.1Qch** Cyclic Queuing and Forwarding (CQF)
  - Every switch introduces a fixed delay for each stream in a particular traffic class
    - Buffer requirements are fixed by switch design, topology of network has no effect
    - Delivery jitter is fixed, based only on traffic class

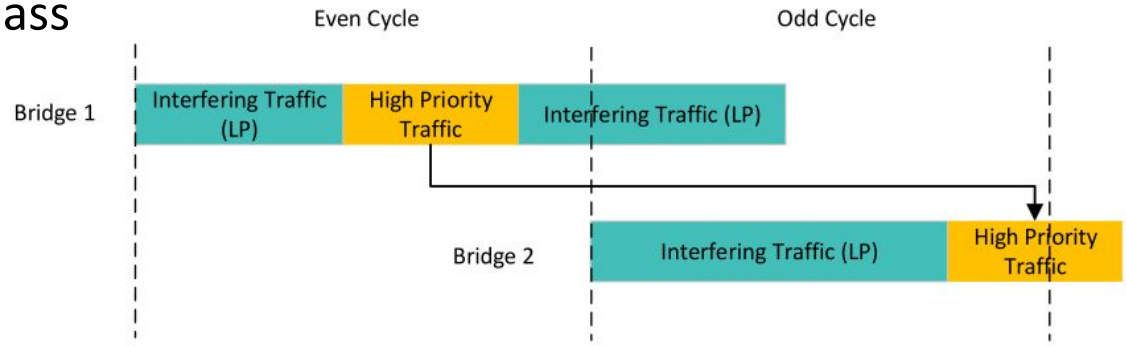


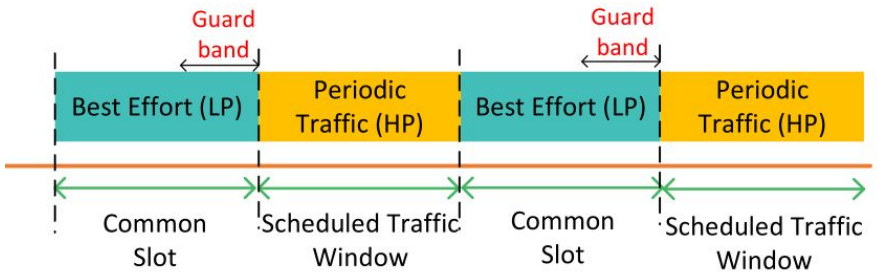
Diagram Source: Ultra-Low Latency (ULL) Networks: The IEEE TSN and IETF DetNet Standards and Related 5G ULL Research

Flow Control - IEEE 802.1Qbv

- What if we can avoid interfering traffic

IEEE 802.1Qbv Enhancements to Traffic Scheduling: Time-Aware Shaper (TAS):

  - follows the **TDMA** paradigm
  - needs precise time synchronization and high configuration complexity
  - **Guard Band** is necessary but can be shorten via **Frame Preemption** (802.1Qbu/802.3br)



