

Advancing EtherNet/IP In-Cabinet with Functional Safety, 10BASE-T1M, and Ecosystem Expansion

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Abstract

EtherNet/IP In-Cabinet system replaced hardwiring between devices with a single composite media and extended EtherNet/IP communication directly into low-cost industrial control components. As adoption grows, there is increasing demand to support functional safety applications within this ecosystem while maintaining performance, electromagnetic compatibility (EMC), and multi-vendor interoperability. This paper examines emerging EtherNet/IP In-Cabinet Safety use cases, key technical challenges associated with implementation—including EMC behavior and system safety response time—in achieving safe, deterministic communication on Single-Pair Ethernet. The paper explores key standards, including new 10BASE-T1M features and its compatibility when used in existing EtherNet/IP In-Cabinet system. The paper further discusses ecosystem expansion through third-party development toolkits and conformance-ready implementations, enabling broader vendor participation and accelerating innovation. The intent is to provide guidance to device vendors, system integrators, and technology partners on achieving safe, interoperable, and scalable in-cabinet safety architectures using EtherNet/IP.

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Agenda

- EtherNet/IP In-Cabinet System Overview and Safety Application Use Case
- Use of CIP Safety for Functional Safety Solution
- Addressing EMC Immunity Requirements and Improvement of Safety Response Time
- Standards Enhancements and Compatibility with the EtherNet/IP In-Cabinet System
- Availability of Reference Toolkits to Help Accelerate Adoption

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EtherNet/IP In-Cabinet Solution Overview

80%
Reduction
in wiring

50%
Reduction in
Testing time

30%
Reduction
in project
Engineering

EtherNet/IP In-Cabinet





Traditional wiring

What is EtherNet/IP In-Cabinet?

- Introduced in April 2021 with ODVA specification of the EtherNet/IP Constrained Device Profile
- EtherNet/IP connectivity for intelligent field devices, including push buttons, contactors, and motor starters
- Seamless controller integration enabling operational data access, predictive maintenance, and CIP Security capabilities
- Foundation for advanced smart-device and smart-system functionality



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Customer Feedback for EtherNet/IP In-Cabinet Solution

"…16 hours to build, and traditionally it would have been 40 or more" – End User

"… took my best panel wirer against In-cabinet solution.. Saved 50% in wiring time– OEM

"… [reduced] cost by $10,000 including wire [and] wiring time – System Integrator

"If we can put this together, anyone can." – End User



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Why are Functional Safety Products Needed?

LARGE ADDRESSABLE MARKET

$4.1B

Product available market for push buttons and motor controls. E-Stops are required products.

Complete the architecture

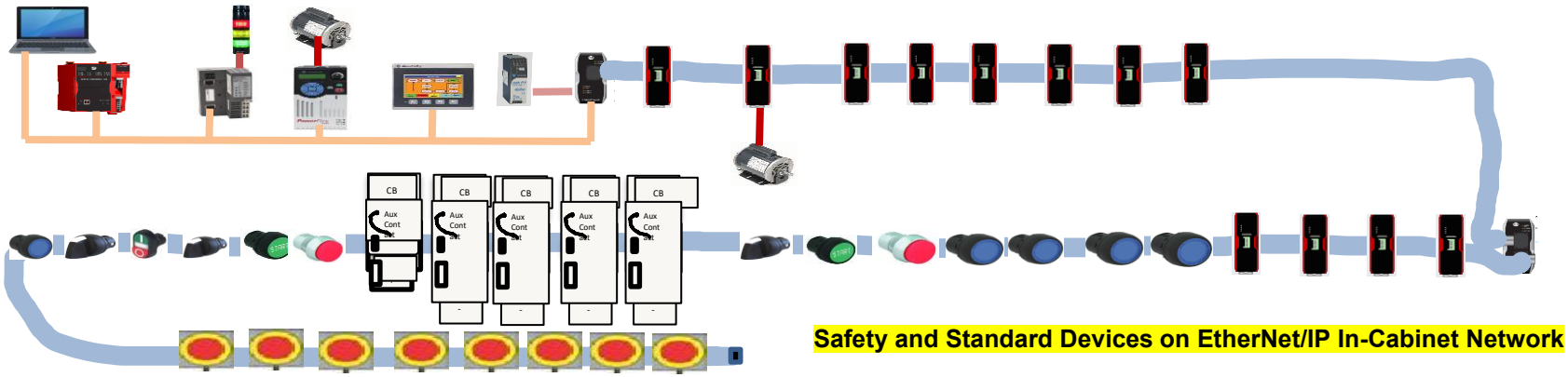
IN-CABINET PLATFORM EXPANSION

Safety architecture can be extended to add additional end nodes to the family of products.

