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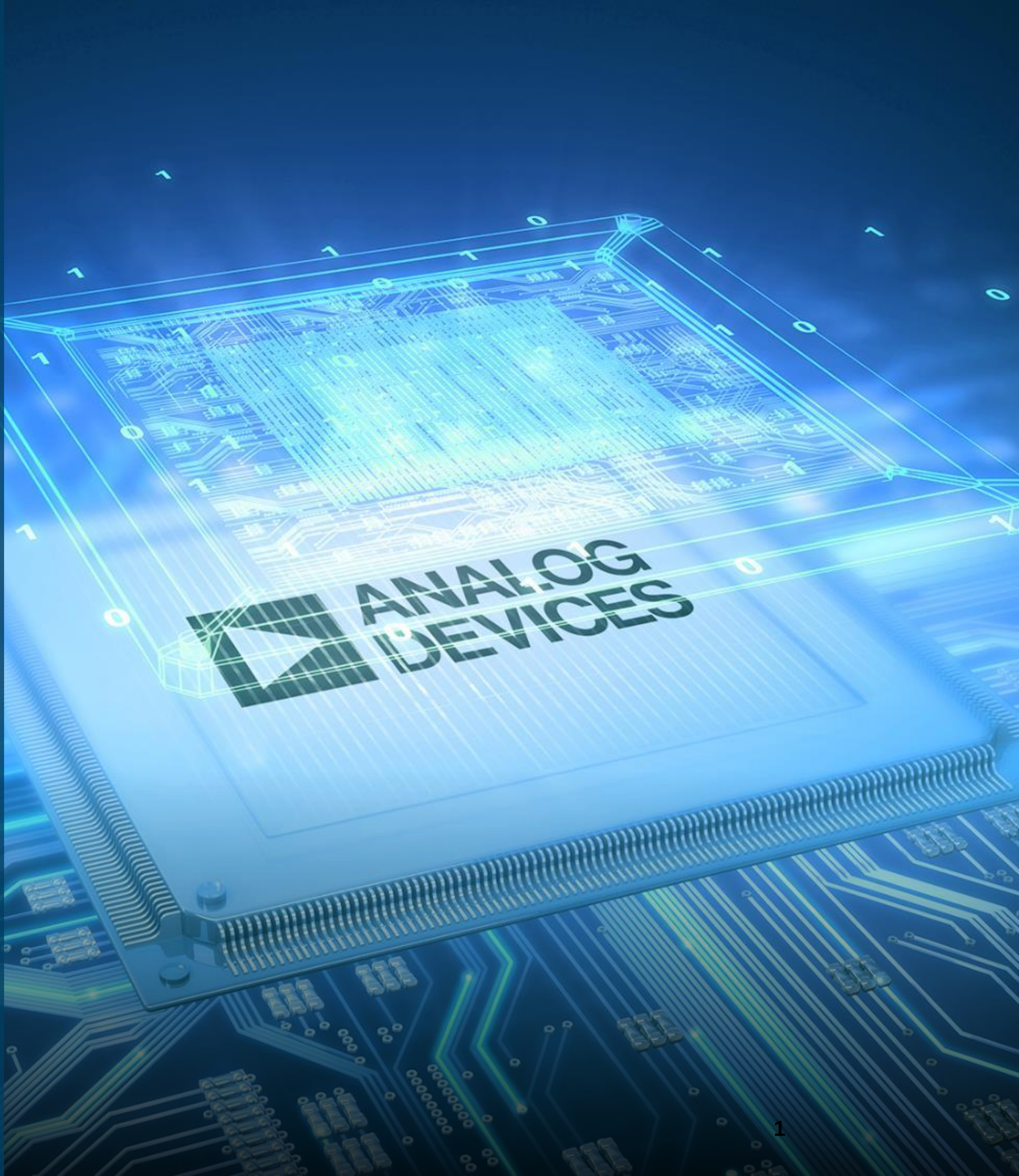
Industry 4.0 – Industrial Ethernet and the Transition to Time Sensitive Networking



CHRIS STELMAR

Field Application Engineer

Discussion Topics

- From Ethernet to Industrial Ethernet
- Major Industrial Ethernet Protocols
- TSN Features for the Industrial Segment
- What's Driving IT / OT Convergence?
- Looking towards the Future

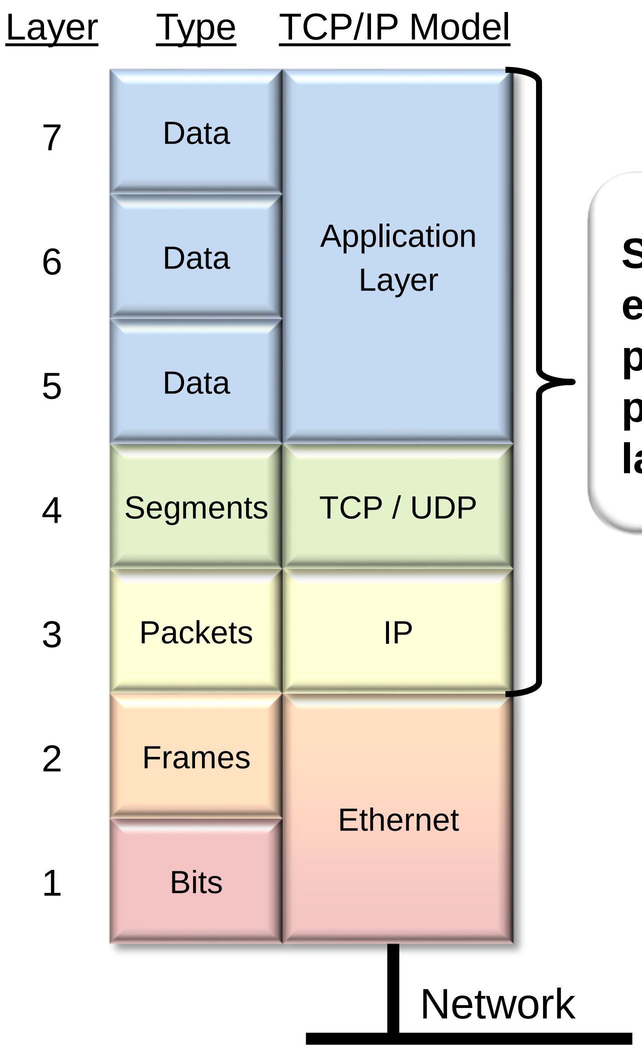
Communication Models and Ethernet

Layer	Type	OSI Model	TCP/IP Model	Authority
7	Data	Application Layer	Application Layer	RFCs, IETF, Industry Org's, etc.
6	Data	Presentation Layer		
5	Data	Session Layer		
4	Segments	Transport Layer	TCP / UDP	
3	Packets	Network Layer	IP	
2	Frames	Data Link Layer	Ethernet	IEEE 802.1
1	Bits	Physical Layer		IEEE 802.3

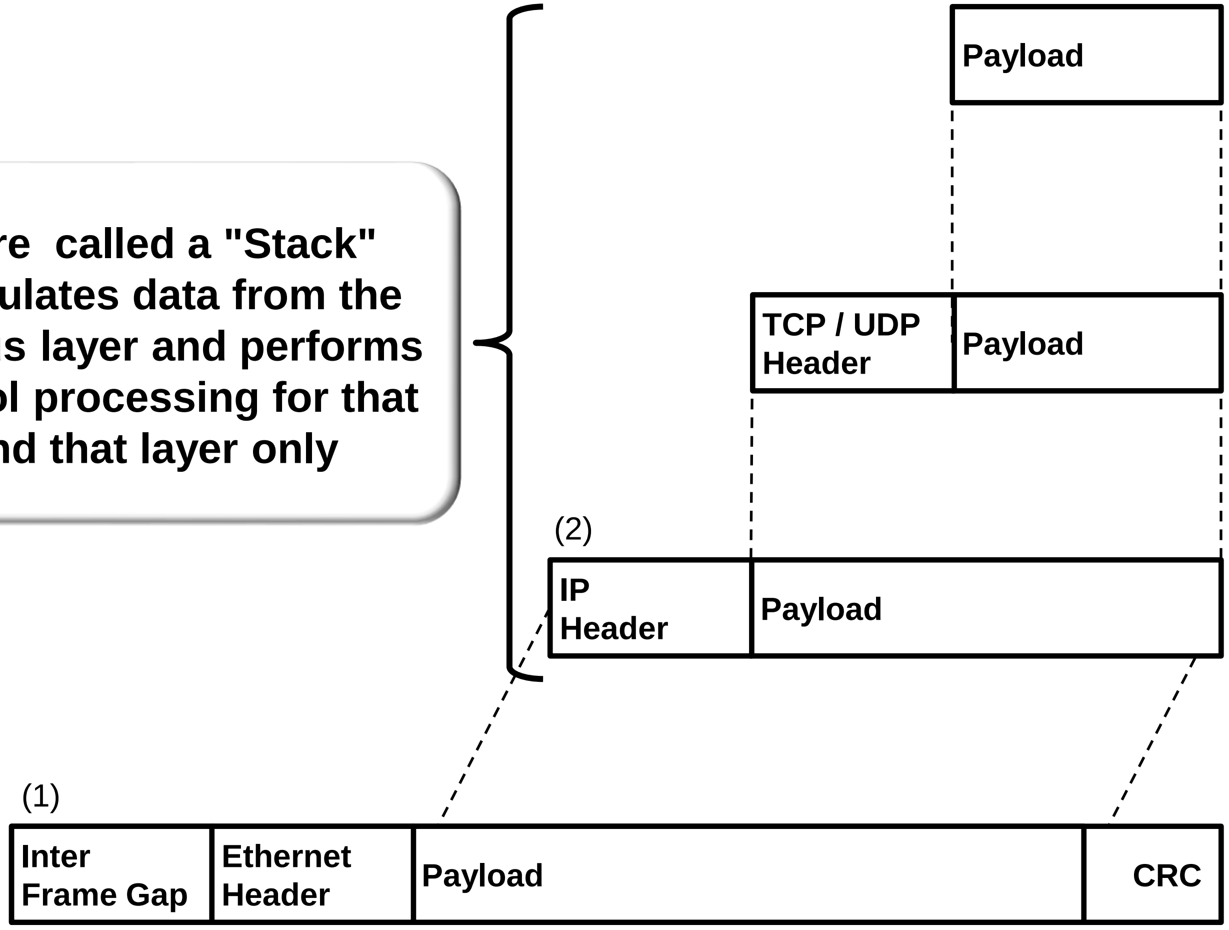
Network

- Wired Ethernet is defined by Layers 1 and 2 of the OSI model
  - Layer 1 = 802.3
  - Layer 2 = 802.1
- 802.3 use components called
  - A "PHY" which is short for "Physical Interface“
  - a "MAC" which is short for "Media Access Control"
- 802.1 defines "Bridging and Management” and uses components called "Switches"