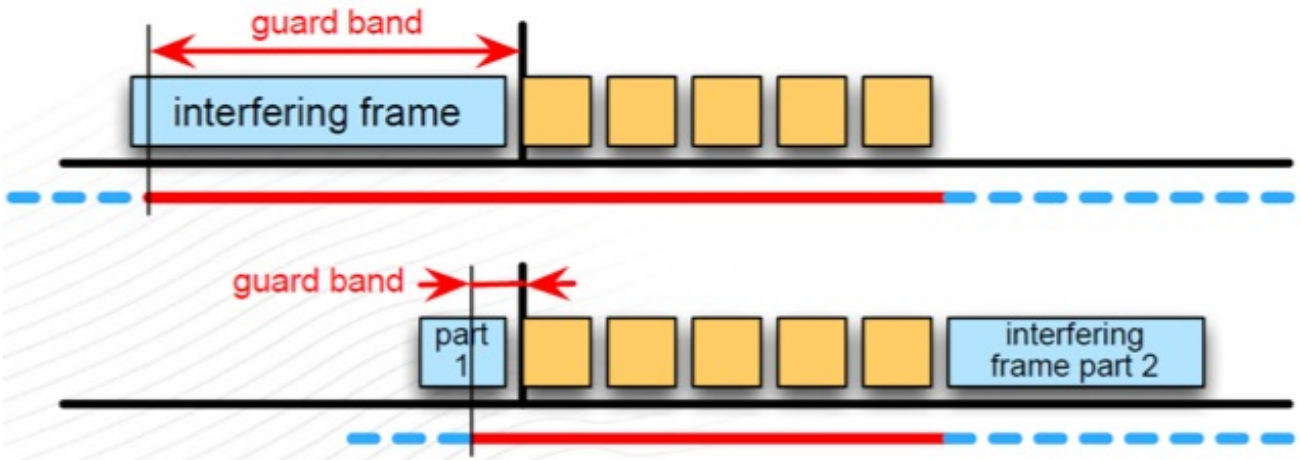


Diagram Source: Ultra-Low Latency (ULL) Networks: The IEEE TSN and IETF DetNet Standards and Related 5G ULL Research

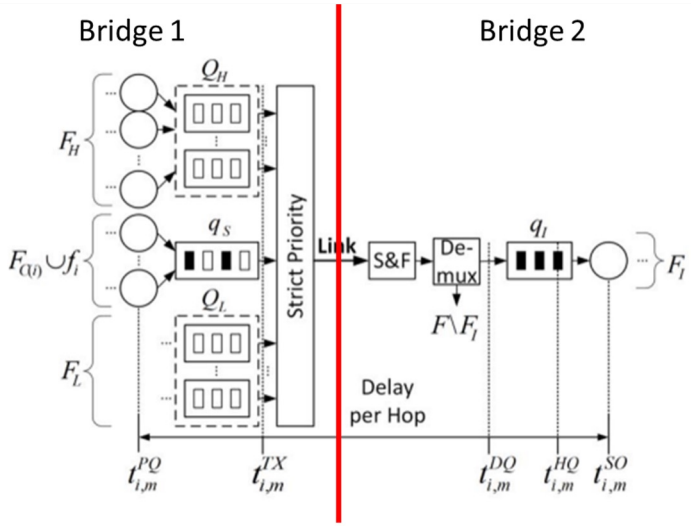
Diagram Source: UNH-IOL_TSN-Overview

Flow Control - IEEE 802.1Qcr

- What if we cannot do precise time synchronization

IEEE 802.1Qcr Asynchronous Traffic Shaping (ATS)

- Smoothen traffic patterns by re-shaping per hop
- Prioritize urgent traffic over relaxed traffic
- Low implementation complexity, especially for **event-driven** flows
- Bounded latency guarantee via **worst-case delay calculation** (may be loose)