Create pull–through

CAPACITY

Maximum of 20 safety devices, 19 standard In-Cabinet devices for typical motor control applications based on market survey.



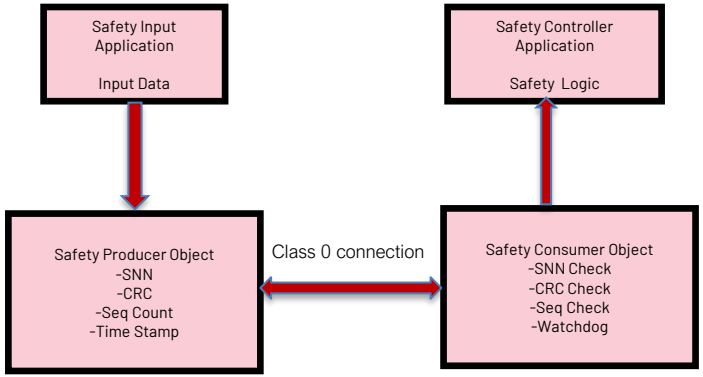
Safety and Standard Devices on EtherNet/IP In-Cabinet Network

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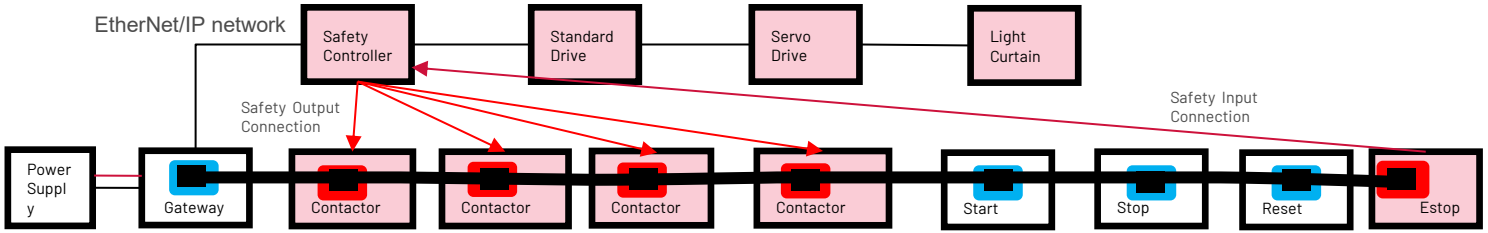
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Use of CIP Safety for Functional Safety Solution

- EtherNet/IP In-Cabinet safety solution requires a Safety Controller, Safety Input Device (e.g., E-stop), and Safety Output Device (e.g., safety contactor or motor starter).
- No changes are required to CIP Safety Volume 5 specification for safety open or safety I/O connections. Safety I/O devices remain compliant with CIP Safety specification and support UDP-only transport profile.
- The EtherNet/IP In-Cabinet gateway (CIP router or switch) acts as a black channel between the Safety Controller and Safety I/O devices.
- CIP Safety does not currently support safety I/O connection aggregation. Gateways must support additional I/O routing for both safety and standard connections.



Safety Input Connection



EtherNet/IP In-Cabinet Safety Solution

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Increased EMC Immunity Requirements for Safety Products

- Functional Safety products are required to pass higher EMC immunity test levels and with increased exposure time per IEC 61000-6-7.

Type of test	Basic standard	Standard Products		Safety Products	
		Test Level Required	Acceptance	Test Level Required	Acceptance
Electrostatic discharge immunity test	IEC 61000-4-2	8 kV / air discharge or 4 kV / contact discharge	B	8 kV / air discharge **or 6 kV / contact discharge (3 times of discharge numbers)**	DS*
Radiated radio-frequency electromagnetic field immunity test	IEC 61000-4-3	10 V/m 80MHz to 1GHz 3V/m 1.4GHz to 6GHz	A	**20 V/m 80MHz to 1GHz** **10V/m 1.4GHz to 2GHz** 3V/m 2 GHz to 6GHz	DS*
Electrical fast transient/burst immunity test (with capacitive coupling clamp)	IEC 61000-4-4	2 kV @5 kHz/100 kHz on power ports 1 kV @ 5 kHz/100 kHz on signal ports	B	2 kV @100 kHz on power ports (factor of 5 for duration) **2 kV @ 100 kHz** on signal ports **(factor of 5 for duration)**	DS*
Conducted disturbances induced by radiofrequency fields immunity test	IEC 61000-4-6	10 V 150 kHz to 80 Mhz	A	**20 V** 150 kHz to 80 Mhz	DS*