Delivering data to the Application

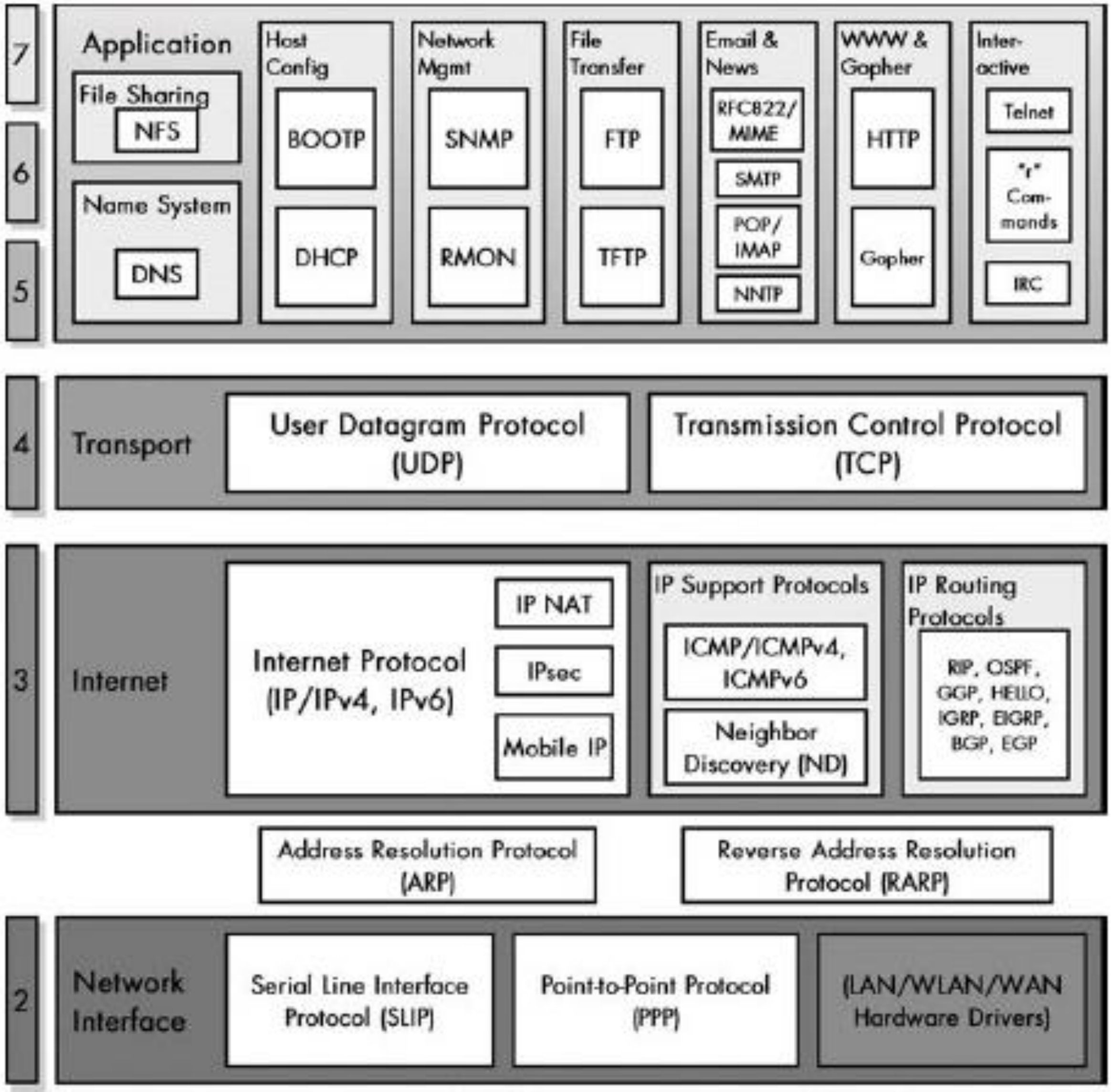


Software called a "Stack" encapsulates data from the previous layer and performs protocol processing for that layer and that layer only



(1) The All-New Switch Book: The Complete Guide to LAN Switching Technology, by Rich Seifert, James Edwards
(2) TCP/IP Guide: A Comprehensive Illustrated Internet Protocol Reference, by Charles M. Kozierok

Each Layer has its own set of protocols



Source: The TCP/IP Guide, A Comprehensive, Illustrated Internet Protocols Reference By Charles M. Kozierok

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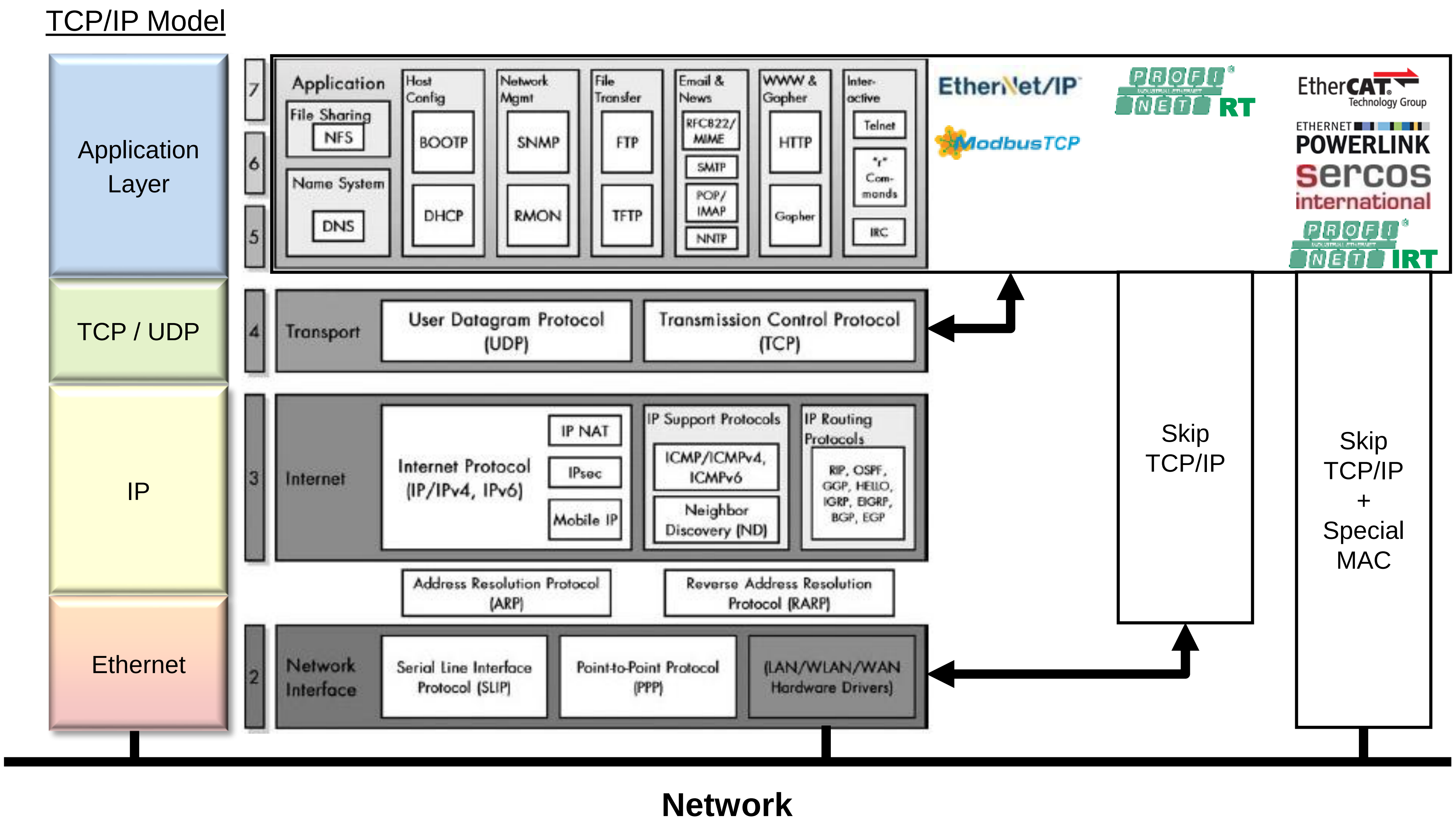
How to meet Real-Time Requirements with Ethernet



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- ► Major Industrial Ethernet Protocols
- ► TSN Features for the Industrial Segment
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- ► Looking towards the Future

Industrial Ethernet Industry Organizations

Organization	Industrial Ethernet Protocol	Sponsoring Company
PROFINET and PROFIBUS International	PROFINET	SIEMENS
Open Device Vendors Association, Inc.	EtherNet/IP	Rockwell Automation, Schneider Electric, Cisco, Rexroth Bosch Group, Omron
EtherCAT Technology Group	EtherCAT	BECKHOFF
Sercos international e.V.	sercos international	Rexroth Bosch Group, Schneider Electric
Ethernet POWERLINK Standards Group	ETHERNET POWERLINK	B&R