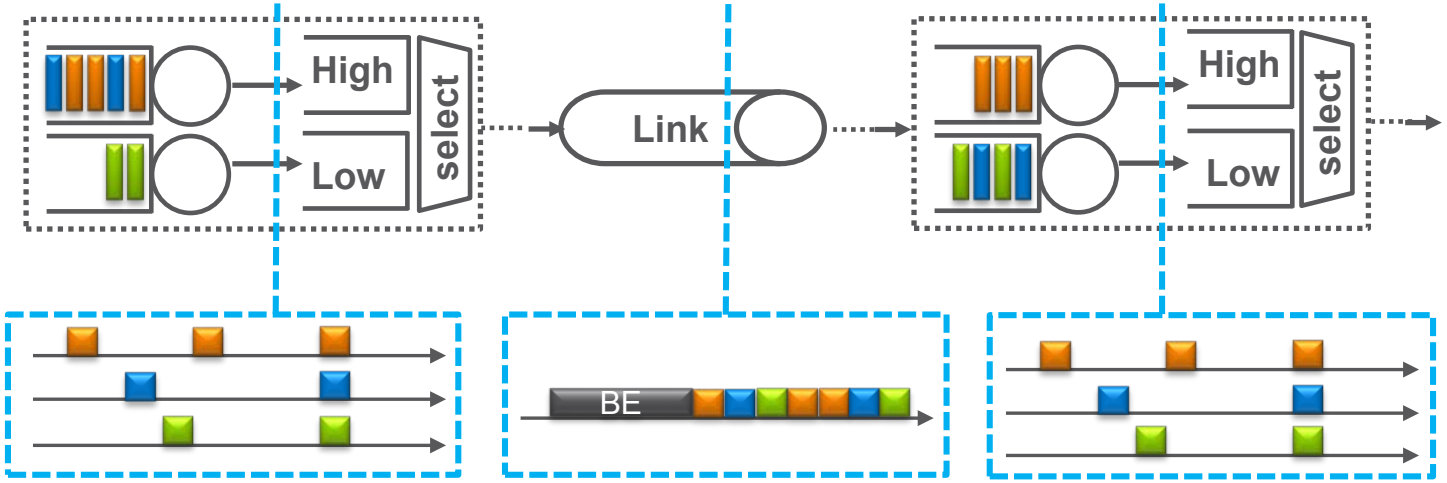


Diagram Source: Urgency-Based Scheduler for Time-Sensitive Switched Ethernet Networks

Diagram Credit: doc.: IEEE 802.11-19/1298r1

Flow Management

Config Data Format: **IEEE 802.1Qcp** YANG Data Model

- Provides a framework for periodic status reporting and configuring 802.1 bridges and bridge components
- A truly universal Plug-and-Play (uPnP) model
- Utilizes the Unified Modeling Language (UML)

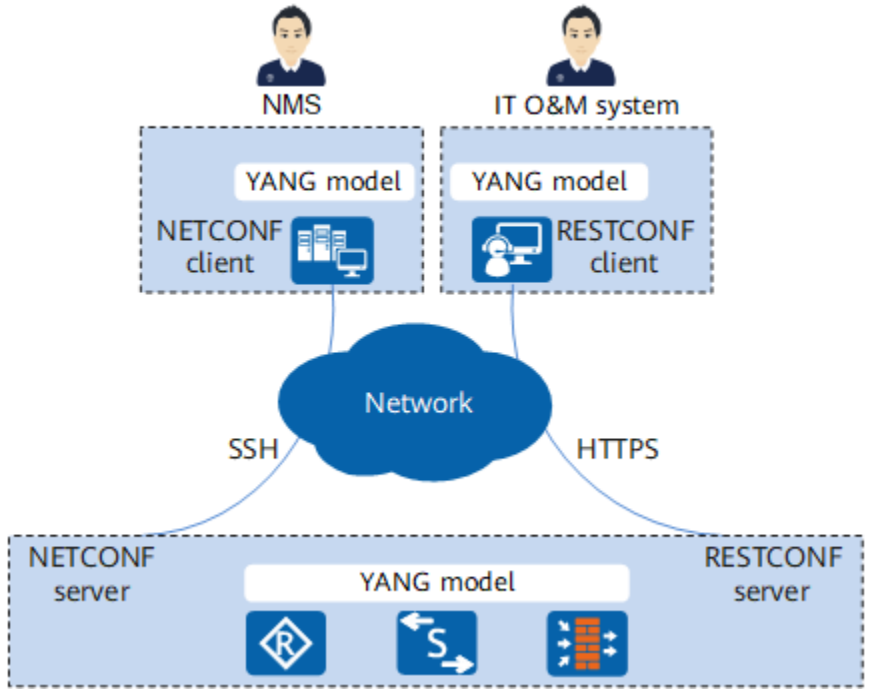


Diagram Source: Huawei Technologies Co., Ltd.

