Advancing EtherNet/IP™ In-Cabinet with Functional Safety, Standards and Ecosystem Expansion

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Abstract

EtherNet/IP In-Cabinet has introduced an innovative approach for connecting industrial control components by replacing traditional point-to-point hardwiring with a shared Single Pair Ethernet (SPE) communication medium. The technology enables direct EtherNet/IP connectivity to low-cost industrial devices such as pushbuttons, contactors, motor starters, and signaling devices, while reducing wiring complexity, engineering effort, testing time, and panel footprint. As adoption increases, users are requesting functional safety capabilities that provide equivalent or improved safety performance compared to conventional hardwired architectures.

This paper examines the integration of CIP Safety™ into EtherNet/IP In-Cabinet systems using the existing CIP Safety specification and UDP-only transport profile. Technical challenges associated with safety deployment are evaluated, including electromagnetic compatibility (EMC) robustness, communication latency, and system safety response time. Enhanced communication interface designs are presented to address stricter EMC requirements for safety-certified products. In addition, safety response time budgets are analyzed to identify limiting factors and potential optimization opportunities.

The paper further explores key standards, including new IEEE 802.3da (10BASE-T1M) features, including compatibility with existing 10BASE-T1S multidrop networks, and new capabilities that may enhance future EtherNet/IP In-Cabinet implementations. Finally, the paper discusses ecosystem expansion through development toolkits, reference hardware platforms, and third-party implementation support, enabling broader industry adoption and multi-vendor interoperability.

Keywords

EtherNet/IP In-Cabinet, Constrained-Node Networks, APL, In-Cabinet, Common Mode Choke, Ethernet, IEEE 802.3, IEEE 802.3cg, EtherNet/IP Constrained Device Toolkit, IEEE 802.3da, 10BASE-T1S,10BASE-T1M, Single-Pair, SPE, Industrial Automation, Process Automation, Fieldbus, ODVA, Reference Topology, Network Power, Select Line, Select Line Protocol, Network Commissioning, Safety, Safety Response Time.

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Definition of terms

Industrial Automation	Discrete, Process, and Hybrid (Batch) Automation
CMC	Common Mode Choke
CT22	Conformance Test Version 22
CPF	Communication Profile Family
CFI	Call For Interest
ECDT	EtherNet/IP Constrained Device Toolkit
EDLT	EtherNet/IP Device Level Toolkit
EMC	Electromagnetic Compatibility
ESD	Electrostatic Discharge
EFT	Electrical Fast Transient
DS	Defined State
UDP	User Datagram Protocol
IP	Internet Protocol
IDC	Insulation Displacement Connector
IEEE Std 802.3cg-2019	Ethernet standard, including 10BASE-T1L and 10BASE-T1S PHYs
PHY	PHYsical layer connecting a link layer to a physical medium
LLDP	Link Layer Discovery Protocol
MAC	Medium Access Control layer (IEEE)
SPE	Single Pair Ethernet
PoDL	Power over Data Line (IEEE single pair power)
PoE	Power over Ethernet
MPoE	Multidrop Power over Ethernet
Fieldbus	Industrial network protocol for real-time control
Industrial Ethernet	Fieldbus protocol operable over Ethernet
Gateway	Network protocol converter spanning ISO model layers
Switch	IEEE 802.3 bridge, forwarding based on MAC addresses
IT	Information Technology
OT	Operational Technology
Point-to-point	Communication link with a single device at each end
Multidrop	Communication link with multiple devices sharing the same link
PLCA	PHY-level Collision Avoidance, multidrop determinism protocol
Network Commissioning	Process of commissioning all devices on a network
NP	Network Power
RPI	Requested Packet Interval
SP	Switched Power
SRT	Safety Response Time
MAC	Media Access Control
PLC	Programmable Logic Controller
I/O	Input/Output modules, provide discrete logical inputs and logical outputs for machine logic control
6TiSCH	IPv6 over the TSCH mode of IEEE 802.15.4e

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Introduction

Industrial control panels have historically relied on extensive hardwired connections between controllers, pushbuttons, motor starters, contactors, signaling devices, and safety components. Although highly familiar, traditional wiring approaches require substantial engineering effort, installation cost, testing complexity, and maintenance burden.

EtherNet/IP In-Cabinet addresses these challenges through implementation of the In-Cabinet EtherNet/IP Usage Profile over a multidrop Single Pair Ethernet infrastructure. The architecture extends EtherNet/IP directly to control components while maintaining compatibility with existing controller, diagnostic, security, and information architecture. Reported benefits include reductions in wiring, panel size, commissioning effort, and overall project cost.

As customers begin deploying EtherNet/IP In-Cabinet at larger scale, demand has emerged for safety-rated devices including emergency stop operators and safety motor starters. Integrating functional safety into a shared multidrop communication medium introduces additional performance and certification requirements that must be addressed while maintaining interoperability and scalability.

What is EtherNet/IP In-Cabinet?

To fully appreciate the value of the EtherNet/IP In-Cabinet solution one must understand where we're coming from or how this solution compares to methods that are currently being used and have been for over a century. The longstanding methodology of In-Cabinet wiring in industrial automation is now on the verge of transformation.

Control wiring for In-Cabinet I/O devices like push buttons and motor starters is crucial in industrial automation. It ensures the interface between physical components and logical control, traditionally hardwired in point-to-point configurations. These devices are essential in electrical control systems for machine control, serving as inputs and outputs for traditional PLC control.

When estimating traditional wiring time, 6 minutes per wire (3 minutes per termination) is a useful guide. Though this may not seem significant for a single wire, control systems often have several hundred wires, depending on their size and complexity. A simple non-reversing motor starter with local panel control, like a Hand/Off/Auto (HOA) selector with a 3-wire start/stop function, requires thirteen physical wire terminations.

Traditional wiring methods consume time. It is important to understand that time and higher costs can be realized in added engineering creating more complex electrical control wiring diagrams, further costs in 'testing' can be realized as all control panels undergo point-to-point wiring to validate and ensure the panel performs as intended.



Figure 1 Conventional Panel

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The EtherNet/IP In-Cabinet Solution will replace traditional hardwiring between devices with a single composite network cable that includes both power and communication. The system achieves a reduction in device complexity by utilizing a multi-drop bus topology, reducing device interface complexity and reducing the average number of interfaces per device.



Figure 2 Installed EtherNet/IP In-Cabinet Solution

The Value of EtherNet/IP In-Cabinet Solution

This shift from traditional hardwiring to a network-based solution offers unparalleled benefits. A recent time study initiative, building two like panels, one traditional and the other an EtherNet/IP In-Cabinet Solution, has shown significant savings on average are achievable; **80%** reduction in wiring time, a **30%** reduction in project engineering time and **50%** reduction in testing time. Further savings can be realized in reduction of capital costs and panel sizes.

The EtherNet/IP In-Cabinet solution is defined in CIP Volume 2 In-Cabinet usage profile requirements including physical layer requirements as well as implementation of UDP-only transport profile and various required objects and services. The In-Cabinet solution allows PLC controllers direct data access using EtherNet/IP connectivity to field level devices such as simple push buttons, contactors, and motor starters. By providing direct data access, vital predictive maintenance data such as the number of operations and number of hours can be obtained by each device. ODVA also specifies the constrained security profile for In-Cabinet devices, making it possible to enable CIP Security for field level devices.