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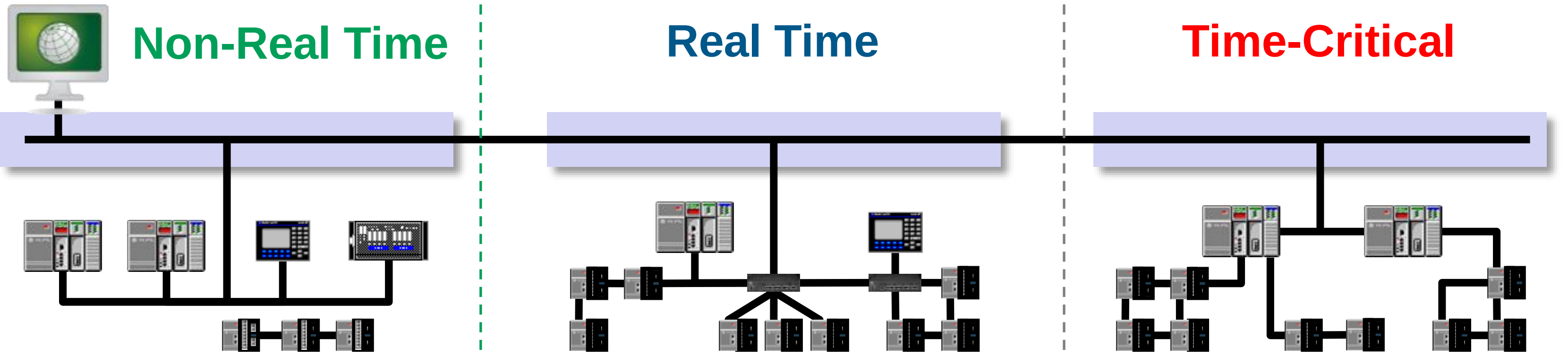
Industrial Ethernet protocols address various levels of real-time

Meet Real Time and Time-Critical performance using multiple protocols

Non-Real Time | Real Time | Time-Critical



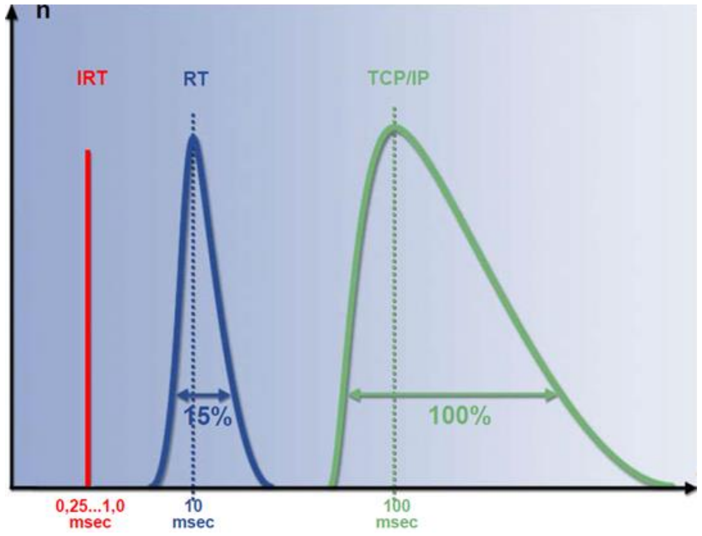
Data Services, IT, etc. | Factory Automation | Motion Control

Real Time

Enterprise Network
"Best Effort"

Factory Network
< 15% jitter | *< 1% jitter*

~100 ms | ~1 ms



Problem: Website doesn't update for 5s
Effect: "Who cares?!"

Problem: *Fill* command 500ms late
Effect: Bottle overflow!

Problem: *Stop* command 50ms late
Effect: Robot *kills* worker

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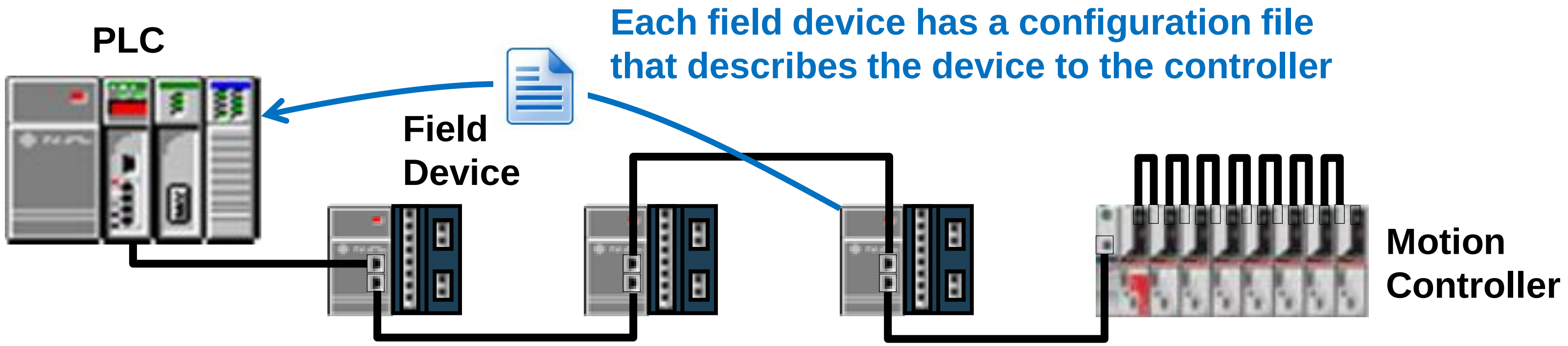
Purpose of Industrial Ethernet Protocols



- The purpose of an industrial Ethernet protocol is data exchange between
  - Controller to / from a Device
  - Controller to / from a Controller
- Each protocol exchanges data differently depending on:
  - Cycle time, Latency, Jitter (precision of data transport)
  - Acyclic information (alarms, diagnostics, etc.)
  - Topology support
  - Device configuration and network configuration
- Each protocol stack is a layer 7 application that controls data exchange and network management

Device and Network Management

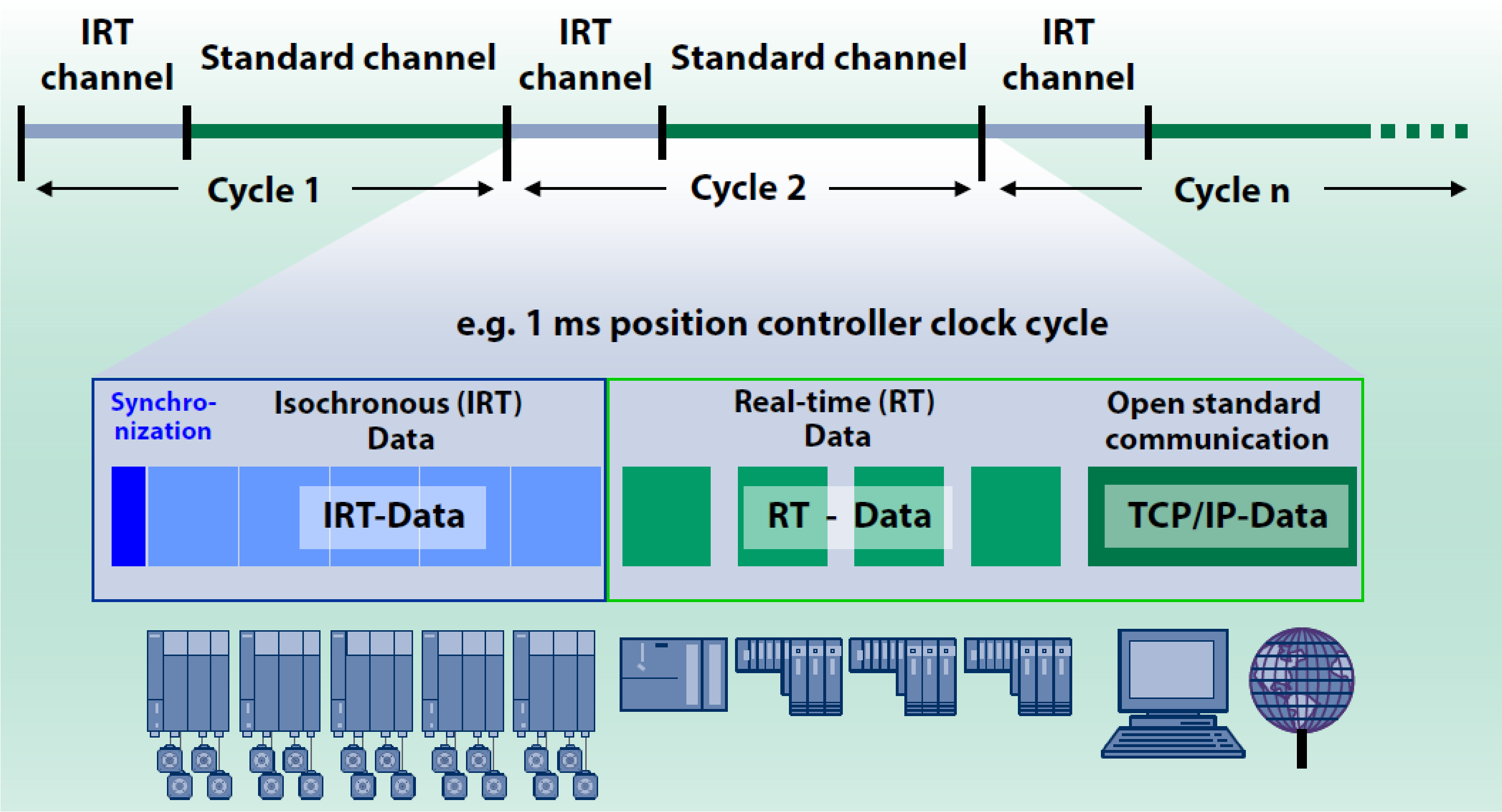
	PROFINET	EtherNet/IP	EtherCAT	sercos international	ETHERNET POWERLINK
Device Configuration	GSD	EDS	ESI	SDD	XDD
Network Configuration	DCP	DHCP or Static	EtherCAT Master	Sercos Master	N/A – Hub Connection
Time Synchronization	IRT: gPTP Peer-to-peer	1588v2 End-to-end	Distributed Clock from Master	Distributed Clock from Master	Synchronization from Master
Topology	Any, Rings w/ MRP (RT) or MRPD (IRT)	Any, Rings w/ DLR	Any	Any	Any