Note: DS stands for Defined State. Performance Criterion DS requires that the functions intended for safety applications are either not affected, or, if affected by the disturbance, the equipment reacts such that a detectable and defined safe state is achieved within a specified time.

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Enhancement of In-Cabinet Communication Interface

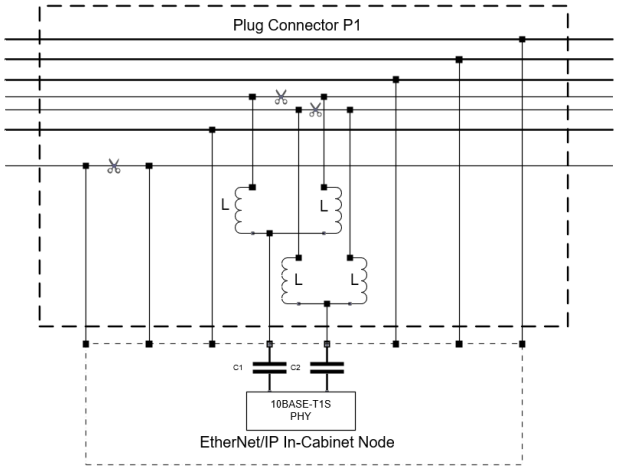
- To meet the increased immunity performance levels, It is recommended to make some improvement to the In-Cabinet communication interface implementation and incorporate Common Mode Choke (CMC).

- EMC Test Specification for Common Mode Choke (CMC) from Open Alliance listed four classes of CMC, and it is recommended to use a class IV device to minimize parasitic capacitance (less than 7pF). One example class IV CMC is TDK ACT1210E-131-2P-TL00.

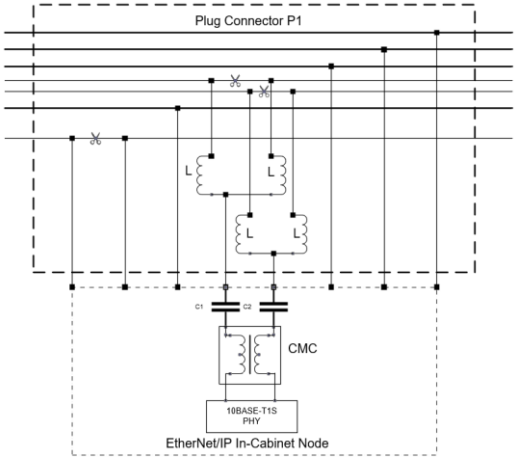
Class	C_{para_max}
I	13 pF < C_{para_max} ≤ 17 pF
II	10 pF < C_{para_max} ≤ 13 pF
III	7 pF < C_{para_max} ≤ 10 pF
IV	C_{para_max} ≤ 7 pF

Table A-1: Parasitic capacitance classes for CMC

IEEE 10BASE-T1S EMC Test Specification for Common Mode Chokes from Open Alliance



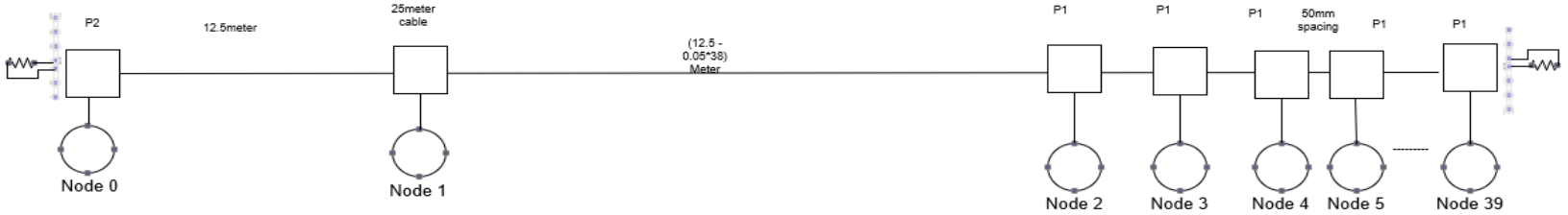
Current EtherNet/IP In-Cabinet Interface Design