Flow Management

Admission control: **IEEE 802.1Qat** Stream Reservation Protocol (SRP)

- Admitting or rejecting flows based on flow resource requirements and the available network resources.
- **Decentralized**: “talkers” guarantee the path to the listener is available and reserve the resources

IEEE 802.1Qcc Enhancements to SRP and Centralization Management

- Allow **centrally-managed** and ad hoc systems to coexist

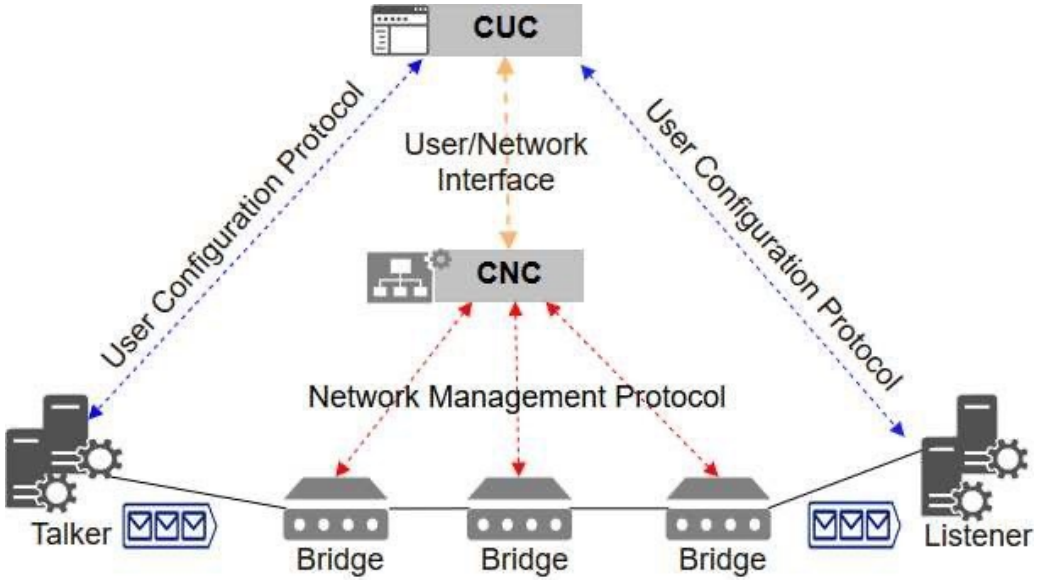


Diagram Source: SDN-based configuration solution for IEEE 802.1 time sensitive networking (TSN)

Reliability - IEEE 802.1CB

- How to protect against **transmission errors** and **link failures**.

IEEE 802.1CB Frame Replication and Elimination for Reliability (FRER)

- **Generation Function**: Sequence numbering and replicating packets in the talker (source) end system and/or in relay systems in the network.
- **Recovery Function**: Eliminating those replicates in the listener (destination) end system and/or in other relay systems.