Data Exchange and Accessing Network Services

	Data Exchange	Standard Network Service (Webserver, Network Mgmt, etc.)
PROFINET	Read / Write to Device Access Point Slot and Sub-slot Addresses	RT: Through TCP/IP IRT: Through TCP/IP at RT Phase
EtherNet/IP	Read / Write to Assembly Object Addresses (other Object optional)	Through TCP/IP
EtherCAT	Read / Write to Mailbox with CAN over EtherCAT (CoE) or Modular Device Profile	Encapsulate TCP/IP in Ethernet over EtherCAT (EoE)
sercos international	Master writes to devices with MDTs and Reads from devices with ATs	Through TCP/IP during Universal Communication Channel Phase
ETHERNET POWERLINK	Read / Write to Device IO Addresses with CAN in Automation Profiles	Through TCP/IP during Asynchronous Phase

PROFINET data exchange details

- PROFINET has two types of communication
  - "RT" = "Real-Time", works with standard MAC, supports cycle times down to 1 ms
  - "IRT" = "Isochronous Real-Time" requires a special MAC, supports cycle times down to 125 μs



Courtesy of PI North America

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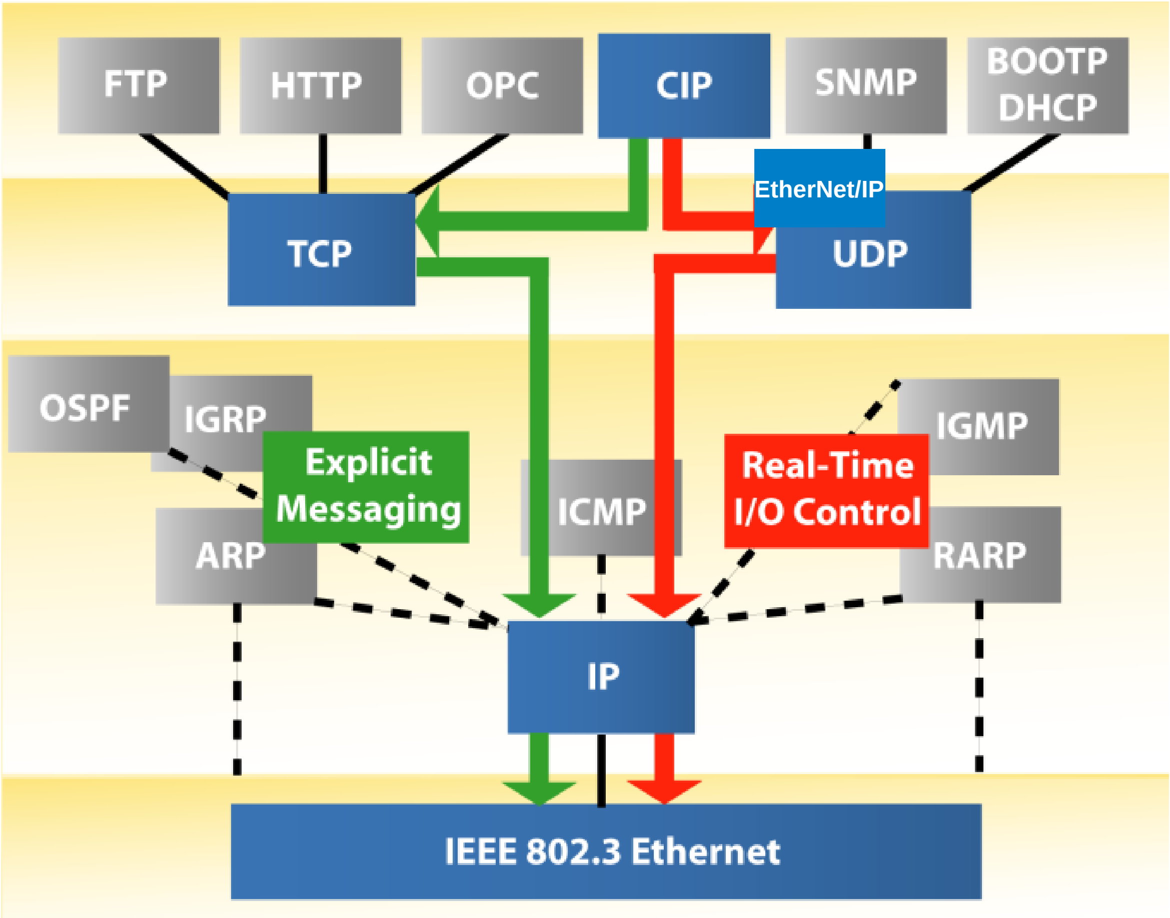
EtherNet/IP data exchange details



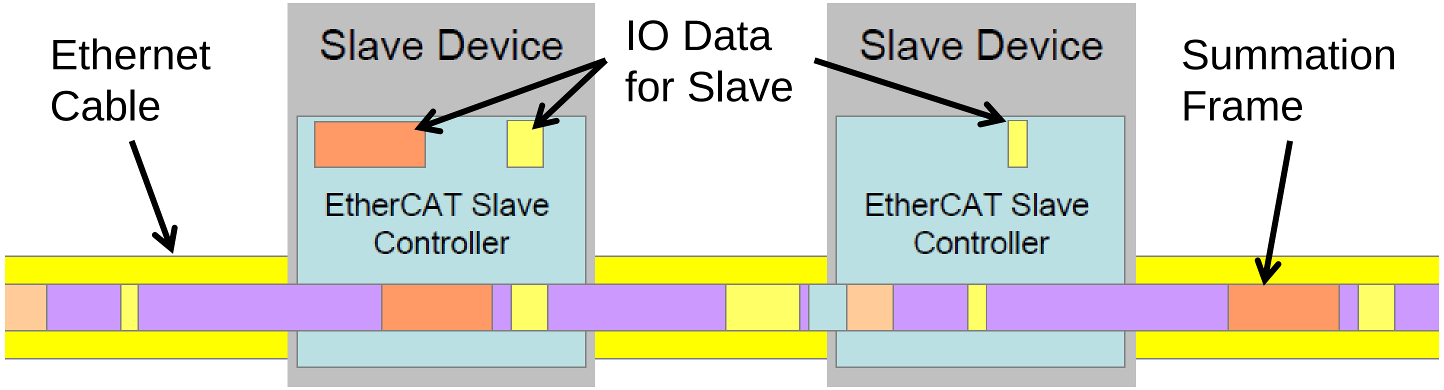
Courtesy of ODVA

- UDP Transport is used for Real-Time IO
  - Bandwidth is manually calculated to ensure on-time delivery
  - “RPI” sets the cycle time
  - Cyclic messages are also called Implicit Messages
- TCP Transport is used for Acyclic IO
  - These types of messages are called Explicit Messages
- Each type of IO requires a connection with the PLC

Courtesy of Open Device Vendors Association (ODVA)

EtherCAT data exchange details

- EtherCAT frames traverse the network like a train
  - This type of Ethernet frame is called a summation frame
  - It contains data for all devices on the network (although multiple messages can serve each device)
- Each slave device reads or writes data as the message goes by (i.e. message does not stop or get stored)
- Allows for very fast data exchange down to 12.5 µs
  - Very low latency, very low jitter
  - Can drive ADCs and DACs directly with data from the EtherCAT frame
  - The most efficient use of an Ethernet frame
- No other Ethernet communication can be on the network at the same time



Courtesy of EtherCAT Technology Group

SERCOS data exchange details

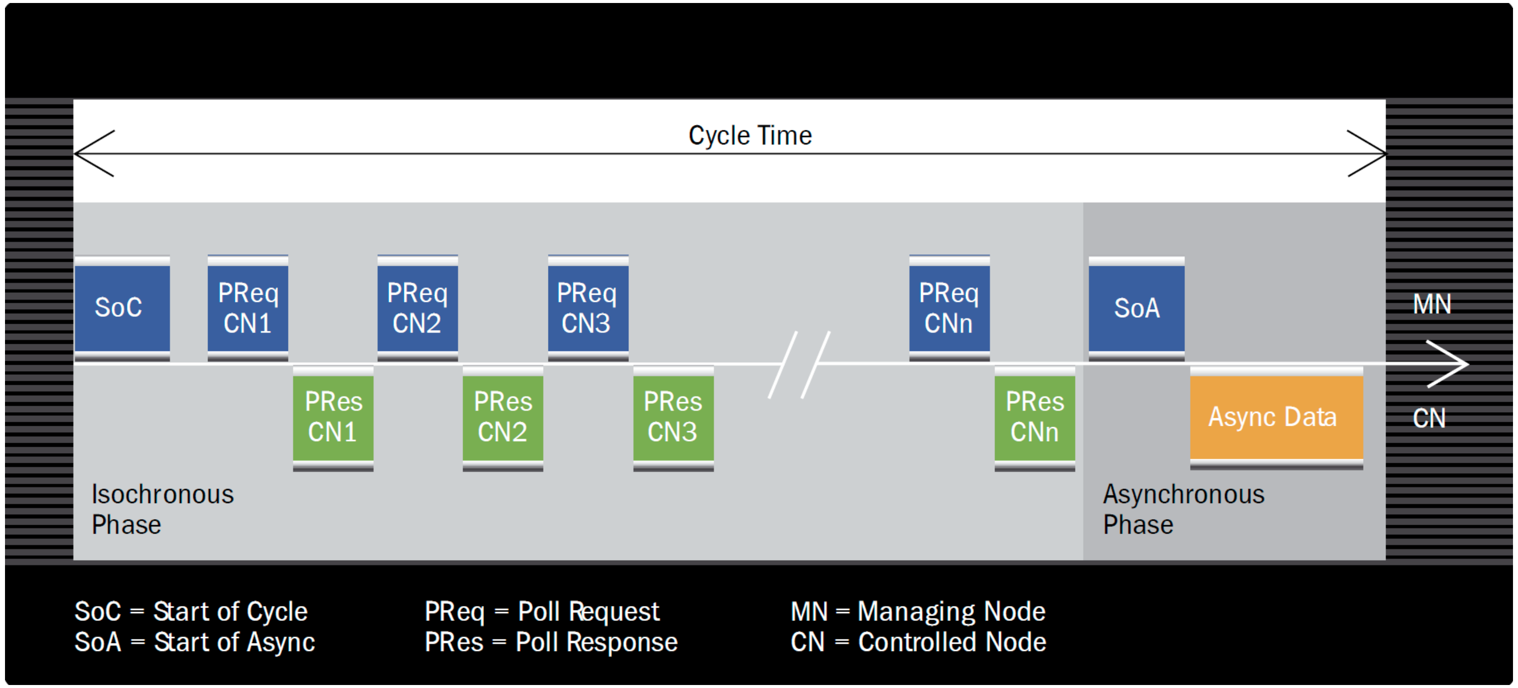
- MDT(s) and AT(s) use the summation frame technique to maintain high precision synchronization between master and slave
  - MDT is a summation frame that the master sends to write data from the master to the slave
  - AT is a summation from that the master sends to read data from the slaves
  - Each slave knows where in the MDT and AT to read or write its data
- At the end of the MDT and AT communication, the rest of the cycle is used for Non-Real Time communication
  - Standard Ethernet or TCP/IP Communication occurs during this time
- Cycle time can be selected between 31.25 µs and 65 ms

Courtesy of SERCOS International

MDT = Master Data Telegram
AT = Acknowledge Telegram

POWERLINK data exchange details

- The master is called a Managing Node (MN) and the slave is called a Controlled Node (CN)
  - The Master sends out a request to a CN and the CN responds
  - The Master does this for all CNs on the network
  - Once all CNs have been serviced, and Start of Asynchronous Phase message is sent out to a slave and it can respond with standard Ethernet or TCP/IP messages
- Cycle Times go down to 100 µs



Courtesy of Ethernet POWERLINK Standards Group

Discussion Topics

- From Ethernet to Industrial Ethernet
- Major Industrial Ethernet Protocols
- TSN Features for the Industrial Segment
- What's Driving IT / OT Convergence?
- Looking towards the Future

Where does TSN fit into Networking?