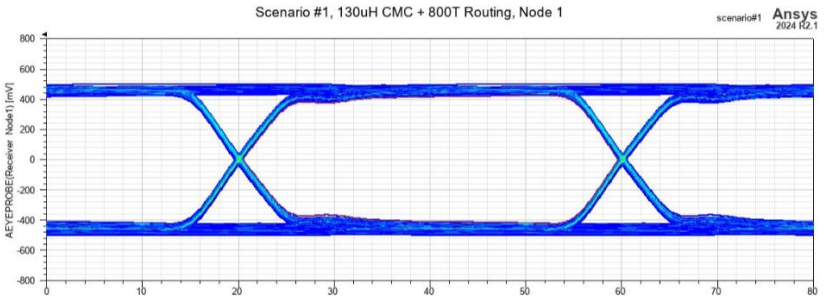
Proposed EtherNet/IP In-Cabinet Interface Design

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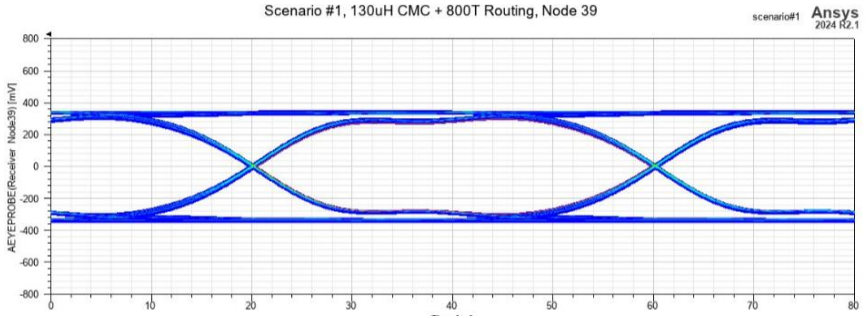
System Simulation Result with Proposed Interface Design



- Simulation of 40 node setup with 25-meter cable. Node 0 is transmitting and all other nodes are receiving nodes.
- Each 10BASE-T1S node interface circuit contains PHY, Common Mode Choke, decoupling capacitors and protection elements. The interface circuit is described in Figure 4: Interface circuitry of IEEE 10BASE-T1S Implementation Specification, TC14 – System Implementation from Open Alliance.



Node 1 Minimum Eye Height **821mV**

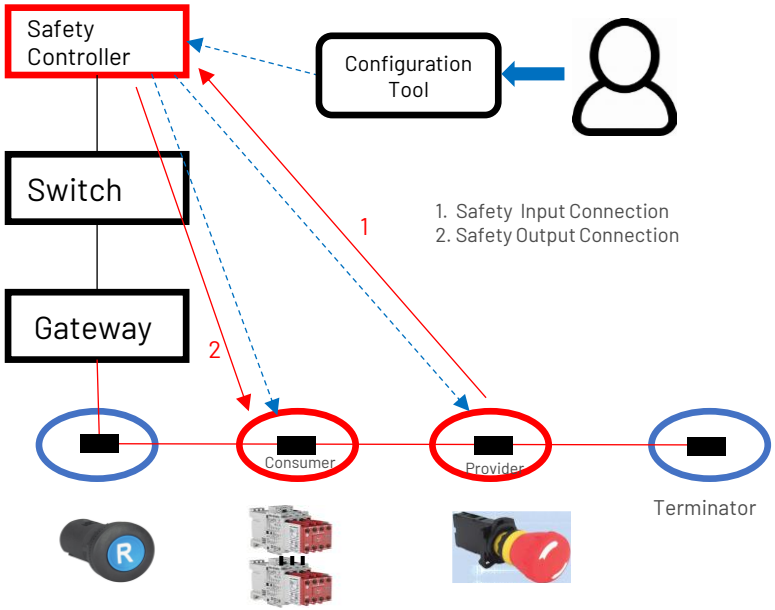


Node 39 Minimum Eye Height **557mV**

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Functional Safety: Safety Response Time (SRT)

- **SRT** = $SRT_{estop} + SRT_{input_conn} + SRT_{PLC} + SRT_{output_conn} + SRT_{contactor}$



