

# Enhancements to Single-pair Ethernet for Constrained Devices

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## Abstract

Industrial Ethernet has exhibited rapid growth, with EtherNet/IP emerging as a leader. The reality is that fieldbuses and sensor networks still retain a large position and many potential network nodes remain hardwired. End users understand and seek the advantages of a harmonized network - based on EtherNet/IP, and the related open ecosystem. Benefits include: reduced complexity and cost by minimization of gateways and elimination of hardwiring, expansion of the qualified labor pool, and improved optimization and maintenance opportunities via Cloud connectivity and analytics. With these benefits numerous industries have flooded into IEEE to develop enhancements for enabling Ethernet to displace other networks at the edge. The resulting Single Pair Ethernet suite offers reduction in wiring, node cost, size, and power consumption, delivering communication and power over a single pair. A deterministic Ethernet bus variant targets very constrained devices, such as in-cabinet components. Prior years' papers proposed a set of enhancements, adopted from or inspired by IETF and IEEE, to extend EtherNet/IP into constrained applications, further enabling the single network vision. This year with an operational concept, the paper discusses IEEE P802.3cg, the current standard and probable follow-on for T1S PHY specification upgrades to expand the market for PHYs, SIG work in the EtherNet/IP System Architecture Special Interest Group and EtherNet/IP Physical Layer Special Interest Group covering UDP-only, capability discovery, profile concepts and modular additions of PHYs, cables, connector, and profile concepts.

## Keywords

EtherNet/IP, Constrained-Node Networks, APL, In-cabinet, 6TiSCH, Ethernet, IEEE 802.3, IEEE 802.3cg, Single-pair, Industrial Automation, Process Automation, Fieldbus, NAMUR, ODVA, Nodal Geography, Actual Nodal Geography, Reference Geography, Network Power, Select Line, Select Line Protocol, Group 5 Messaging, IDC - Insulation Displacement Connector, Device Commissioning, Network Commissioning

## Definition of terms (optional)

The terms “Switched Power” and “Control Power” are used interchangeably throughout this paper.

Nodal Geography is defined for Constrained Devices on EtherNet/IP as an ordered set of identity object device keys for all nodes on a network.

Industrial Automation	-	Discrete, Process, and Hybrid (Batch) Automation
NAMUR	-	Process Automation user group, Germany
APL	-	Advanced Physical Layer, organization bringing Ethernet to Process
IETF	-	Internet Engineering Task Force, standards body for IP-related protocols
IP	-	Internet Protocol
6TiSCH	-	IETF standards and drafts for low power wireless supporting IP
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
MAC	-	Medium Access Control layer (IEEE)
SPE	-	Single Pair Ethernet
PoDL	-	Power over Data Line (IEEE single pair power)
Fieldbus	-	Industrial network protocol for real-time control
Industrial Ethernet	-	Fieldbus protocol operable over Ethernet
Edge	-	Leaf nodes attached to a network core, i.e., sensor and actuators
Gateway	-	Network protocol converter spanning ISO model layers
Switch	-	IEEE 802.3 bridge, forwarding based on MAC addresses
IT	-	Information Technology
OT	-	Operational Technology
MES	-	Manufacturing Execution Systems
Purdue Model	-	Layered functional automation model
IIoT	-	Industrial Internet of Things
Intrinsic safety	-	Method to allow safe equipment operation in explosive environments
Point-to-point	-	Communication link with a single device at each end
Multi-drop	-	Communication link with multiple devices sharing the same link
PLCA	-	PHY-level Collision Avoidance, multidrop determinism protocol
Full-duplex	-	Simultaneous communication in both direction on a link
Half-duplex	-	Communication in a single direction at a time on a link
CAN	-	Communication protocol, Controller Area Network
MCU	-	Micro Controller Unit
ASIC	-	Application-Specific Integrated Circuit
Network Commissioning	-	Process of commissioning all devices on a network
Device Commissioning	-	For a Constrained Devices on EtherNet/IP network is the setting of the IP Address at a minimum.
Nodal Geography	-	Constrained Devices on EtherNet/IP as an ordered set of identity object device keys for all nodes on a network.
NP	-	Network Power
SP	-	Switched Power
SP Tap	-	Supplemental Power Tap, also referenced as Power Tap
MAC	-	Media Access Control

RS	-	Reconciliation Sublayer
PCS	-	Physical Coding Sublayer
PMA	-	Physical Medium Attachment
PMD	-	Physical Medium Dependent

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## **Purpose of Paper**

Industrial Ethernet has exhibited rapid growth, with EtherNet/IP emerging as a leader in the “Internet of Things” movement. This paper presents set of operational concepts driving successful EtherNet/IP deployment to many low end Constrained Devices “Things” such as contactors and push buttons, thus enabling the single-network vision - where all devices in an industrial plant can communicate with the same set of protocols, while balancing node cost, node size, and ease of commissioning the smart system.