Layer	Type	OSI Model	TCP/IP Model	Authority
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5	Data	Session Layer		
4	Segments	Transport Layer	TCP / UDP	
3	Packets	Network Layer	IP	
2	Frames	Data Link Layer	Ethernet	IEEE 802.1
1	Bits	Physical Layer		IEEE 802.3

Network

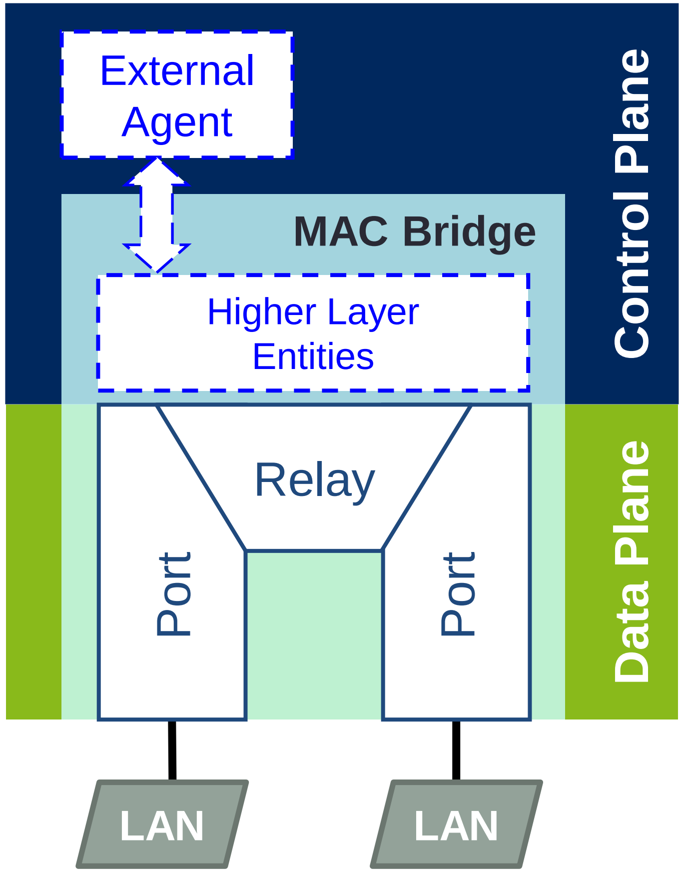
- Specifications for Ethernet and the Internet were not developed for deterministic communication
- Layer 2 has the most impact on making Ethernet-based communication deterministic (closest to the Physical Layer)
- The IEEE 802.1 organization is responsible for Layer 2 standardization, as a consequence, making Ethernet deterministic falls under their purview
- The task group within IEEE responsible for deterministic Ethernet is called "Time Sensitive Networking" or TSN

How TSN evolved within Ethernet Standardization

- Bridging was originally defined by IEEE 802.1D
- When VLANs were added to this specification it became IEEE 802.1Q
- However, this didn't address the deterministic requirements for industries like Factory Automation
  - VLANs added many Quality of Service (QoS) options which improved deliverability of various traffic classes, but **not** in a deterministic fashion
  - Various industry organizations were formed starting in 1999 to address these requirements
  - PNO, ODVA, ETG, etc. develop their own "non-standard" deterministic Ethernet variants
- IEEE began to address determinism with the formation of the Audio Video Bridging (AVB) Task Group in 2006
- The charter of the AVB Task Group was expanded for a wider range of deterministic Ethernet requirements in 2012
  - This is the Task Group we now call Time Sensitive Networking (TSN)

Basic concepts for Ethernet switching

- 802.1Q provides the specification for bridging of 2 or more Ethernet ports
- IEEE uses the "Baggy Pants" model to describe bridging requirements
- Control Plane is for network management
  - Control protocols are implemented by Higher Layer Entities
  - External Agent can provide both control and data distribution
- Data Plane is for distribution of application data
  - Consists of a relay and at least 2 ports



Source: IETF 86 Tutorial, "Media Access Control Bridges and Virtual Bridged Local Area Networks", March 2013

Overview of TSN Features

- TSN is a set of 802.1 features for time-sensitive data transmission over Ethernet that can be "Mixed and Matched"
  - Use of features depends on device performance requirements
  - Devices advertise their capabilities and the network is configured accordingly
- Features are targeted at industrial, automotive, and AVB

Industrial Focused Features

- Time Synchronization, IEEE 802.1AS-Rev
- Scheduled Traffic, IEEE 802.1Qbv
- Frame Preemption, IEEE 802.1Qbu / 802.3br
- Per-Stream Filtering and Policing, IEEE 802.1Qci
- Frame Replication and Elimination for Reliability, IEEE 802.1CB
- Stream Reservation, IEEE 802.1Qcc

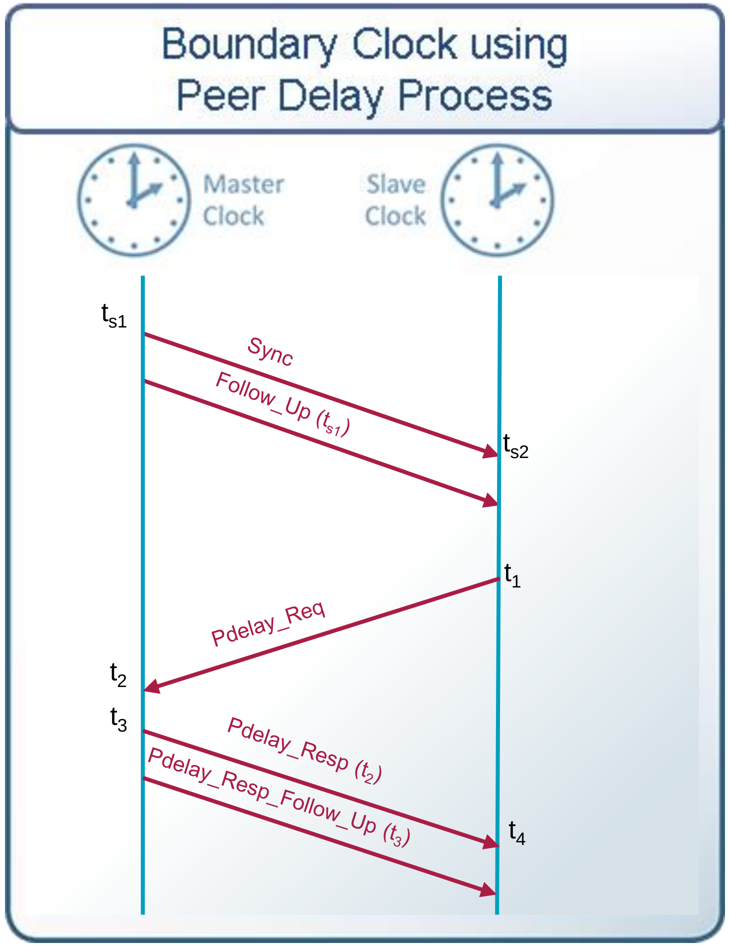
AVB Focused Features

- Time Synchronization, IEEE 802.1AS-Rev
- Forwarding and Queuing, IEEE 802.1Qav
- Stream Reservation, IEEE 802.1Qat
- AVB Systems, IEEE 802.1BA

- All features found in Industrial Ethernet can be found in TSN

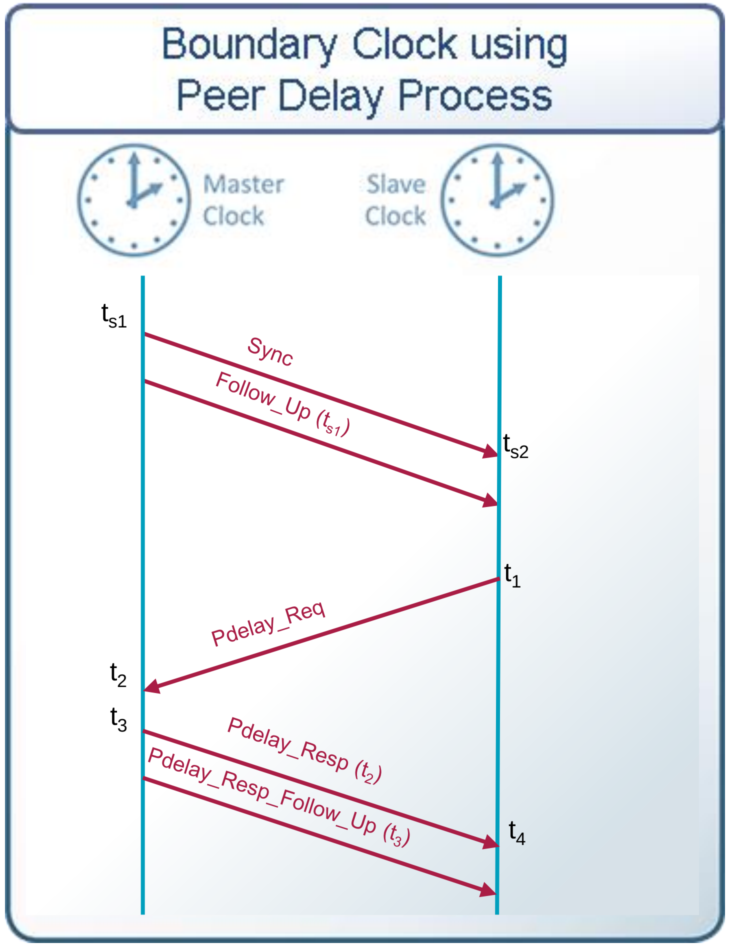
Time Synchronization, IEEE 802.1AS-2011

- Purpose: provide network with accurate, reliable, simple-to-use time
- How? Use a time synchronization profile of IEEE 1588v2
- One Grand Master provides time
  - Best Master Clock Algorithm (BMCA) used to select the Grand Master
  - Performed periodically (Announce messages)
- Synchronize time across the network
  - Uses a two-step process
  - Performed periodically (Sync and Follow_Up messages)
  - i.e. the grand master is the master to its slave device,
    that slave device is a master to its slave, and so on…
- Peer delay keeps time synchronized
  - Uses a two-step process
  - Performed periodically
    (Pdelay_Req, Pdelay_Resp and Pdelay_Resp_Follow_Up messages)
- Uses Layer 2 transport