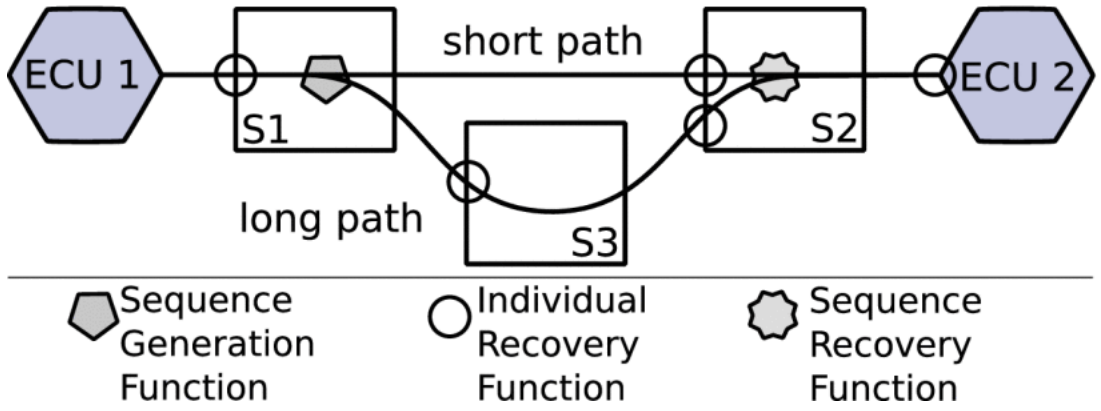


Diagram Source: Challenges and Limitations of IEEE 802.1CB-2017

Wireless TSN

TSN Wireless Support

- **5G**: 3GPP Rel-16 industry expansion
- **Wi-Fi**: IEEE 802.11be (Wi-Fi 7)

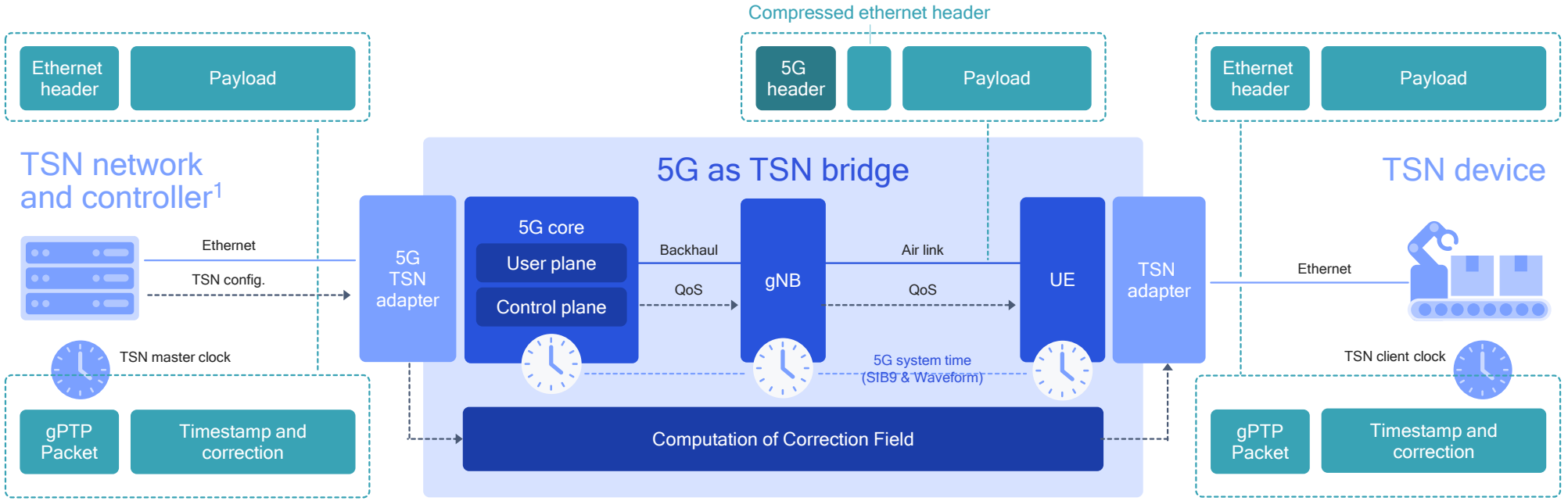


Diagram Source: Qualcomm / Sustainable Concept for Green Logistics and Energy Efficiency in Manufacturing

Research Challenges and Opportunities

Scheduling and Routing

- Can we figure out better approaches?
- What is the “best” approach for each scenario and application?

IEEE 802.1CB

- How to find “best” set of multiple paths.
- Insufficient Buffer Dimensioning (Path length differences)
- Out-of-Order Delivery

Wireless TSN

- Time Synchronization
- Scheduling Efficiency

Multi-Domain TSN, and many more…