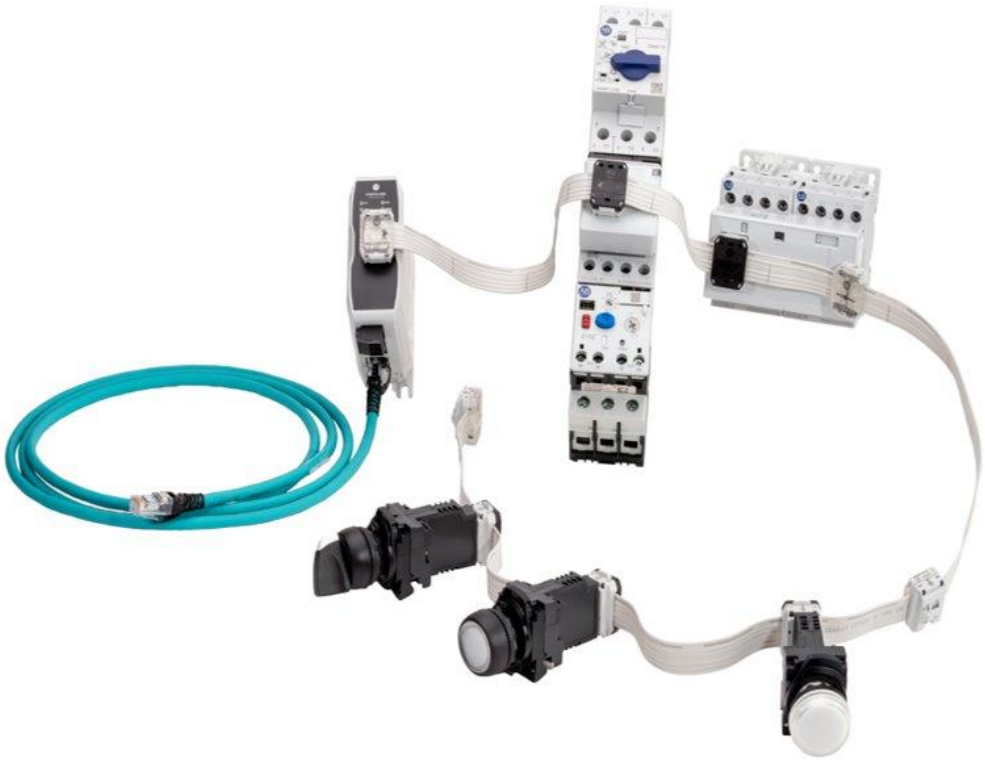


Figure 3 Implementation of EtherNet/IP In-Cabinet Solution

The EtherNet/IP gateway, shown in Figure 3 as the first device, connects the devices on the In-Cabinet bus to a standard EtherNet/IP network to allow communication between a controller and the devices.

The Gateway has an integrated First Power Tap, and supplies both NP (Network Power) and SP (Switched Power) to a multidrop bus system. Network Power supplies communication electronics with a capacity of 4 Amps, whereas Switched Power is intended for larger loads, such as contactor coils, providing continuous 4 Amps current and up to 8 Amps boosted output current.

Customer Feedback for EtherNet/IP In-Cabinet Solution

A key objective of the EtherNet/IP In-Cabinet initiative is to simplify control panel design and implementation by replacing traditional point-to-point control wiring with a standardized Ethernet-based communication infrastructure. While engineering analysis and laboratory demonstrations indicate significant benefits, successful market adoption depends on measurable value delivered to OEMs, system integrators, and end users.



Figure 4 Large Control Panel with Motor Starters and Pushbuttons



Figure 5 Small Control Panel with Pushbuttons

Figure 4 and Figure 5 illustrate several customer-built prototype panels utilizing the EtherNet/IP In-Cabinet architecture. The photographs demonstrate the dramatic reduction in wiring density and elimination of large bundles of point-to-point control wiring.

One of the primary objectives of the EtherNet/IP In-Cabinet initiative is to simplify panel construction while reducing the engineering effort associated with traditional point-to-point control wiring. Feedback collected from customers provides compelling evidence that these objectives are being realized in practice.

Significant Reduction in Panel Build Time
A recurring theme among customer feedback is the dramatic reduction in labor required to assemble control panels. An end user stated: “16 hours to build, and traditionally it would have been 40 or more.”

Reduced Wiring Effort
Beyond total assembly time, customers consistently identified wiring reduction as one of the most visible benefits of the technology. An OEM who compared traditional construction methods with an EtherNet/IP In-Cabinet implementation reported: “Took my best panel wirer against the In-Cabinet solution. Saved 50% in wiring time.”

Measurable Cost Savings
In addition to labor reductions, customers reported direct financial benefits associated with simplified architecture. A system integrator stated: “[Reduced] cost by $10,000 including wire [and] wiring time.”

Simplicity and Ease of Adoption
Another important theme emerging from customer feedback is the simplicity of implementation. One end-user evaluation concluded with the remark: “If we can put this together, anyone can.”

Collectively, these customer testimonials demonstrate that the EtherNet/IP In-Cabinet architecture delivers measurable operational value while helping industrial users simplify panel design, reduce labor dependency, and accelerate deployment of modern industrial control systems.

EtherNet/IP In-Cabinet Functional Safety Use Cases

The initial EtherNet/IP In-Cabinet architecture demonstrated how standard control devices such as pushbuttons, pilot devices, contactors, and motor starters can be integrated into a simplified Ethernet-based infrastructure. However, many industrial applications also require functional safety capabilities, creating a need to extend the architecture beyond standard control functions.

Addressing a Large Market Opportunity
Safety devices represent a sizable portion of the industrial control market. Emergency stop stations, safety relays, safety contactors, and related products are commonly deployed across manufacturing facilities and machine automation systems. Expanding the EtherNet/IP In-Cabinet ecosystem to include functional safety products enables a more complete solution portfolio capable of addressing a broader range of customer applications.

Enabling Platform Expansion
The addition of functional safety products significantly expands the scalability of the EtherNet/IP In-Cabinet architecture. Rather than creating separate wiring infrastructures for standard control and safety functions, the architecture can be extended to support safety-capable end nodes within the same system framework. This approach creates a "pull-through" opportunity for broader platform adoption. Customers deploying standard EtherNet/IP In-Cabinet products can naturally expand their installations to include safety devices without introducing additional network technologies or specialized wiring practices. As a result, the overall solution becomes more attractive for machine builders seeking a unified communication architecture.

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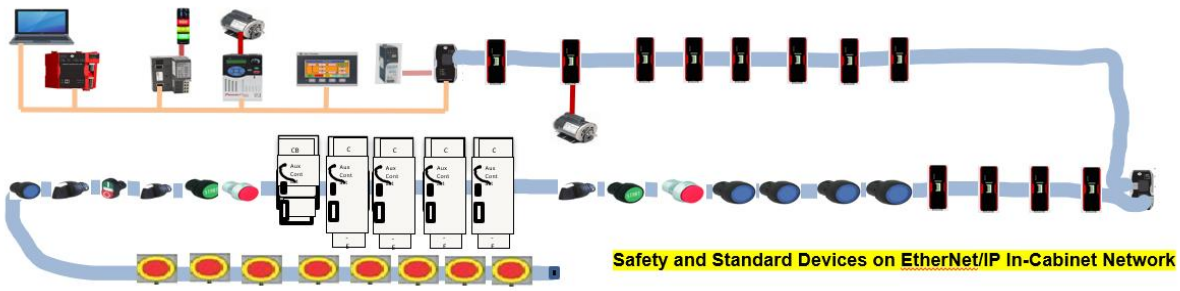


Figure 6 Safety and Standard Devices on EtherNet/IP In-Cabinet Network

Figure 6 illustrates an example system containing a mixture of standard control devices and safety devices connected through a common EtherNet/IP In-Cabinet infrastructure. The architecture includes safety-capable emergency stop stations and motor control devices alongside conventional control components. In this example, the system supports up to twenty safety devices and nineteen standard In-Cabinet devices within the same installation while utilizing the available cable length efficiently. This illustrates that safety integration can be achieved without fundamentally changing the network topology or installation methodology used for standard devices.

Use of CIP Safety for Functional Safety Solution

The proposed EtherNet/IP In-Cabinet safety architecture leverages the existing CIP Safety technology without requiring protocol modifications. A typical safety solution shown in Figure 7 consists of:

- Safety input device (Emergency Stop or Safety Switch)
- Safety controller
- Safety output device (Safety Contactor or Safety Motor Starter)
- EtherNet/IP In-Cabinet gateway acting as a transparent communication component within the safety black channel architecture.