Time Synchronization, IEEE P802.1AS-Rev

- Purpose: improve GM switchover performance and allows support for multiple time domains
- Extension to IEEE 802.1AS-2011 (backward compatible)
- One or more Clock Domains provide time
  - Best Master Clock Algorithm (BMCA) ***or a fixed configuration*** is used to select the Grand Master ***for each Clock Domain***
  - ***Provides for Redundant GMs***
  - Performed periodically (Announce messages)
  - ***Other Clock Domains may be used for Application timing, etc.***
- Synchronize time across the network
  - Uses a two-step process, ***option to use a one-step process***
  - Performed periodically (Sync and *Follow_Up* messages)
  - i.e. the grand master is the master to its slave device, that slave device is a master to its slave, and so on…
- Peer delay keeps time synchronized
  - Uses a two-step process , ***option to use a one-step process***
  - Performed periodically (Pdelay_Req, Pdelay_Resp and *Pdelay_Resp_Follow_Up* messages)



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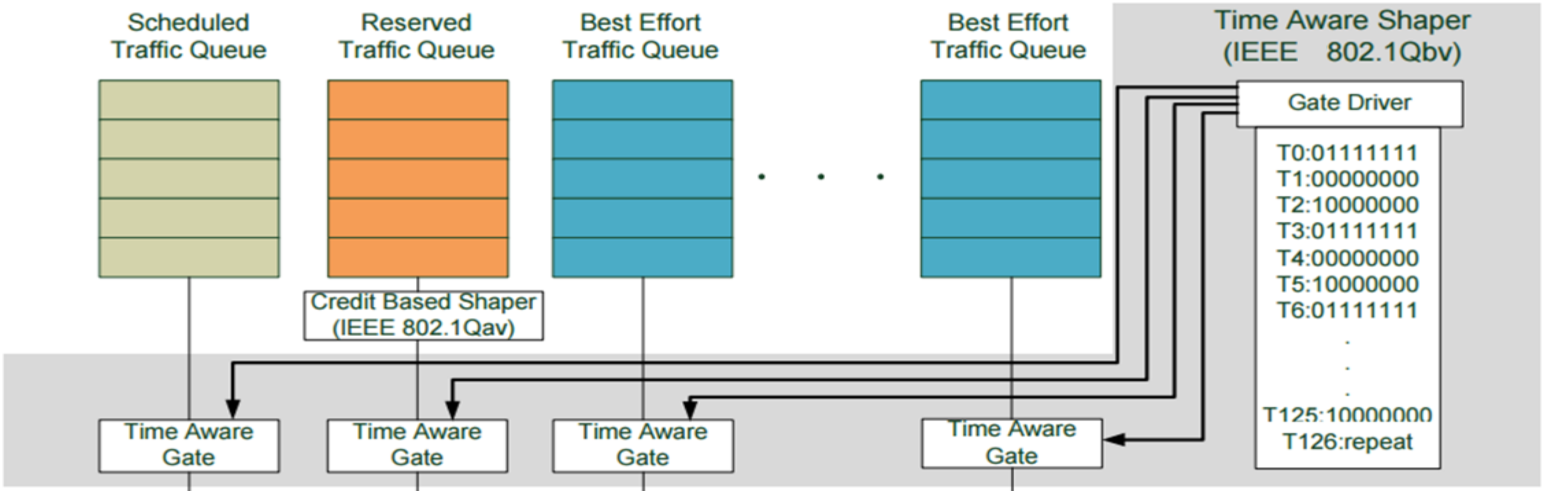
Scheduled Traffic, IEEE 802.1Qbv

- Purpose: Avoid interfering traffic
  - Provides bounded latency and guaranteed bandwidth for a TSN Stream within a Traffic Class (determinism)
- How? Divide Ethernet traffic into different classes
  - traffic class of TSN Stream determined by VLAN Priority Code Point (PCP)
  - ensure only specific traffic class(es) has access to the network for a given time
  - create a time-protected “channel” used by that traffic class alone
- Each egress port is gated, messages queued until scheduled time arrives
  - Send all queued messages until time window closes
  - Builds on 802.1AS so everyone has accurate time in network



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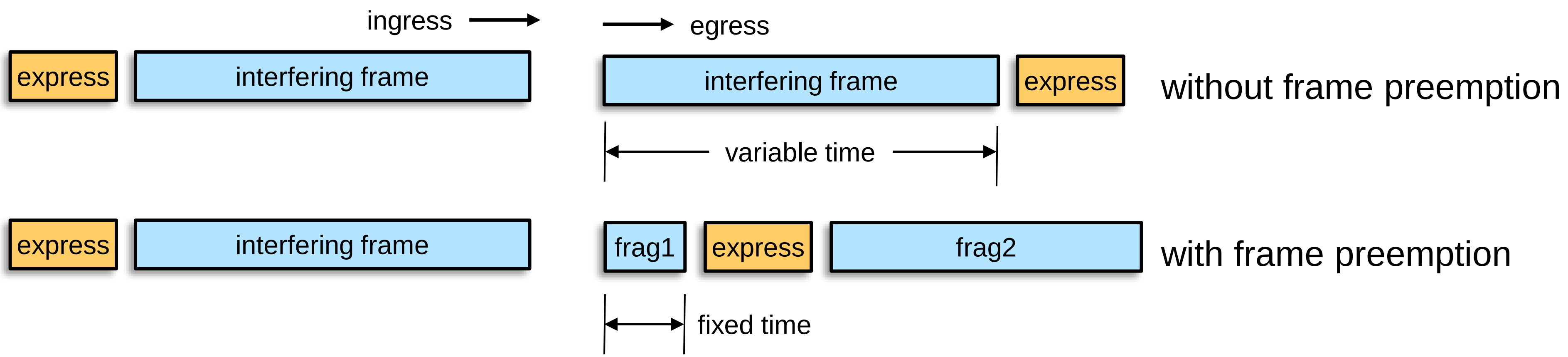
Preemption, IEEE 802.1Qbu / 802.3br (1 of 3)

- Purpose: Ensure high priority traffic arrives at a destination with bounded latency
- How? Break-up lower priority (interfering) frames into smaller frames allowing high priority (express) traffic to move ahead with minimum interference
  - accomplished at the Layer 2, requires modifications to the MAC behavior (802.3)
  - higher level applications are unaware of frame preemption



Without frame preemption, one can image two frames ingressing a switch (here as on the same port) such that the interfering frame begins to egress first. The express frame will be delayed the entire time of the interfering frame, which will vary based on the size of the interfering frame. With frame preemption, the same ingress behavior results in a bounded delay for the express frame as the interfering frame is fragmented.