## Industrial Network Convergence

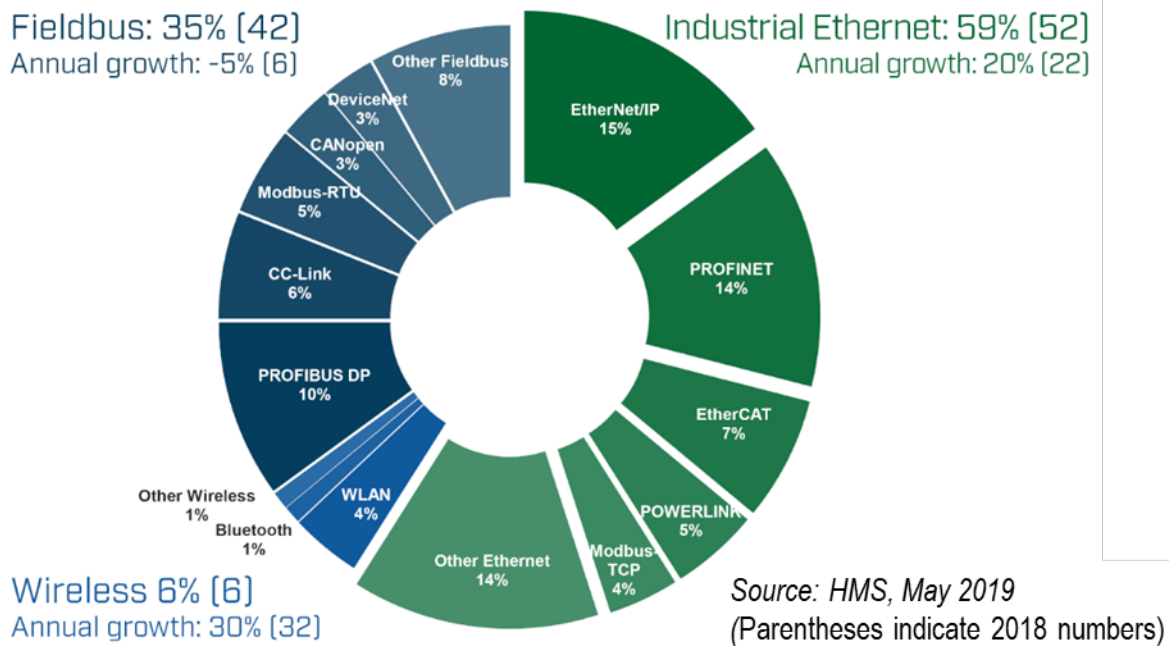
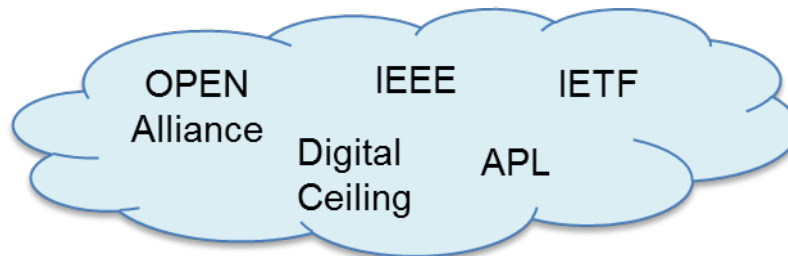


Figure 1: Market share for industrial automation networks

As shown in Figure 1 Industrial Ethernet solutions have been growing rapidly, with EtherNet/IP emerging as a leader. Traditional fieldbus solutions and sensor networks form a shrinking portion. Many potential Industrial Ethernet nodes remain hardwired. Their conversion is a focus of this paper.

## The Single Network Vision

Many end users understand and are seeking the advantages of a harmonized network - based on Ethernet, Internet Protocol (IP), and the related open ecosystem. This desire is expressed within organizations across many industries. Some examples are referenced in Figure 2.



*Figure 2: Organizations promoting expansion of Ethernet and/or IP at the edge*

The Automotive industry has been working toward an all-Ethernet vehicle. The industry formed the OPEN (One Pair EtherNet) Alliance to promote a variety of Single Pair Ethernet (SPE) solutions. Ethernet now pushes to the edge to displace other networks in the vehicle.