SRT Component	Abbr.	Value	Component Breakdown	Representative values	unit
ESTOP Reaction Time	SRT_{estop}	10	Internal safety cycle time	10	ms
Safety Input Connection Network Reaction Time (Timeout Multiplier + Network Delay Multiplier)*RPI	SRT_{input_conn}	40	Safety Input Connection RPI	10	ms
			Timeout Multiplier	2	
			Network Delay Multiplier	200%	
Controller Reaction Time	SRT_{PLC}	15	Safety Task Period	10	ms
			Watchdog	5	ms
Safety Output Connection Network Reaction Time (Timeout Multiplier + Network Delay Multiplier - 1)*RPI	SRT_{output_conn}	30	Safety Output Connection RPI	10	ms
			Timeout Multiplier	2	
			Network Delay Multiplier	200%	
Safety Contactor Reaction Time	$SRT_{contactor}$	10	Internal safety cycle time	10	ms
System Safety Reaction Time	**SRT**	**105**			ms

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Safety Response Time Improvement

- 10BASE-T1S in multidrop mode is widely adopted in automotive applications. With PLCA providing fair and equal access to all nodes, 10BASE-T1S/M latency is too long for many control loop applications, requiring minimum of 2ms to 100ms.

Mixed criticality traffic-Automotive

- Devices in automotive networks have traffic with different application specific latency requirements for their traffic.
- Example: Propulsion related control loops with low latency requirements. Closure modules (door, trunk) with very forgiving latency requirements.

Mixed Safety and Standard Nodes-Industrial

- Safety nodes such as Estops and safety contactors, on In-Cabinet network requires a RPI of 5ms to 10ms.
- Standard nodes such as pushbuttons and standard contactors, on In-Cabinet network requires a RPI of 50ms to 100ms.

- CFI PLCA Multidrop Latency, Jitter, and Scalability Enhancements was passed at IEEE 802.3 July Plenary, Montreal, Quebec, Canada.

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Differentiated Services for Improved Safety Response Time

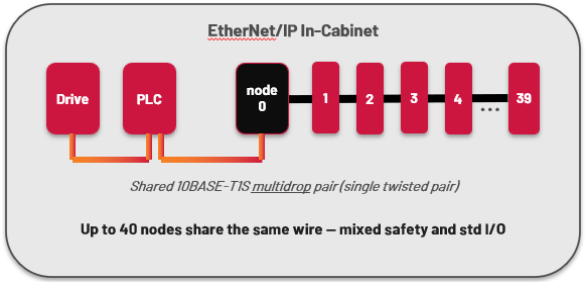
- Node-Based Differentiated Services
  - Differentiate between nodes with different latency requirements
  - Example:
    - Low Latency nodes can send frequently (e.g., in every cycle)
    - Medium latency nodes send less frequently (e.g., in every other cycle)
    - Best effort nodes send infrequently (e.g., in every fourth cycle)

Reference: https://www.ieee802.org/3/ad_hoc/ngrates/public/calls/25_1009/2025_10_09a_NEA_Differentiated_Services_10BaseT1S-v1-no-backup.pdf

cycle	Node N0	Node N1	Node N2	Node N3	Node N4	Node N5
1	X	X			X	
2	X		X	X		
3	X	X				X
4	X		X	X		
5	X	X			X	
6	X		X	X		
7	X	X				X
8	X		X	X		
9	X	X			X	
10	X		X	X		
11	X	X				X
12	X		X	X		
13	X	X			X	
14	X		X	X		
15	X	X				X
16	X		X	X		

Low Latency Node | Medium Latency Nodes | Best Effort Nodes

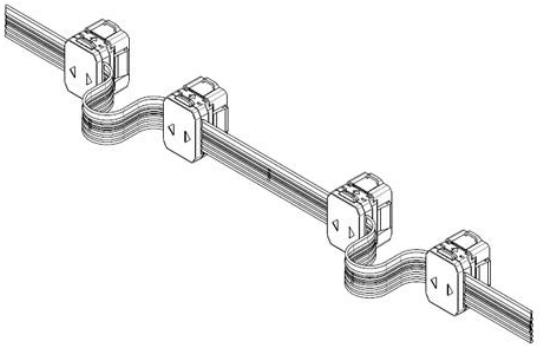
- Traffic-Based Differentiated Services
  - Differentiate different types of traffic within node 0
  - Example:
    - Safety traffic is time-critical and will get high priority
    - Standard I/O all travel on the same pair as safety I/O, will have medium priority
    - Explicit messages and other type of traffic have low priority.