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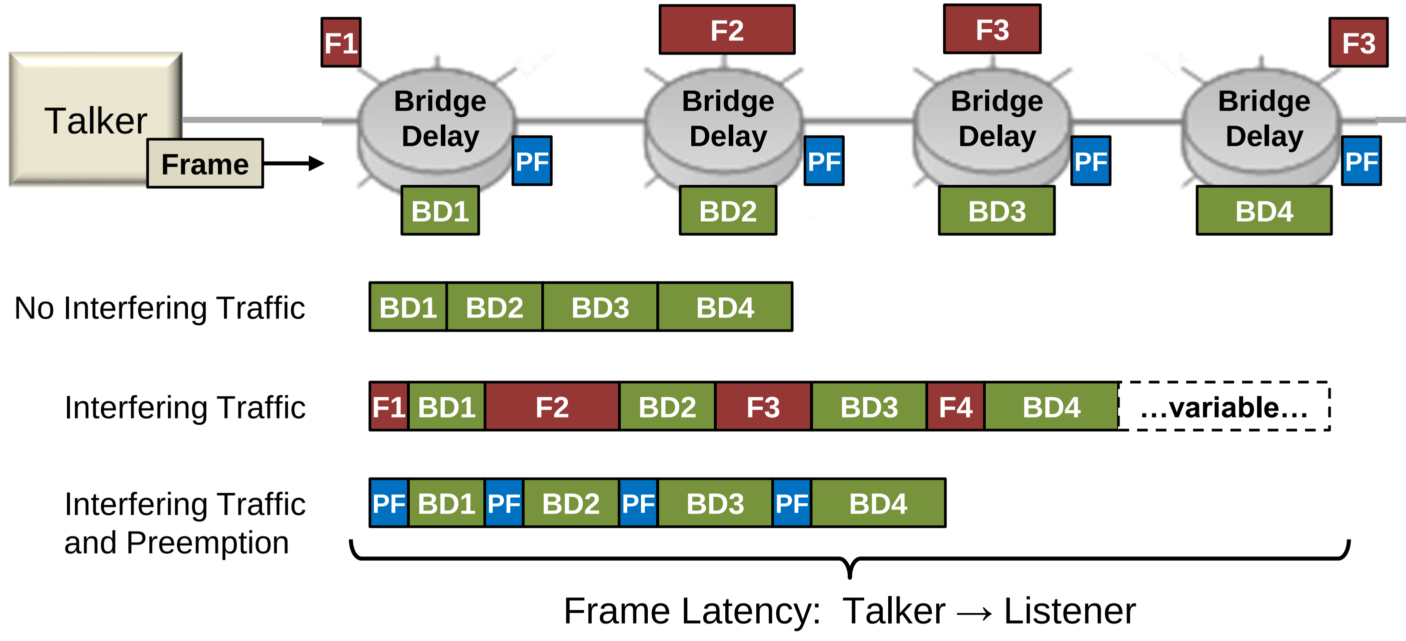
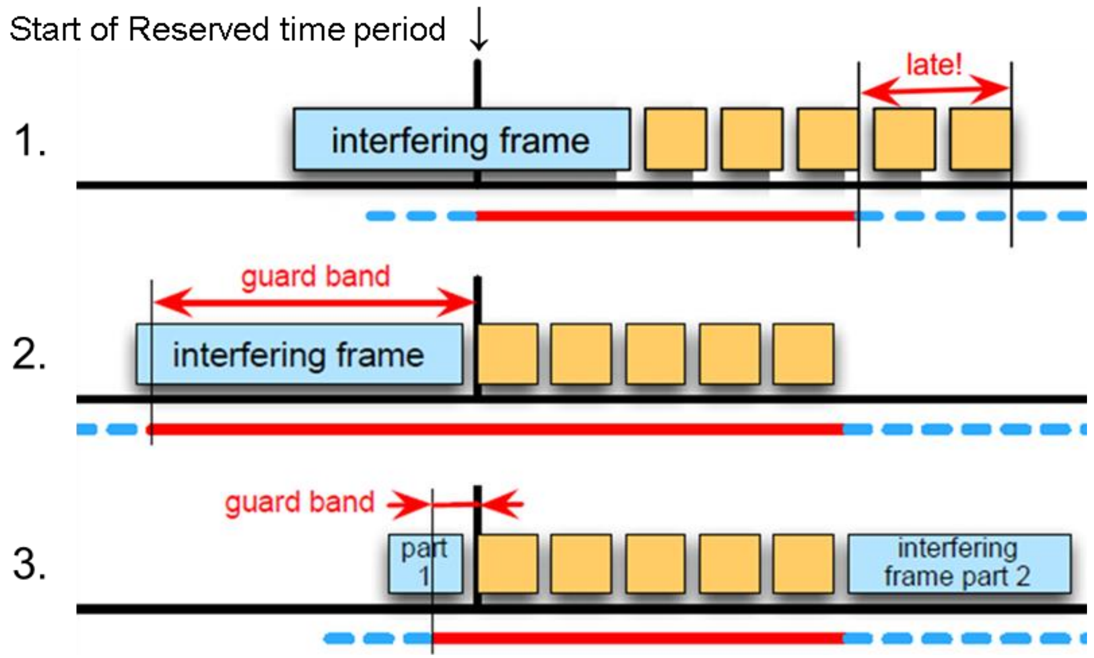
Preemption, Latency Example (2 of 3)

- Preemption allows unscheduled traffic to be prioritized to have a fixed latency
  - With no interfering traffic: Latency is the sum of all Bridge Delays
  - With interfering traffic and no preemption: Latency is the sum of all Bridge Delays and the sum of all Frame Delays. Latency is variable due to variable frame lengths.
  - With interfering traffic and preemption: Latency is the sum of all Bridge Delays and the sum of all Preemption Frame Delays. Latency is fixed due to fixed preemption frame lengths.



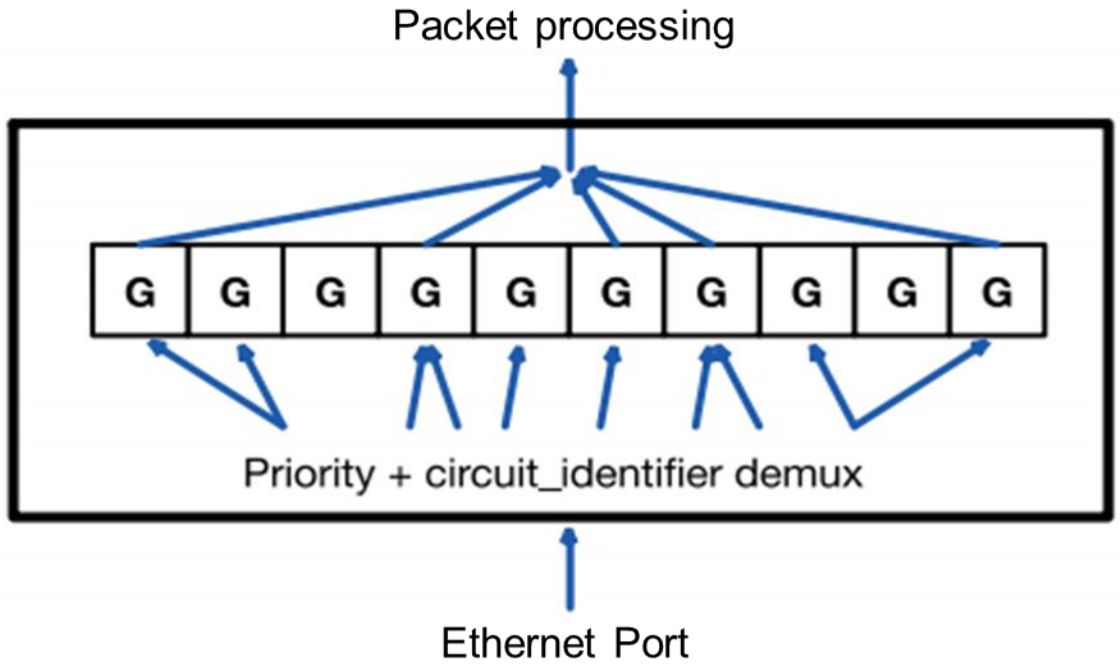
Preemption, IEEE 802.1Qbu / 802.3br (3 of 3)

- Scheduled traffic ensures high priority traffic arrives "on-time", but unscheduled traffic can still cause scheduled frames to be late
  1. An unscheduled frame that starts transmission before the start of a reserved time period can extend outside its allocated window, interfering with more critical traffic
  2. Guard bands solves this problem, but reduce bandwidth efficiency
  3. Preemption breaks interfering frames into smaller “fragments” to solve this



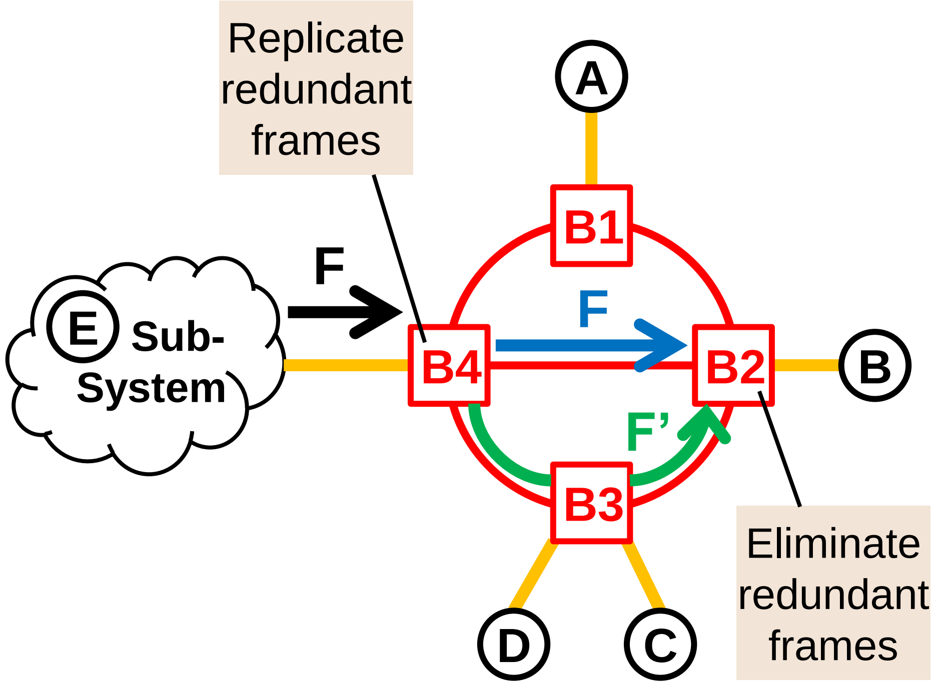
Per-Stream Filtering and Policing, IEEE 802.1Qci

- Purpose: Prevent traffic overload conditions (DDoS or erroneous delivery) from affecting the receiving node
- How? Filtering traffic on a per stream basis by providing a *gate* for each stream
  - per-stream *gate* is either open (passes frame) or closed (drops frame) to enforce a “contract” for a stream
  - once a “contract” is violated, the *gate* remains closed until management action changes its state
- Contract functions could be
  - Frame size
  - Bandwidth based
    - simple octets/time
    - profiles (leaky bucket)
  - Burst sizes based
  - Time based