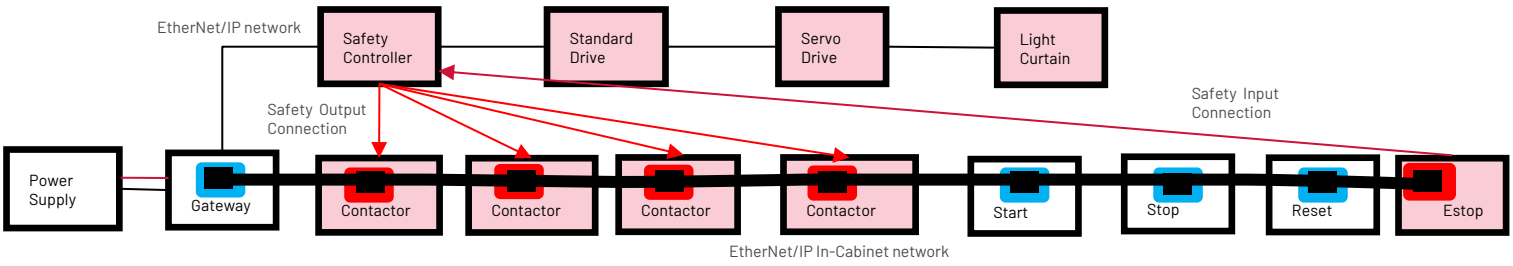


Figure 7 EtherNet/IP In-Cabinet Safety Solution with Safety Controller

The architecture supports controller-to-device (C2D) safety use cases and maintains compliance with established CIP Safety mechanisms including:

- Safety Network Number (SNN)
- Sequence counting
- CRC validation
- Timestamp verification
- Consumer watchdog supervision

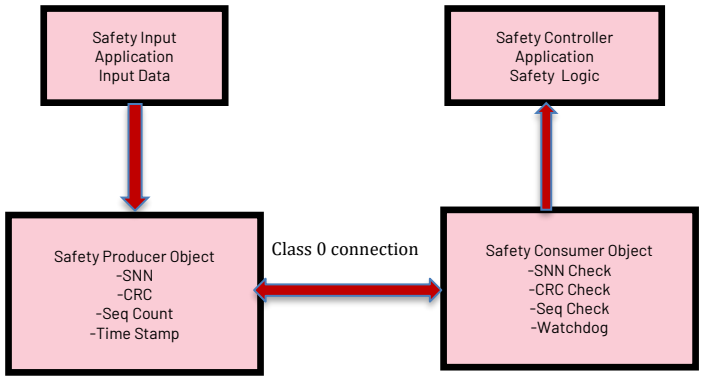


Figure 8 Illustration of EtherNet/IP In-Cabinet Safety Input Connection

No changes are required to CIP Safety Volume 5 specification for safety open or safety I/O connections. EtherNet/IP In-Cabinet Safety I/O devices will conform to the CIP Safety specification and support UDP-only transport profile. EtherNet/IP In-Cabinet gateways must provide enhanced routing capabilities to support both standard and safety traffic. CIP Safety currently does not support safety I/O connection aggregation, meaning each safety connection must be maintained and routed independently. In-Cabinet gateways are required to handle additional I/O routing resources for both standard EtherNet/IP connections and CIP Safety connections.

Increased EMC Immunity Requirements for Safety Products

Functional Safety industrial products are subject to elevated EMC immunity requirements relative to standard industrial devices. IEC 61000-6-7 requires higher test levels and safety-specific acceptance criteria intended to ensure that a safe state is achieved following disturbances.

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*

Table 1 Comparison of EMC Immunity Levels Between Standard Products and Safety Products

Comparison of EMC immunity levels between standard products and safety products is shown in Table 1. Examples of increased requirements include:

- Radiated immunity increased from 10 V/m to 20 V/m in the 80 MHz to 1 GHz range.
- Conducted RF immunity increased from 10 V to 20 V.
- Increased EFT test levels to 2 KV on signal port and increased exposure requirements.
- Increased ESD stress level to 6 KV for contact discharge and increase of discharge numbers.

DS (Defined State) is the performance criterion applicable to safety-related functions. During disturbance testing, the product shall either maintain normal safety operation or transition to a detectable and predefined safe state within the specified response time. No hazardous or undefined system behavior is permitted.

Enhancement of EtherNet/IP In-Cabinet Communication Interface

To achieve the increased immunity performance levels required for safety-related industrial applications, it is recommended that the EtherNet/IP In-Cabinet communication interface be enhanced through the addition of a Common Mode Choke (CMC). A CMC provides high impedance to common-mode noise while maintaining very low impedance to differential 10BASE-T1S communication signals. As a result, common-mode disturbances induced by electromagnetic interference (EMI) are significantly attenuated without degrading normal data transmission performance. This improvement can increase communication robustness and help maintain reliable operation during EMC disturbances.

The current EtherNet/IP In-Cabinet node interface design is shown in Figure 9. The design follows the ODVA physical layer specification and utilizes four in-line inductors in conjunction with DC-blocking capacitors to connect the PHY to the multidrop communication channel. The purpose of the inductors is to match the differential capacitance of 10BASE-T1S node, reduce reflections when the node is connected to a 10BASE-T1S multidrop network. IEEE 10BASE-T1S multidrop networks are particularly sensitive to node capacitance because every connected device contributes to the overall channel loading. Excessive capacitance degrades eye opening, reduces noise margin, and limits the maximum achievable network size and cable distance.

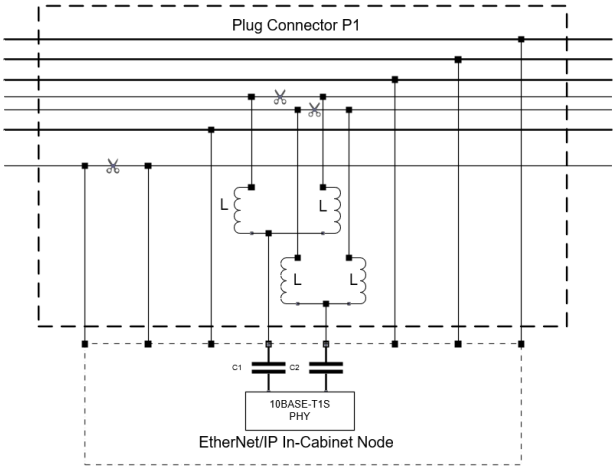


Figure 9 Current EtherNet/IP In-Cabinet Interface Design

The ODVA specification is designed around a target differential node capacitance of approximately 13 pF to maintain the desired channel characteristics and signal integrity. The addition of a common mode choke introduces a new design challenge. Every CMC contains parasitic capacitance between windings. Excessive parasitic capacitance effectively increases the node loading seen by the multidrop network. To

address this concern, the Open Alliance IEEE 10BASE-T1S EMC Test Specification defines four classes of common mode chokes based on their parasitic capacitance characteristics.

CMC Class	Maximum Parasitic Capacitance
Class I	13 pF < Cpara,max ≤ 17 pF
Class II	10 pF < Cpara,max ≤ 13 pF
Class III	7 pF < Cpara,max ≤ 10 pF
Class IV	Cpara,max ≤ 7 pF

Table 2 Parasitic Capacitance Classes for CMC defined by Open Alliance

For EtherNet/IP In-Cabinet applications, Class IV devices are recommended due to their extremely low parasitic capacitance. With parasitic capacitance below 7 pF, Class IV chokes minimize their impact on the multidrop transmission channel while still providing substantial common-mode noise attenuation. One commercially available example is the TDK ACT1210E-131-2P-TL00.

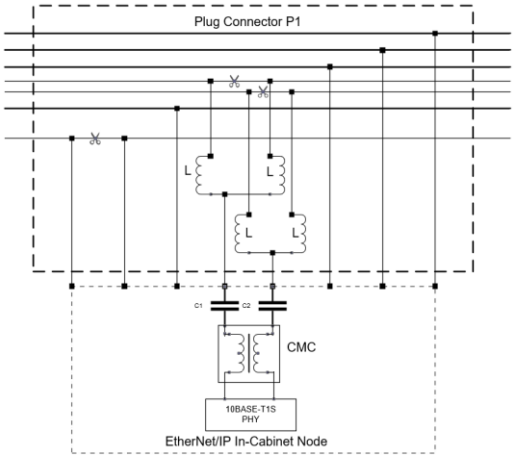


Figure 10 Proposed EtherNet/IP In-Cabinet Interface Design

The proposed EtherNet/IP In-Cabinet interface design, shown in Figure 10, introduces a Class IV common mode choke while maintaining the existing DC-blocking capacitors and transient protection components. This modification is intentionally minimal to preserve compatibility with current ODVA-compliant implementations while improving immunity performance.