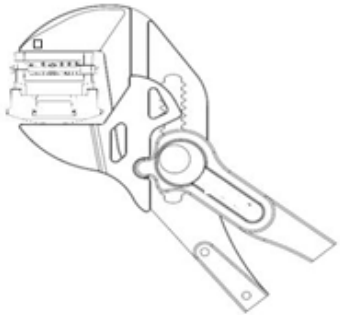


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Standards: ODVA Companion Publication

- Multidrop media needed new installation guidance.
- EtherNet/IP In-Cabinet Media Planning and Installation Manual (Pub 361)
  - https://www.odva.org/publication_download/in-cabinet-media-planning-and-installation-manual/





- System architecture
- Cable and connector installation
- Power budget
- Data performance
- Tools
- Verification
- Troubleshooting

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PUB00361R0

In-Cabinet Media Planning and Installation Manual

Published

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Standards: IEEE Enhancements

- EtherNet/IP In-Cabinet specified IEEE 10BASE-T1S in multidrop mode to economically meet the use-case

- *Enhancements to 10BASE-T1S Multidrop*
  - IEEE Std 802.3da-2026 (10BASE-T1M PHY)

Published

A. The T1M PHY is **backward compatible** with T1S systems (In-Cabinet is future-proof)
B. New T1M features may be incorporated to bring advantages to In-Cabinet

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Potential In-Cabinet Benefits of Adopting Enhancements

- PHY improvements may allow increased distance and higher node count
- Multidrop plug-and-play power may improve power management and conserve some energy
- Dynamic PLCA (D-PLCA) allows plug-and-play tools without interfering with control
  - Configuration, Network monitoring
- Time Sync is now “permitted”
- IEEE LLDP can open OT management of power, PLCA, and location

EtherNet/IP Physical Layer SIG Consideration

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Standards: IEC International Standard

- Previous versions of EtherNet/IP have been incorporated into IEC standards
- ODVA PHY specification for SPE are not yet published in IEC
  - **In-Cabinet (10BASE-T1S)**
  - Ethernet-APL + Ethernet-SPE (10BASE-T1L and 100BASE-T1L)

Since In-Cabinet represents a paradigm shift from hardwired cabinets, it is believed to be beneficial to incorporate the In-Cabinet media into IEC in a way that can be referenced by other SDOs

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IEC integration of In-Cabinet

- Physical layer, media, and installation guidance need are being integrated into a set of standards.
- Estimated 2028 publication.
- IEC TC65 (Industrial-process measurement, control and automation) / SC 65C (Industrial networks):
  - WG 9 (Industrial wired communication systems)
    - IEC 61158-2-2 (Industrial communication networks - Fieldbus specifications - Part 2-2: Physical layer specification and service definition – Type 2 elements)
    - Various IEC 61784 amendments to fieldbus profiles for CPF 2
  - JWG 10 (Industrial Cabling)
    - IEC 61918 (Industrial communication networks - Installation of communication networks in industrial premises)
    - IEC 61784-5-2 (Industrial communication networks – Profiles – Part 5-2: Installation of fieldbuses – Installation profiles for CPF 2)

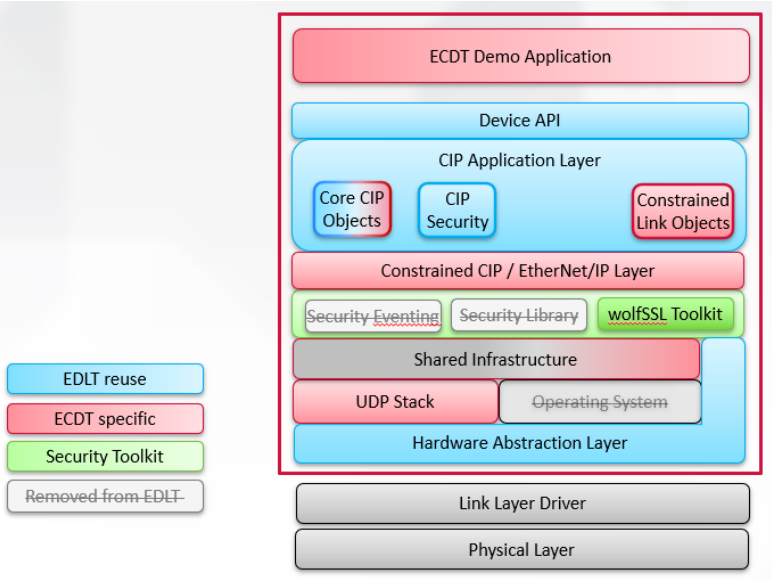
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EtherNet/IP Constrained Device Toolkit ECDT