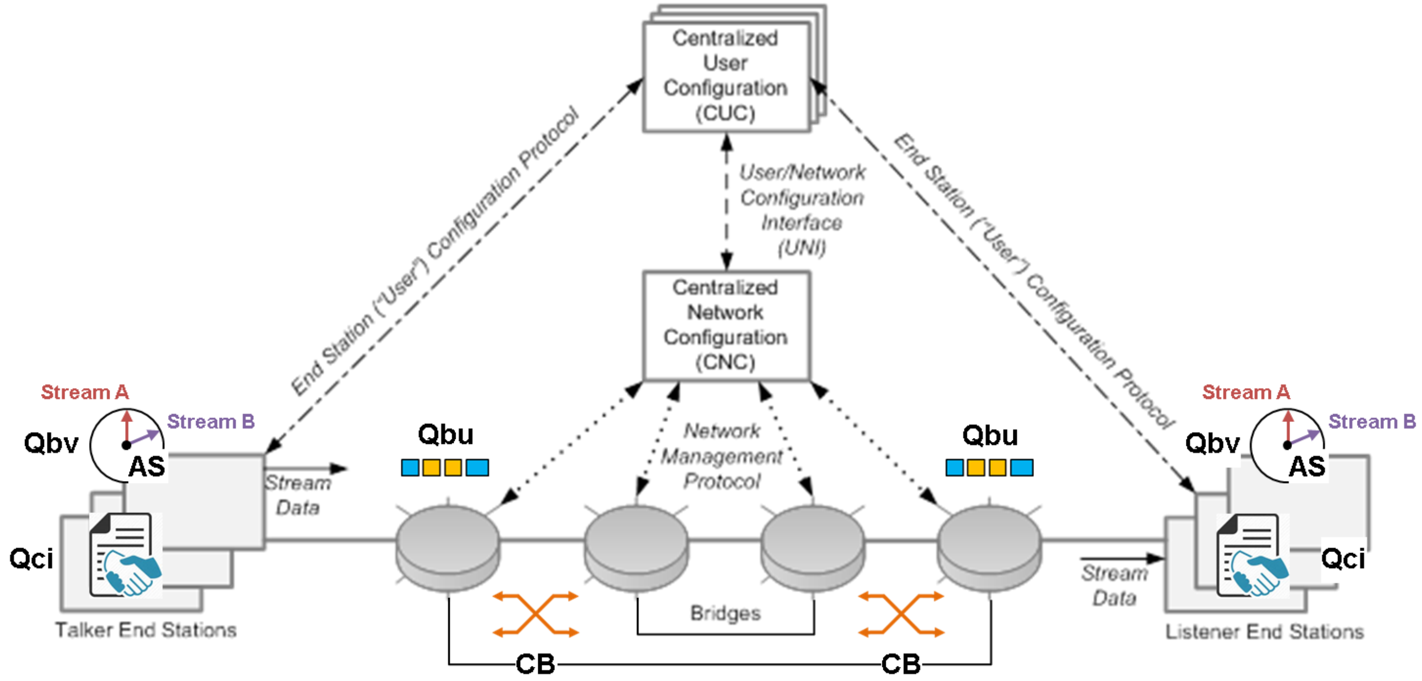
Frame Replication and Elimination for Reliability, IEEE 802.1CB

- Purpose: Provide lightweight redundancy for reliable delivery of traffic streams
- How? Frame replication and elimination
  - accomplished at Layer 2
  - no action or awareness necessary at higher layers
- Send two copies of a message along maximally disjoint path to ensure delivery
- Use of redundant paths minimize packet loss due to
  - Link or device failures
  - Congestion
- Discard duplicate frames upon reception

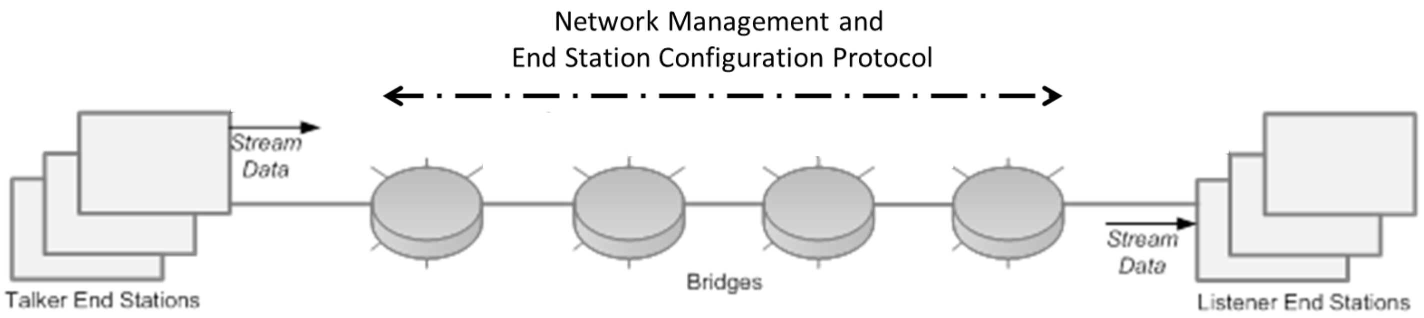


TSN Network Configuration, IEEE 802.1Qcc

Centralized Architecture



Distributed Architecture



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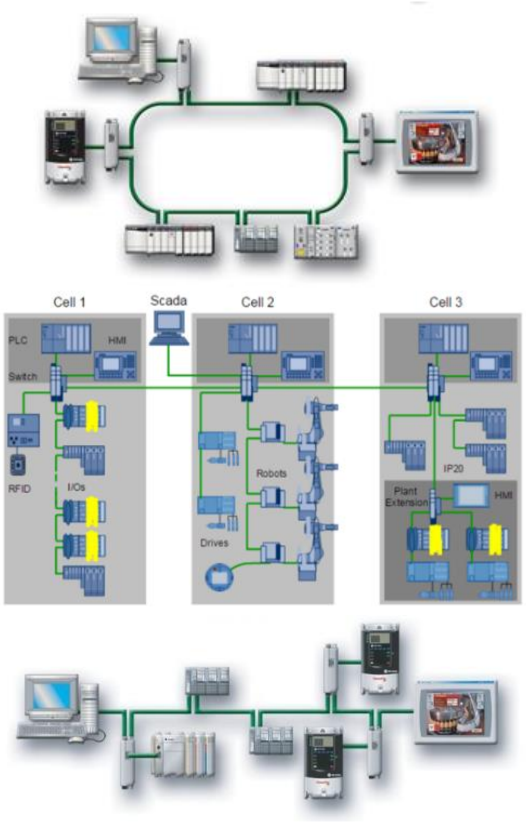
Convergence is merging factory floor and enterprise networks

Meet performance requirements of factory floor equipment

Factory Floor



- 100Mb and 1Gb networks
- Down to 125us cycle times
- < 1us latency, <100ns jitter
- 10x – 100x more devices
- Reliable delivery of data
- No traffic overload or Interference

Interconnected OT (Factory) and IT (Enterprise) Networks

Enterprise

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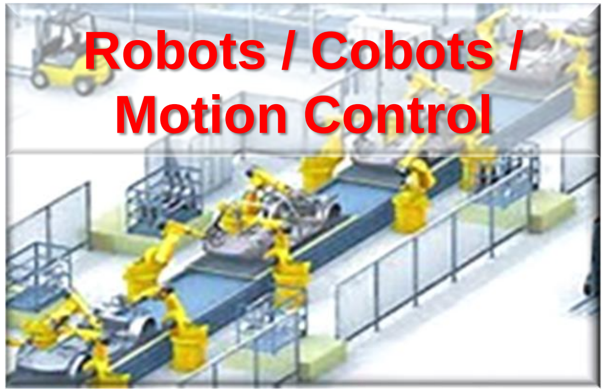
Market segments driving convergence

Core Markets



Provides an Ethernet solution that connects:

- Machine-to-Machine
- Controller-to-Controller
- Controllers to Devices

Its all about the use of Ethernet networks to guarantee "on-time", reliable delivery of data

Emerging Markets

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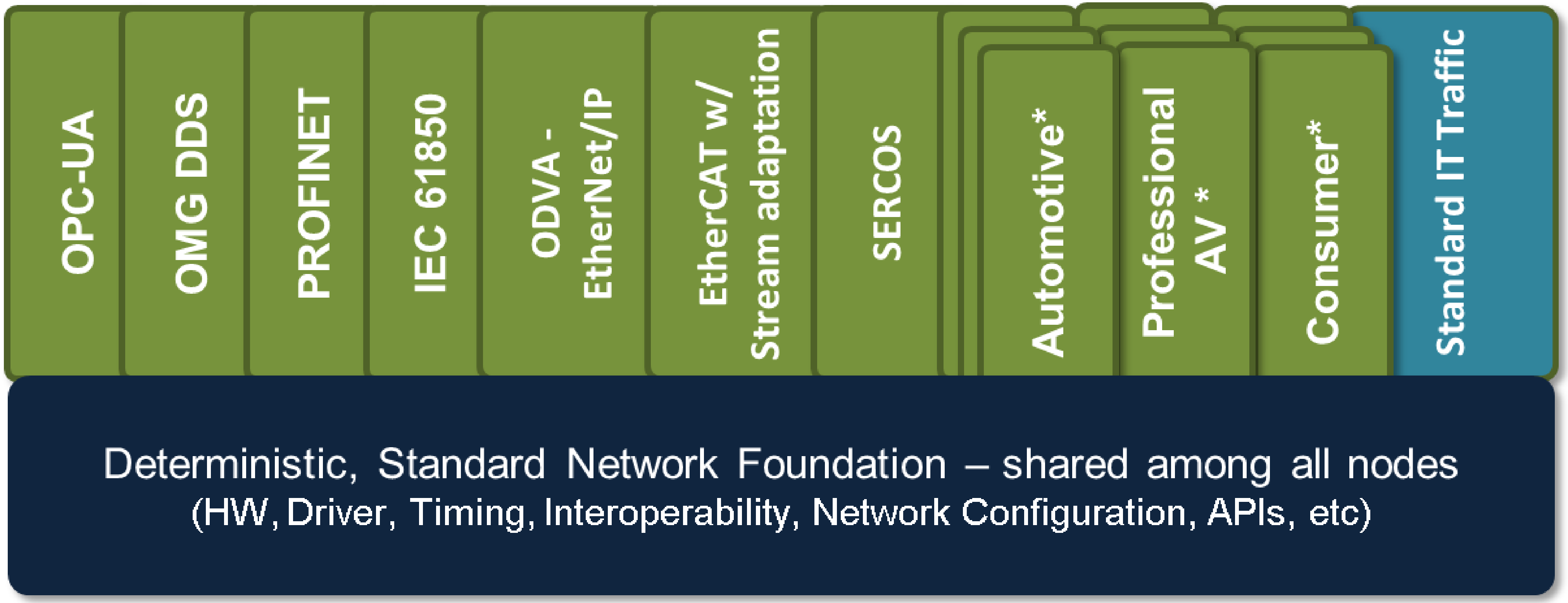
Looking towards the future

Real-time Application Protocols Can Share the Wire With Standard IT Traffic



Avnu Assures the Tested, Standard Network Foundation for Concurrent Applications

IIC Assures the Interoperability of the Standard Network Foundation

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