The Digital Ceiling partner ecosystem is promoting Ethernet-based smart LED lighting and associated sensors for occupancy, security, etc.

Process Automation end users (NAMUR) demanded Ethernet and IP-based automation protocols for instruments and related devices. The Advanced Physical Layer (APL) organization, including ODVA and their peer organizations are responding with solutions.

IEEE continues to extend the standards for Single Pair Ethernet (SPE) to meet the specialized needs at the edge.

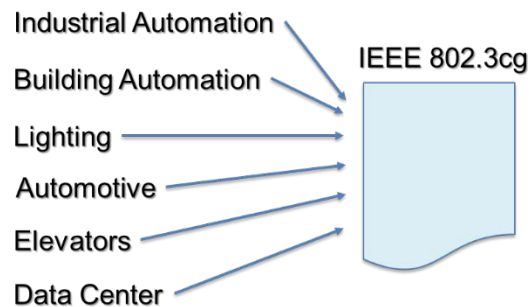
These initiatives exist due to compelling advantages of a single network:

- Higher performance for a similar cost (compared to the displaced networks)
- Elimination of costly application-level gateways
- Leverage of a large existing ecosystem (protocols, security, network switches, etc.)
- Reduced installation, maintenance, and management complexity
- Simplified integration with cloud applications
- Reduced interoperability issues

## IEEE contributions

Within IEEE, a family of Single Pair Ethernet (SPE) standards have been developed. These enable communication and optional power over a single pair, facilitating reduction in wiring, node cost, size, and power consumption.

Early SPE standards included 100BASE-T1 (100 Mb/s), 1000BASE-T1 (1000 Mb/s), and optional power known as PoDL. In February of 2020, another family member was released: IEEE Std 802.3cg-2019. The new standard introduces a pair of 10 Mbit/s SPE PHYs that are targeted for constrained applications. Numerous industries, illustrated in Figure 3, sought Ethernet enhancements to displace edge networks and contributed to the standard.



*Figure 3: Industries seeking Ethernet enhancements to help displace other edge networks*

IEEE Std 802.3cg-2019 includes the following 2 PHYs:

### 10BASE-T1L:

- Addresses long distance
- Targeted at process automation instruments
- 1000 m, intrinsic safety compatible, legacy wiring

### 10BASE-T1S:

- Addresses low cost control
- Targeted at replacing:
  - CAN, CAN FD, MOST, and FlexRay protocols in automotive
  - Hardwired components for in-cabinet industrial automation
  - I2C and SPI in data centers
- 25 m multidrop option
- Determinism by PHY-level Collision Avoidance (PLCA) protocol

## Constrained EtherNet/IP application areas

Figure 4 shows several new application areas for EtherNet/IP at the network edge. These are constrained applications for field devices. From basic control, up through the enterprise, 100BASE-TX Ethernet and emerging 1000BASE-T Ethernet is suitable and likely to remain in place. At the field level, these are not well suited to meet the listed constraints.

Constrained EtherNet/IP application areas include Process Automation and the related application area of Low-power Wireless. They also include On-machine components. Each has unique constraints as shown. These application areas are discussed further in [2].

Another important application is In-cabinet components – the focus of this paper. Here the transition is primarily from hardwiring to networked devices. Very strict constraints exist for low cost, small size, and low power.