The benefits of the proposed interface design include:

- Improved suppression of radiated and conducted common-mode disturbances.
- Reduced susceptibility to IEC 61000-4-4 electrical fast transient events.
- Improved robustness during IEC 61000-4-3 radiated immunity testing.
- Improved robustness during IEC 61000-4-6 conducted immunity testing.
- Minimal impact on differential signal quality.
- Continued compatibility with existing EtherNet/IP In-Cabinet multidrop physical-layer requirements.

System Simulation with Proposed Interface Design

To evaluate the suitability of the proposed 10BASE-T1S interface design for large EtherNet/IP In-Cabinet installations, a comprehensive system-level signal integrity simulation was performed using a circuit model. The simulated network consisted of forty 10BASE-T1S nodes distributed across a 25-meter multidrop cable segment, representing the worst-case scenario expected in industrial control cabinets. In the simulation, Node 0 operated as the transmitting device while all remaining nodes functioned as receiving nodes.

Each node implemented the proposed interface circuitry, including the 10BASE-T1S PHY, common-mode choke (CMC), decoupling capacitors, and transient protection components. The interface topology was based on the implementation guidance provided in the Open Alliance TC14 10BASE-T1S System Implementation Specification. The objective was to assess the cumulative impact of interface components, node loading, cable attenuation, and physical spacing on network signal quality.

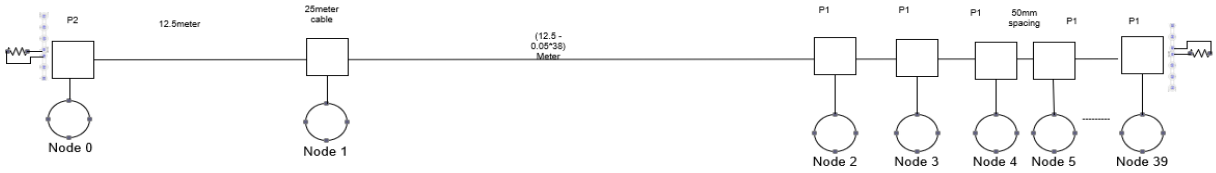


Figure 11 System Simulation with 40 EtherNet/IP In-Cabinet Devices

Figure 11 illustrates the simulated network topology captured at two locations within the network. The first eye diagram shown in Figure 12 corresponds to Node 1, located near the transmitting node, while the second eye diagram shown in Figure 13 represents Node 39, the node furthest from the transmitter. These locations were intentionally selected to provide insight into best-case and worst-case signal quality conditions.

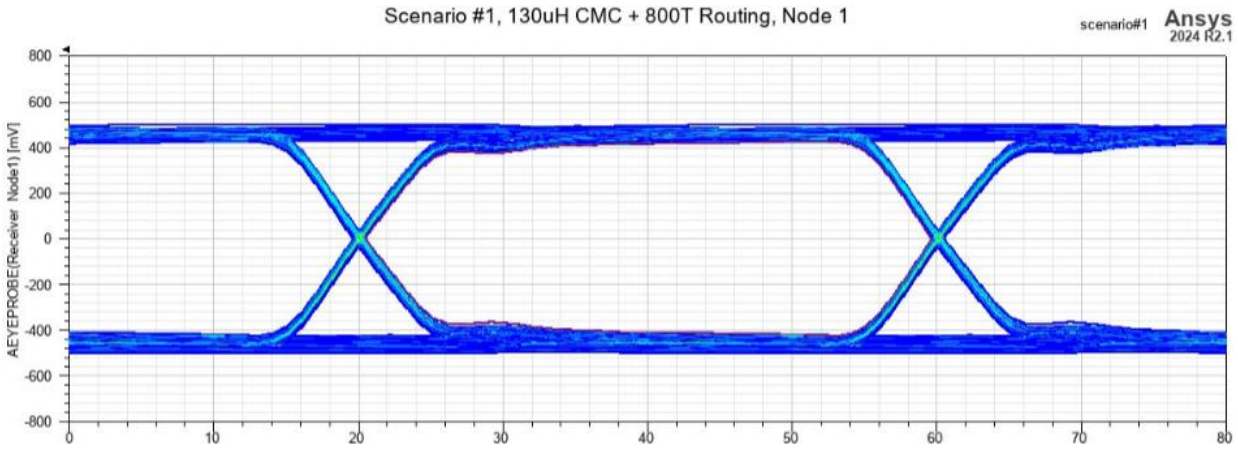


Figure 12 Eye Diagram at Node 1

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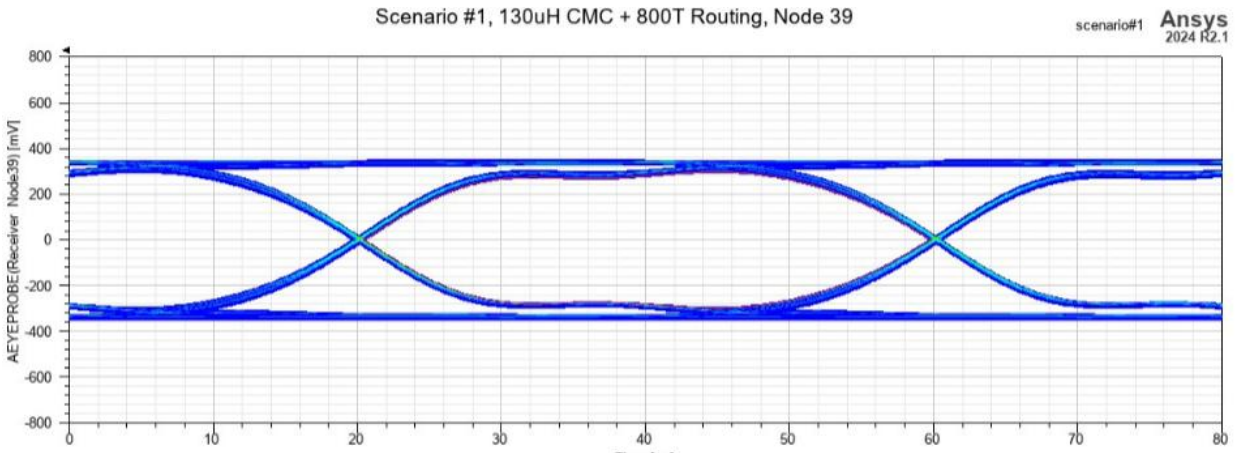


Figure 13 Eye Diagram at Node 39

The simulation results demonstrate robust signal performance throughout the network. Node 1 achieved a minimum eye height of 821 mV, while Node 39 maintained a minimum eye height of 557 mV despite experiencing the highest accumulated channel loss and loading effects. Although signal amplitude decreases along the network due to cable attenuation and multiple attached nodes, the resulting eye openings remain well-defined and provide substantial operating margin for reliable data reception. The results indicate that the proposed interface design successfully preserves signal integrity across a fully populated 40-node EtherNet/IP In-Cabinet network.

Functional Safety: Safety Response Time (SRT)

Safety Response Time (SRT) is the maximum elapsed time between the occurrence of safety demand and the transition of the controlled equipment to a safe state. In industrial automation systems, SRT is a critical parameter used during safety function design and validation because it determines how quickly a hazardous condition can be mitigated. For an emergency stop function, the SRT begins when the E-stop device is actuated and ends when the final control element, such as a safety contactor, removes energy from the hazardous equipment.