Several vendors offer EtherNet/IP protocol toolkits, with many now expanding their portfolios to support EtherNet/IP In-Cabinet applications. Rockwell Automation's EtherNet/IP Constrained Device Toolkit (ECDT) simplifies the integration of Single Pair Ethernet (SPE) into products using 10BASE-T1S, 10BASE-T1L, and 6TiSCH network technologies.

Toolkit Features

- EtherNet/IP In-Cabinet Support
- Physical Layer ODVA Compliance Vol 2 Chapter 8
- CIP Security
- Shared Object Library
- Connection Origination
- Link Layer Discovery Protocol (LLDP)
- Networks Diagnostics Support
- ARM Processor Support
- SPI / MII interface support 10BASE T1S
- ControlFlash Support



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EtherNet/IP Constrained Device Toolkit ECDT

Benefits of using the toolkit:

- Implements the Common EtherNet/IP objects
- Configured for the UDP Only EtherNet/IP Transport profile
- Configured for the In-Cabinet EtherNet/IP Usage Profile
- LLDP supported for identification and IP Address Commissioning
- Select Line Link Object and Select Line protocol
- Implements CIP Security, Resource-Constrained CIP Security Profile
- Supports adding device specific application objects
  - Example code for adding new CIP objects
- Flash update support
- Abstraction Layer allows for support of different ethernet stacks, security stacks

Proven

- Implemented in Multiple In-cabinet Devices that have been released
- These devices have been ODVA test and passed CT22 testing
- Support for ADI MAX32672
  - Drivers are available as part of the toolkit

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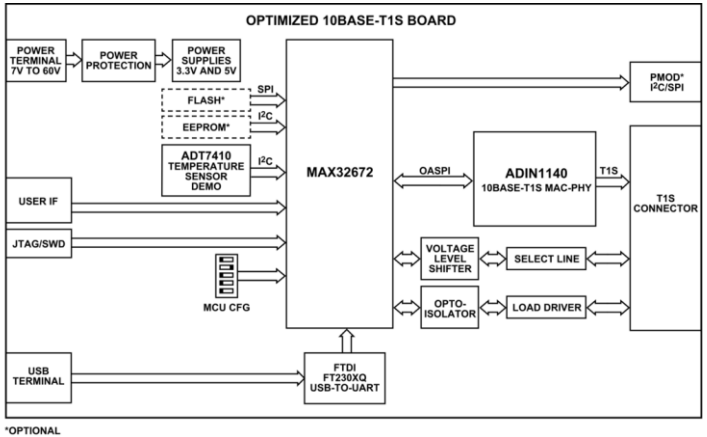
EtherNet/IP In-Cabinet Reference HW from Analog Devices

Vendors are developing hardware reference designs for EtherNet/IP In-Cabinet applications. These reference designs will help simplify device development, accelerate adoption, and reduce implementation effort. One example is the EtherNet/IP In-Cabinet hardware reference platform developed by Analog Devices.



Hardware References

- Reference schematics for MAX32672 MCU and ADIN1140 10BASE-T1S MAC-PHY to create an EtherNet/IP In-cabinet device
- Reference development hardware board
- Documentation and development tools to help product development
- EVAL-ADIN1140EBZ



EtherNet/IP In-Cabinet support

- Simple hardware product examples, temperature sensor, pushbutton inputs
- Example firmware for an In-Cabinet devices using the Constraint EtherNet/IP stack (ECDT)
- Support for In-Cabinet bus media, J1 connector, Select Line support

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Conclusion

- EtherNet/IP In-Cabinet has transitioned from specification to deployment, with customer feedback validating the anticipated value proposition.
- The ecosystem continues to expand, with functional safety devices representing a key new application area for In-Cabinet technology.
- International standards adoption is underway, helping drive broader industry acceptance and interoperability.
- ODVA members are encouraged to innovate and extend the ecosystem with new device types and capabilities.
- A growing set of tools, reference designs, documentation, and implementation resources are available to accelerate member adoption.

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