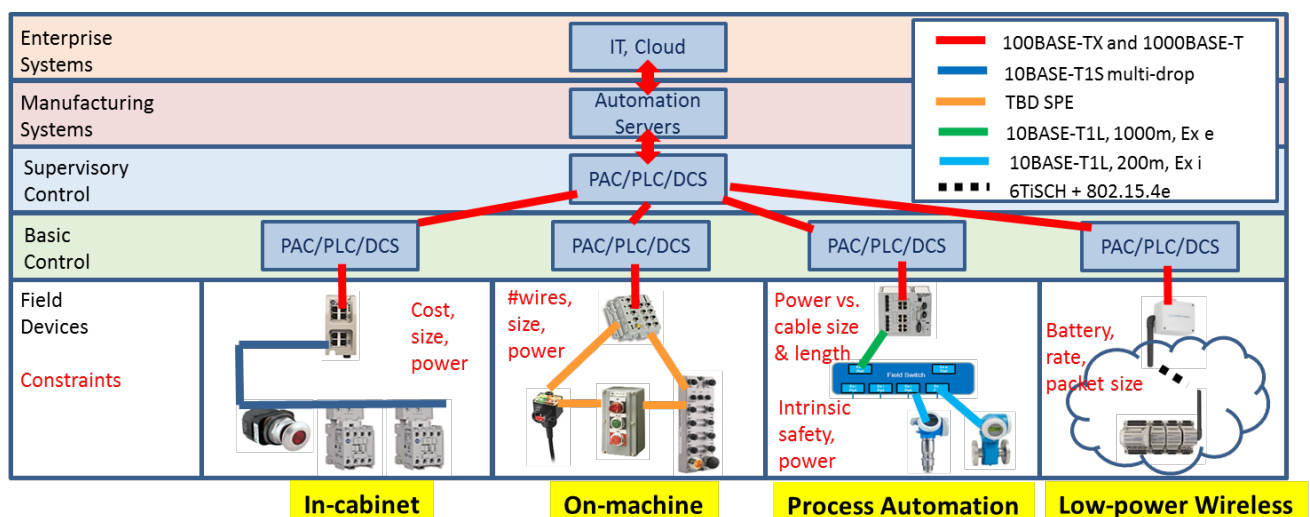


Figure 4: Candidate constrained application areas for EtherNet/IP



## Single-pair Ethernet for Constrained In-Cabinet Devices

The following section covers the Constrained In-Cabinet Device viewpoint and describes how the Single Pair Ethernet technology can be applied in this space.

### Constrained In-Cabinet Devices Problem Space

The amount of control power (24VDC) wiring required to control pilot devices (such as push buttons, indicator buttons, contactors, etc.) is substantial, as reference, Figure 5 Constrained In-Cabinet Devices Problem Space, indicated by the “red wire” in the graphic. The wired connections, typically referred to as “hard wired connections”, supply control power to the pilot devices for operation.



Figure 5 Constrained In-Cabinet Devices Problem Space

The number of wires for a simple in-cabinet application would require numerous hours for commissioning and is error prone if needed to be replicated. Once commissioned, “hard-wired” systems provide a high overhead for maintenance including, component updates or troubleshooting errors during operation or commissioning process while providing little to no intelligent data for analytics.

### Constrained In-Cabinet Devices Customer Requirements

Based on the Constrained In-Cabinet Device problem space, following are extracted key customer requirements based on *extensive customer listening sessions*:

- *It must be Economical*
  - *It must use low cost media*
  - *It must allow for a reduction in price and size of typical products*
  - *It must allow the use of commercial off-the-shelf power supplies*
  - *It must result in a lower “total cost of ownership” than hard wired solutions*
- *It must be Simple to use*
  - *It must use a single easy to use media connector*
  - *It must include a simple (or no) network commissioning methodology*
  - *It must eliminate the need for media trunk and drop distance calculations*
- *Just Enough Functionality*
  - *It must simplify In-Cabinet wiring for panel builders*
  - *It must deliver both Network Power to power device electronics and Switched (Control) Power to facilitate the actuation of Contactors and Relays*
  - *It must support Non-Safety and Safety devices on the same wire*

### Single-Pair Ethernet for Constrained In-Cabinet Devices

Single Pair Ethernet consists of multiple technical speeds and topologies, *reference Constrained EtherNet/IP application areas*. To match customer needs of just enough functionality, ease of use and low cost, 10BASE technologies would suffice, namely 10BASE-T1S. Following are key technical characteristics of 10BASE-T1S that could be leveraged in the Constrained In-Cabinet applications:

- *Low Power ~250mW, with in-cabinet applications, the thermal dissipation of devices is constrained.*
- *Lower Cost, as most of the target pilot devices are low cost, the communication interfaces to such devices would need to be low cost to maintain commercial acceptance of this solution.*

- *Constrained Ethernet (UDP only), with a small physical footprint of pilot devices, typically there are physical constraints to the package size of the electronics deployable in this solution, hence, a constrained Ethernet stack to reduce the memory requirements.*
- *10Mbps ½ duplex, since the end nodes are typically are pilot devices, system performance measures, such as communication speed, can be chosen to be minimum, following the IEEE 802.3cg 10BASE-T1S Specifications.*
- *Media to be a Multi-conductor cable, 25-meter cable length, Multi-Drop topology to help the Constrained In-Cabinet problem space to reduce the total commissioning time, providing a level of ease of use in adopting this solution.*

## Technical Architecture for Constrained In-Cabinet Devices

A technical architecture running Single Pair Ethernet 10BASE-T1S is proposed in the figure below.