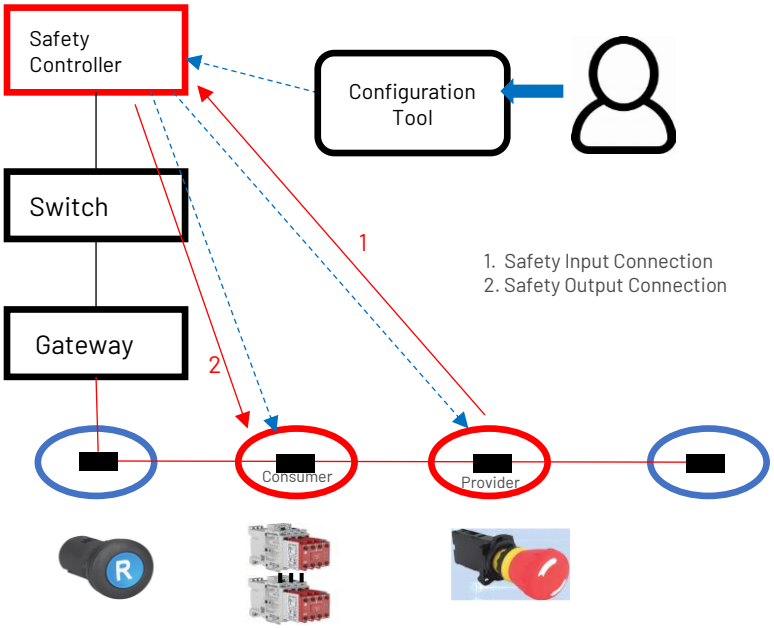


Figure 14 Illustration of Safety Communication Path

Figure 14 is an Illustration of Safety Communication Path. A safety input device, represented by the E-stop, transmits through a CIP Safety input connection to the Safety Controller. Upon detection of a safety demand, the Safety Controller processes the safety logic and transmits the resulting command through a CIP Safety output connection to the safety output device controlling the contactor. The total SRT is influenced by both device processing delays and communication delays.

To simplify the analysis, the total Safety Response Time (SRT) is partitioned into individual timing components corresponding to each stage of the safety function as depicted in Figure 15. This decomposition enables system designers to allocate timing budgets, identify dominant sources of delay, and verify that the overall safety function satisfies the required risk reduction objectives.

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

Figure 15 Equation for Safety Response Time Calculation

For the Safety Input Connection from Figure 14, the Safety Controller acts as the safety consumer and receives safety-related data produced by the safety input device. This connection contributes to the Safety Input Connection Network Reaction Time (SRTinput_conn). For the Safety Output Connection from Figure 14, the Safety Controller produces a safety output message to the safety output device after processing the safety request, this connection contributes to the Safety Output Connection Network Reaction Time (SRToutput_conn).

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
aSystem Safety Reaction Time	**SRT**	**105**			ms

Table 3 Safety Response Time (SRT) Calculation Example

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Table 3 provides a representative Safety Response Time (SRT) calculation by decomposing the total response time into individual system components. The analysis includes the E-stop reaction time, Safety Input Connection network reaction time, PLC/controller processing time, Safety Output Connection network reaction time, and safety contactor reaction time. Using the representative values shown, the calculated system Safety Response Time is **105 ms**.

The largest contributors to the response time are the Safety Input Connection and Safety Output Connection, both of which are influenced by CIP Safety communication parameters such as the Requested Packet Interval (RPI), timeout multiplier, and network delay multiplier.

The Safety Input Connection Network Reaction Time (SRTInputConn) is calculated by adding the timeout allowance and network delay allowance, both expressed as multiples of the Requested Packet Interval (RPI):

For this example:

$$SRT_{InputConn} = (2 + 2.0) \times 10 \text{ ms}$$
$$SRT_{InputConn} = 40 \text{ ms}$$

Where:

- RPI = 10 ms
- Timeout Multiplier = 2
- Network Delay Multiplier = 200% = 2.0

The Safety Output Connection Network Reaction Time (SRTOutputConn) is calculated by adding the timeout allowance and network delay allowance, then subtracting one RPI to account for the output update timing:

For this example:

$$SRT_{OutputConn} = (2 + 2.0 - 1) \times 10 \text{ ms}$$
$$SRT_{OutputConn} = 3 \times 10 \text{ ms}$$
$$SRT_{OutputConn} = 30 \text{ ms}$$

Where:

- RPI = 10 ms
- Timeout Multiplier = 2
- Network Delay Multiplier = 200% = 2.0

The remaining response time is attributed to device and controller processing delays, including the E-stop device (10 ms), safety controller execution (15 ms), and contactor operation (10 ms).

This breakdown provides a practical method for evaluating the impact of communication and device response times on the overall safety function and identifying the parameters that most significantly influence system-level Safety Response Time.

Safety Response Time Improvement

10BASE-T1S multidrop Ethernet has gained traction in automotive applications by enabling multiple devices to communicate over a single shared pair, reducing both wiring complexity and network cost. The Physical Layer Collision Avoidance (PLCA) mechanism defined in IEEE 802.3cg provides fair and equal

access among all participating nodes. This approach is well suited for many automotive control applications; however, the resulting worst-case communication latency can become a limiting factor for applications requiring fast and predictable response times. End-to-end latency is influenced by factors such as node count, packet size, transmit opportunities, and network loading. As the number of nodes increases, worst-case transmission delays can increase significantly because each device must wait for its assigned transmission opportunity. Depending on network size and traffic conditions, latencies ranging from several milliseconds to tens of milliseconds may be observed. These delays may be excessive for time-critical automotive and industrial control applications.

Mixed-Criticality Traffic Requirements for Automotive and Industrial Applications

The challenge of supporting mixed-criticality traffic has long been recognized in automotive networks. Different devices on the same network often have significantly different latency requirements. For example, propulsion-related control loops may require very low communication latency to maintain system stability and performance, while body control functions such as door modules, trunk controllers, lighting systems, or occupant comfort features can tolerate substantially longer communication delays.

A similar situation exists in industrial automation networks, particularly in emerging EtherNet/IP In-Cabinet architectures where both safety and standard control devices share a common 10BASE-T1S multidrop infrastructure. Safety devices such as emergency-stop stations, safety contactors, and safety I/O modules require rapid and predictable communication updates to achieve competitive overall Safety Response Times (SRT). Typical Requested Packet Intervals (RPI) for these devices are often in the range of 5 ms to 10 ms. In contrast, standard devices such as pushbuttons, pilot lights, standard contactors, and non-critical I/O may operate satisfactorily with communication update rates in the range of 50 ms to 100 ms. This disparity in application requirements creates a need for mechanisms that can prioritize latency-sensitive traffic without sacrificing the scalability and simplicity advantages of EtherNet/IP In-Cabinet network.

Improving latency performance for critical devices while maintaining efficient operation for less time-sensitive traffic is an important objective for future enhancements to 10BASE-T1S multidrop systems.

IEEE 802.3 CFI Study Group Activities

Recognizing these challenges, the IEEE 802.3 Physical Layer Collision Avoidance (PLCA) Multidrop Latency, Jitter, and Scalability Enhancements Call for Interest (CFI) was approved during the July 2026 IEEE 802.3 Plenary Session held in Montreal, Quebec, Canada.

The study seeks to develop a deeper understanding of the limitations of the existing PLCA access mechanism and to evaluate potential approaches for reducing latency and improving determinism. The results of the CFI are expected to establish the technical foundation, scope, and objectives for a potential future IEEE 802.3 project to enhance multidrop Ethernet performance.

Differentiated Services for Improved Safety Response Time

The baseline PLCA mechanism provides equal channel access opportunities to all nodes on a 10BASE-T1S multidrop network. Treating all nodes and traffic identically can result in latency performance being dictated by the least demanding applications. To address this challenge, differentiated services approaches have been proposed to provide preferential access to latency-sensitive devices and traffic while preserving the scalability advantages of multidrop Ethernet.

Node-Based Differentiated Services

One approach is to classify nodes according to their latency requirements and allocate transmission opportunities at different frequencies. Rather than participating equally in every PLCA cycle, nodes with more stringent timing requirements are granted more frequent access opportunities.



Figure 16 Node-Based Differentiated Services

For example:

- Low-latency nodes participate in every PLCA cycle.
- Medium-latency nodes participate in alternate cycles.
- Best-effort nodes participate only periodically, such as every fourth cycle.

This approach effectively reduces the worst-case waiting time for critical devices by decreasing contention from less time-sensitive nodes. Communication resources are allocated according to application requirements rather than equally across all participants. For industrial networks, safety devices such as emergency-stop stations, safety contactors, and safety I/O modules would typically be categorized as low-latency nodes, while standard control and monitoring devices could utilize medium-latency or best-effort service classes.

Traffic-Based Differentiated Services

A second approach differentiates traffic types within a node rather than differentiating between nodes. This method is particularly attractive for industrial automation systems because a single field device often generates multiple traffic classes with different timing requirements.

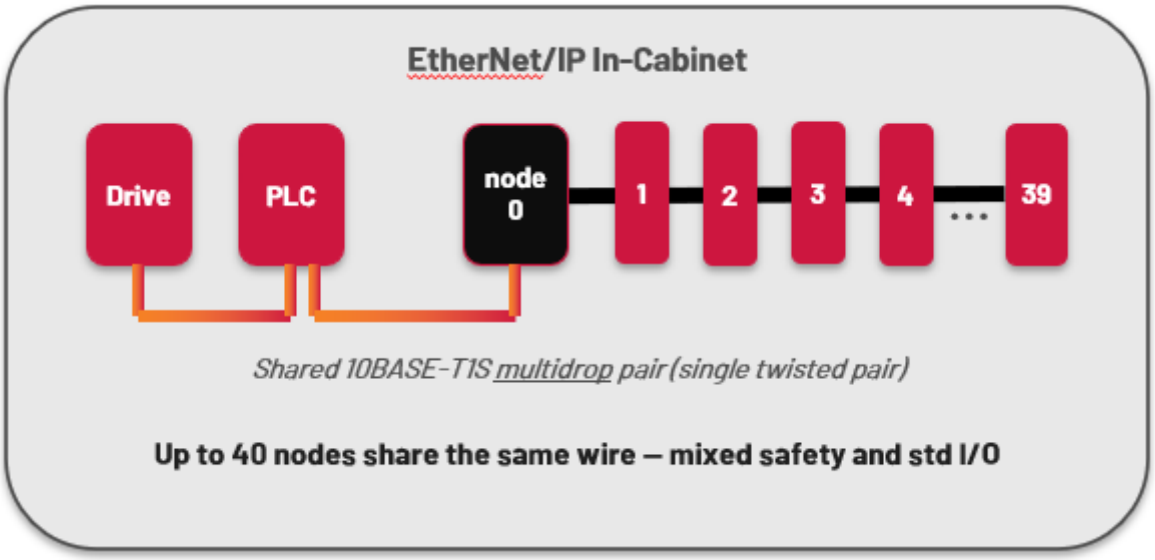


Figure 17 Traffic-Based Differentiated Services

For example, an EtherNet/IP In-Cabinet node may simultaneously carry:

- Safety I/O traffic, requiring the lowest latency and highest transmission priority.
- Standard I/O traffic, requiring predictable but less aggressive response times.
- Explicit messaging, diagnostics, configuration, and engineering traffic, which are tolerant of longer delays.

By assigning priorities to individual traffic classes, safety-related traffic can receive expedited transmission opportunities without requiring separate physical networks. This enables both safety and standard communications to coexist on the same multidrop pair while ensuring that critical traffic experiences significantly lower latency.

In summary, the analysis demonstrates that communication delays constitute a significant portion of the overall Safety Response Time (SRT), accounting for 70 ms of the 105 ms example system response time. Consequently, improvements in network latency and determinism can directly enhance the responsiveness of safety functions. Emerging 10BASE-T1S multidrop networks present an opportunity to reduce communication-related delays through advanced traffic management mechanisms. By implementing differentiated services that prioritize latency-sensitive safety traffic, future multidrop Ethernet networks can reduce both Safety Input and Safety Output Connection reaction times. These enhancements have the potential to improve overall Safety Response Time, increase system responsiveness, and enable more competitive industrial safety solutions.

Standards Enhancements and Compatibility with the EtherNet/IP In-Cabinet System
Standards within ODVA, IEEE, and IEC are evolving in ways that are related to In-Cabinet.

ODVA Companion Publication

ODVA has published the “EtherNet/IP In-Cabinet Media Planning and Installation Manual” as Pub 361. This is available for download at https://www.odva.org/publication_download/In-Cabinet-media-planning-and-

installation-manual/. Topics include valid system architecture, cable and connector installation, power budget, data performance estimation, required tools, verification, and troubleshooting.

IEEE Enhancement Standard

ODVA EtherNet/IP In-Cabinet currently operates using the Single Pair Ethernet (SPE) that was standardized within IEEE Std 802.3cg-2019 as 10BASE-T1S. Optimizations were made to economically achieve lowest-cost Ethernet over short distance for Automotive and Industrial use cases.

10BASE-T1S implemented numerous cost optimizations:

- Fewer wires and connections
- Single coupling circuit (typically capacitor versus transformer)
- Single set of EMC protection components
- Less pins in the PHY interface
- Two-level, self-clocking signals
- Multidrop mode to reduce the average number of Ethernet interfaces per device by 2x

ODVA EtherNet/IP In-Cabinet specified 10BASE-T1S in multidrop mode at 25m. The IEEE minimum of 8 nodes in a multidrop was increased to 40 nodes by a “compensation” technique using inductors to reduce impairment of the communication signal. The attached nodes are fully compliant with the 10BASE-T1S PHY, but the multidrop media is enhanced.

Various industries requested enhancement to IEEE Std 802.3cg-2019 in multidrop mode to meet extended use cases. There were requests from conveyance companies (elevators and escalators), overhead lighting, industrial for small in-field machine areas, and others. These applications potentially benefit from low-cost multidrop Ethernet if the reach and node count were increased. The enhancements are standardized in IEEE Std 802.3da-2026.

IEEE Std 802.3da-2026 Overview

A new 10BASE-T1M PHY was specified, but the data communication format and signal levels are identical to 10BASE-T1S. T1S and T1M are nearly identical. There is often the wrong assumption that T1M replaces T1S and that T1S is obsolete. However, a primary objective is that the T1M PHY **maintains compatibility** when used along with T1S PHYs in T1S media systems.

In one enhancement, the T1M specification defines optional channel enhancements (tighter specifications) allowing increased distance (>= 50 m required) and node count (>= 16 required). Substantial work was done to simulate the multidrop media (the IEEE “mixing segment”). The increased distance and node count are recognized as achievable by compensation techniques. This approach was informed by and mirrors ODVA In-Cabinet specification analysis and decisions.

The T1M media may be composed of a series of trunk sections, interconnected via interposing TCIs (Trunk Connection Interfaces), and terminated on each end. Each TCI may connect to a multidrop node and may contain compensation inductors.

The In-Cabinet media matches this structure and should exceed the requirements.

- ODVA In-Cabinet media is composed of a series of trunk sections (a continuous flat cable split by each connector), interconnected via interposing IDC connectors (TCIs), and terminated on each end. Each IDC connector connects to a node and contains inductive compensation.

The In-Cabinet tradeoff of distance and node count is different, but it is likely that 50m and 16 nodes could be supported without any changes. IEEE did not specify any specific cable or connector for the T1M media enhancements. This is left to outside organizations to specify.

Another enhancement is the optional plug-and-play multidrop power. IEEE Std 802.3cg-2019 did not specify multidrop power. The SPE term Power over Data Lines (PoDL) has caused a lot of confusion in the market. Likely IEEE will move forward with variants of the term Power over Ethernet (PoE) – which is better established in the market. IEEE P802.3da specifies Multidrop PoE (MPoE). The MPoE specification is not part of T1M (a data specification), but it is a compatible companion specification.

MPoE can operate on or separately from the communication pair (or both). The MPSE (Power Sourcing Equipment) will not apply full power unless one or more MPDs (Powered Devices) are discovered. There are 30V (1.1W unit load) and 57V (4W unit load) system types. A multidrop supports up to 16-unit loads. Each device can consume up to 16-unit loads. The MPSE protects against faults. Energy is conserved if all devices are removed. Management of power is possible.

Another enhancement is the optional dynamic PLCA node ID allocation method. IEEE Std 802.3cg-2019 did not specify how PLCA node IDs were assigned, except that management interfaces were available for the purpose. A Dynamic PLCA (D-PLCA) method was invented. New nodes entering a system listen for PLCA beacons, and traffic. Then they try using PLCA slots to establish their IDs. Static PLCA IDs can be configured to avoid any D-PLCA collisions with that traffic. It is also possible to establish an initial or replacement coordinator. D-PLCA offers an improvement in multidrop performance with less management.

Another enhancement is optional multidrop Time Sync. It was previously demonstrated within IEEE that multidrop Time Sync could work with proper code in the Times Sync Service Interface (TSSI). Now it is “permitted” by the standard.

Another enhancement is the optional LLDP management of the new features. This allows better management of a system where the switching infrastructure contains multidrop segments.

Potential In-Cabinet Benefits of Adopting Enhancements

It is possible that IEEE P802.3da multidrop enhancements (T1M and related specifications) will offer opportunities for In-Cabinet enhancements. At the very least, a larger market drives lower chip costs and variety. Opportunities require further vetting.

While it is media enhancements (mixing segment specifications) that allow increased distance and higher node count, the specifications may drive PHY receiver improvements. The T1M mixing segment specifications are likely to be less stringent than ODVA specifications. It is possible that T1M PHYs will allow higher node count with existing In-Cabinet media.

It is also possible that the increased distance would be valuable outside the cabinet. This would require an IP67 connector scheme.

The multidrop plug-and-play power could be considered. It may improve power management and conserve some energy. It could be used separately on NP and SP pairs.

In-Cabinet already has an automatic PLCA allocation method that is compatible with real time control. D-PLCA has a method to specify a range of static PLCA node IDs. This offers the possibility of using the In-Cabinet allocation to establish a real time range and to also allow other plug-and-play devices to enter the multidrop system in a non-interfering basis. An example is to plug a configuration or network monitoring tool into a multidrop system.

Time Sync is already possible for an In-Cabinet system with proper drivers.

In-Cabinet already uses LLDP for configuration and management purposes. Devices include support for specific ODVA TLVs for location, PLCA assignment, IP address management, and factory reset including

security. IEEE specified LLDP could allow the broader OT system inventory to include In-Cabinet segment information about power, PLCA, and location.

Enhancements are under consideration in the EtherNet/IP Physical Layer SIG.

IEC International Standardization

Previous versions of EtherNet/IP have been incorporated into IEC standards. More recent SPE-related ODVA specifications are not yet 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.

Media specification and installation guidance are being integrated through inter-related IEC standards. Projects to update the 2028 standards release under way in IEC TC65 (Industrial-process measurement, control and automation) / SC 65C (Industrial networks) for cooperative development within WG 9 and JWG 10.

Since this is work-in-progress – the details may be changed.

WG 9 (Industrial wired communication systems) is responsible for the communication stack, including the physical layers defined in IEC 61158-2-2 (Industrial communication networks - Fieldbus specifications - Part 2-2: Physical layer specification and service definition – Type 2 elements). One reason to define an IEC 61158 Type is that the In-Cabinet power system and the relative location method using the Select Line are not part of the IEEE Ethernet specifications and they require specification.

WG9 is also responsible for various IEC 61784 amendments to fieldbus profiles. CIP protocol would be within Communication Profile Family 2 (CPF 2). The new physical layer types will be bound to CIP, UDP, and IP. Ethernet-SPE and Ethernet-APL are defined as physical layers within the existing EtherNet/IP profile and In-Cabinet is defined as a new EtherNet/IP profile due to the constrained protocol profile.

JWG 10 (Industrial Cabling) is responsible for connectors, cable, and installation. IEC 61918 (Industrial communication networks - Installation of communication networks in industrial premises) is a base standard that can be referenced by multiple fieldbus profiles. It contains some SPE cabling and installation specifications within Annex Q and Ethernet-APL within Annex R. IEC 61784-5-2 (Industrial communication networks – Profiles – Part 5-2: Installation of fieldbuses – Installation profiles for CPF 2) would specify In-Cabinet cabling and installation, by reference to and extension of IEC 61918.

EtherNet/IP Constrained Device Toolkit

One of the key challenges in accelerating the adoption of EtherNet/IP In-Cabinet has been reducing the development effort required to implement industrial Ethernet connectivity in compact, cost-sensitive devices. Device vendors have traditionally been responsible for developing and integrating much of the required hardware and software infrastructure themselves. This can increase design complexity, extend development time, and create additional certification and maintenance burdens.

To address this challenge, vendors are providing EtherNet/IP protocol toolkits and making them commercially available. One of the toolkits is the EtherNet/IP Constrained Device Toolkit (ECDT) from Rockwell Automation, is based on its standard EtherNet/IP Device Level Toolkit (EDLT). The toolkit, illustrated in Figure 18, provides a reusable implementation of core EtherNet/IP and CIP technologies while supporting emerging industrial networking technologies such as 10BASE-T1S, 10BASE-T1L, and 6TiSCH.

The toolkit will maximize SPE interoperability and minimize implementation efforts for In-Cabinet product development.

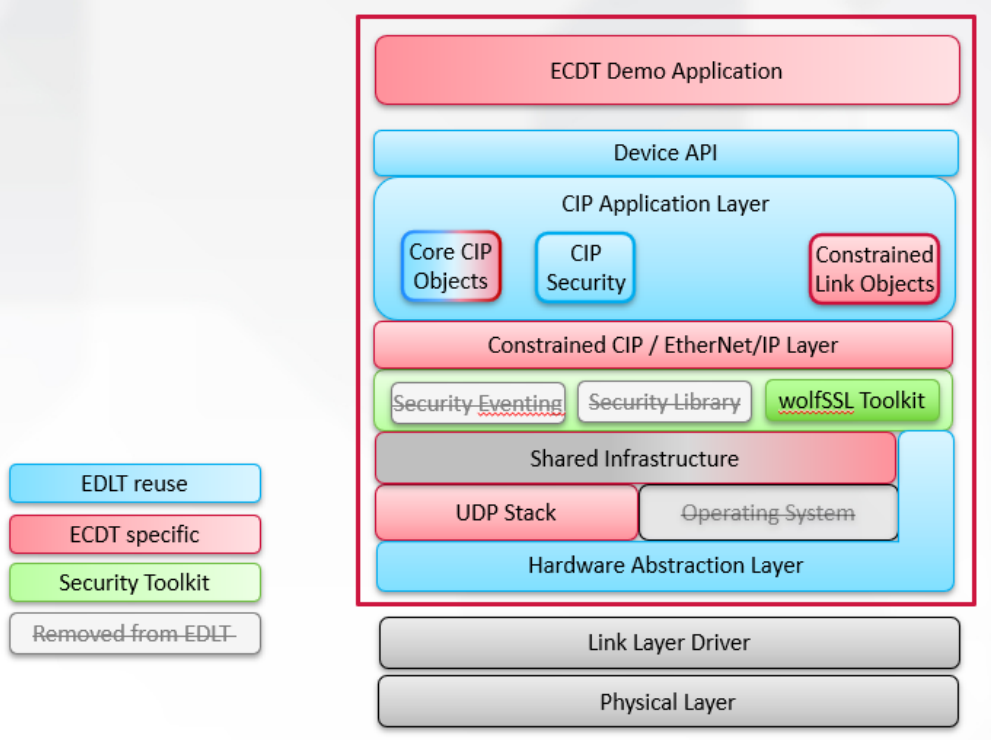


Figure 18 EtherNet/IP Constrained Device Toolkit (ECDT)

List of Toolkit Features

- **In-Cabinet Support** – Native support for EtherNet/IP In-Cabinet devices, enabling rapid integration of sensors, actuators, pushbuttons, stack lights, and distributed I/O products.
- **Physical Layer ODVA Compliance (Vol. 2, Chapter 8)** – Meets the ODVA-defined 10BASE-T1S physical layer requirements to help ensure interoperability and conformance across compliant devices.
- **CIP Security** – Supports secure device authentication, encrypted communications through CIP Security.
- **Shared Object Library**– Provides a common set of EtherNet/IP objects, reducing development effort and ensuring consistent device behavior.
- **Connection Origination** – Enables devices to establish and manage EtherNet/IP connections.
- **Link Layer Discovery Protocol (LLDP)** – Supports network discovery and topology reporting to simplify commissioning and network management.
- **Network Diagnostics Support** – Provides diagnostic and health-monitoring services that help accelerate troubleshooting and improve system availability.
- **ARM Processor Support** – Optimized for ARM-based embedded processors commonly used in compact industrial devices.
- **SPI / MII Interface Support for 10BASE-T1S** – Supports both SPI and MII PHY interfaces, providing flexibility for integration with a wide range of PHYs.
- **PHY Level Collision Avoidance (PLCA)** – Supports IEEE 802.3cg PLCA operation to improve determinism and network efficiency.
- **Firmware Update Support** – Enables firmware upgrade to simplify product deployment, maintenance, and lifecycle management.

Benefits of Using the Toolkit

- Implements Common EtherNet/IP Objects
  The toolkit includes implementations of the standard EtherNet/IP and CIP objects. By providing these commonly used objects out of the box, developers can significantly reduce implementation effort and focus engineering resources on application-specific functionality rather than protocol infrastructure.
- Configured for the UDP-Only EtherNet/IP Transport Profile
  The toolkit is preconfigured to support the EtherNet/IP UDP-Only Transport Profile used by EtherNet/IP In-Cabinet devices. This eliminates the need for extensive customization and helps ensure conformance with ODVA specifications.
- Configured for the EtherNet/IP In-Cabinet Usage Profile
  Native support for the EtherNet/IP In-Cabinet Usage Profile enables rapid development of compliant devices. The toolkit incorporates the network behaviors, services, and configuration requirements needed for In-Cabinet deployments.
- LLDP Support for Device Identification and IP Address Commissioning
  Built-in Link Layer Discovery Protocol (LLDP) capabilities enable automatic device identification and support streamlined commissioning workflows.
- Select Line Link Object and Select Line Protocol Support
  The toolkit supports the Select Line Link Object and associated protocol services used by EtherNet/IP In-Cabinet devices. These capabilities simplify topology management, device discovery, and network commissioning.
- CIP Security Implementation
  Support for CIP Security, including the Resource-Constrained CIP Security Profile, enables secure communications suitable for embedded In-Cabinet devices.
- Support for Device-Specific Application Objects
  The toolkit supports the addition of manufacturer-specific application objects, allowing suppliers to differentiate products while maintaining interoperability with standard EtherNet/IP services.
- Flash Update Support
  Integrated flash update capabilities simplify firmware maintenance and product lifecycle management. Support for software updates allows manufacturers to deploy enhancements, security updates, and feature improvements without requiring hardware changes.
- Platform Abstraction Layer
  The toolkit includes an abstraction layer that separates application software from underlying Ethernet, UDP, and security stack implementations.
- Successfully Deployed in Commercial In-Cabinet Products
  The toolkit has been implemented in multiple EtherNet/IP In-Cabinet devices that have progressed from development into commercial deployment. This demonstrates the maturity of the solution and provides adopters with confidence that the toolkit has been validated in real-world applications.
- Conformance Tested and ODVA Certified
  Devices built using the toolkit have successfully completed ODVA CT22 conformance testing.
- Support for Analog Devices MAX32672
  The toolkit includes support for the Analog Devices MAX32672 microcontroller platform, enabling rapid development on a commercially available hardware platform that aligns well with the performance and resource requirements of many In-Cabinet devices.

EtherNet/IP In-Cabinet Reference HW from Analog Devices

To accelerate adoption of EtherNet/IP In-Cabinet technology, several ODVA member companies are developing reference hardware platforms that provide a proven starting point for product development. These reference designs reduce development risk, shorten implementation cycles, and help ensure conformance with ODVA specifications. One example is the EtherNet/IP In-Cabinet reference platform developed by Analog Devices, which combines the AD3306 10BASE-T1S MAC-PHY with the MAX32672

microcontroller and Rockwell Automation's constrained EtherNet/IP software stack. The platform, shown in Figure 19, provides a complete development environment that enables manufacturers to quickly prototype and evaluate In-Cabinet devices.

The reference platform includes hardware schematics, PCB layout files, development tools, example applications, and software drivers needed to create compliant EtherNet/IP In-Cabinet products. Example applications demonstrate common In-Cabinet use cases, including pushbutton inputs, temperature sensing, and common communication interfaces such as SPI and UART. More information about reference hardware from Analog Devices can be found here EVAL-ADIN1140EBZ

Support for Select Line communications, and EtherNet/IP In-Cabinet profile requirements allows developers to evaluate network discovery, commissioning, and topology management capabilities using readily available hardware. By providing ready-to-use hardware and software foundation, the reference platform helps device suppliers reduce engineering effort, accelerate ODVA conformance testing, and bring EtherNet/IP In-Cabinet enabled products to market more quickly.

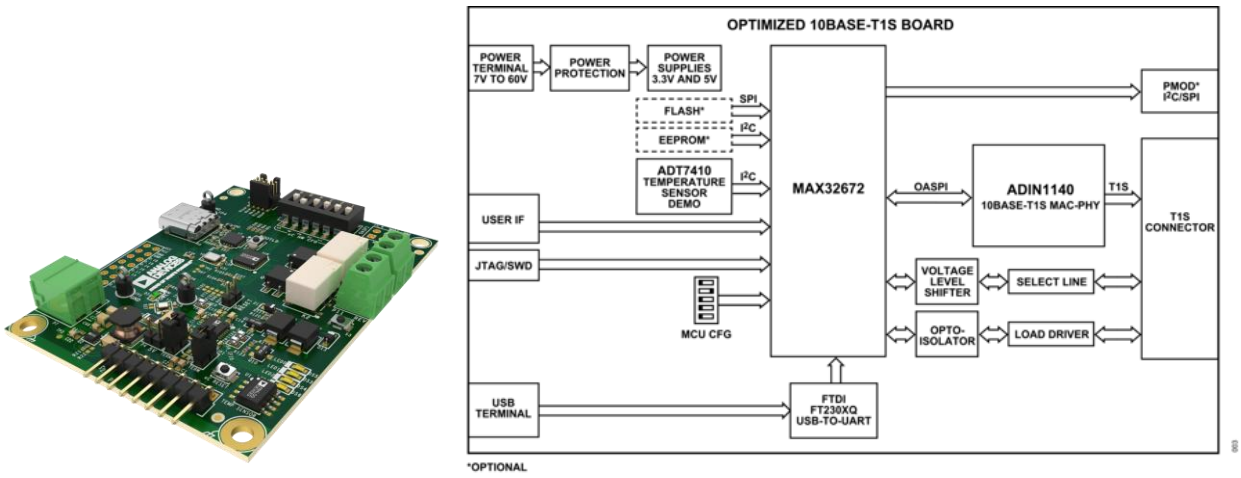


Figure 19 EtherNet/IP In-Cabinet Reference HW from Analog Devices

Conclusion

EtherNet/IP In-Cabinet has successfully transitioned from specification to deployment. Since the technology was introduced by ODVA in 2021, commercially available products have been released, and customer feedback has validated the expected benefits of reduced wiring, simplified installation, improved diagnostics, and easier maintenance.

The ecosystem continues to expand through new device categories. Initial deployments focused on panel operators, indicators, contactors, and motor control devices. The architecture is now evolving to support additional applications, including functional safety devices, further extending the value of a common EtherNet/IP In-Cabinet infrastructure.
Industry adoption is supported through standards development. EtherNet/IP In-Cabinet technology is being incorporated into international standards activities, helping promote greater interoperability, broader market acceptance, and long-term ecosystem growth across the industrial automation industry.

ODVA members now have access to a comprehensive ecosystem of implementation resources, including firmware toolkits, reference hardware platforms, development guides, example applications, and conformance testing support. These resources help reduce development effort, lower technical risk,

improve interoperability, and accelerate the global adoption of EtherNet/IP In-Cabinet technology. Numerous opportunities exist to expand the value of EtherNet/IP In-Cabinet through the introduction of new products, enhanced capabilities, and application-specific solutions.

EtherNet/IP In-Cabinet has evolved from a new ODVA specification into a proven industrial networking solution. Multiple products are now commercially available and deployed in customer applications. These deployments have demonstrated the value of reduced wiring, simplified installation, enhanced diagnostics, and improved maintainability. The ecosystem continues to expand with new device categories including functional safety products, increasing alignment with international standards, and a growing set of development resources. Together, these advancements are accelerating the adoption of EtherNet/IP In-Cabinet and enabling a new generation of intelligent, connected industrial automation products.

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