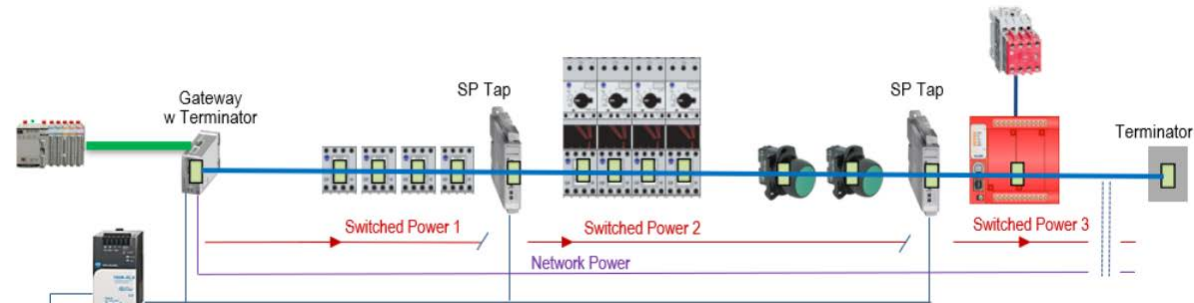


Figure 6 Technical Architecture for Constrained In-Cabinet Devices using Single Pair Ethernet

Notable points –

1. A Multi-conductor flat cable connecting multiple devices delivers power (switched power and network power) in a multi-drop topology which enables 10BASE-T1S communication, represented with a “blue line” in the figure above.
2. 4-wire Ethernet connection to a controller, represented with a “green line” in the figure above.
3. The overall system is powered by a 24VDC power supply. There are two power channels defined: NP (Network Power) and SP (Switched Power). NP power is used to power the communication circuit of the whole network. SP power is utilized for all the output loads (contactor control coil, sounder, etc.)
4. Gateway provides power for both NP and SP channels.
5. SP Tap is required to inject new SP power to the system when Gateway is not capable of providing SP power for all the loads.

## Proposed Timeframe

Figure 7 ODVA SIG Proposed Timeline highlights a timeframe of activities to publishing a complete specification for Single-pair Ethernet for Constrained In-Cabinet devices.

Definition of the communication protocol and related specification is being defined by the ENIP System Architecture SIG, focused on delivering 3 ESEs pronouncing the UDP only Transport profile for T1S (currently to be published April '20), CIP Security for Constraint In-Cabinet Devices and Constrained In-Cabinet Application profile for T1S.

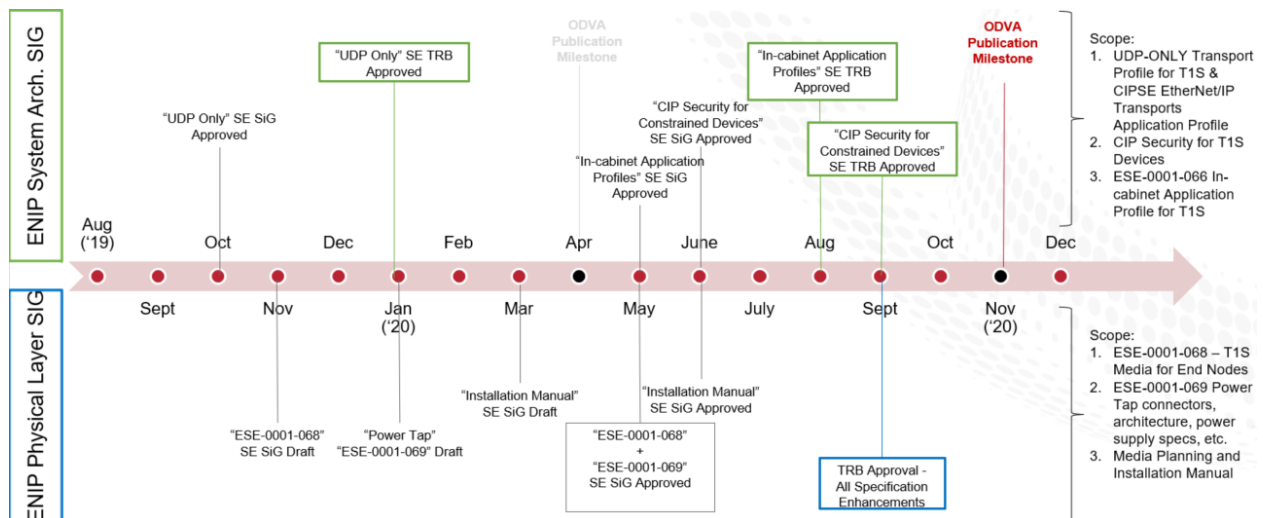


Figure 7 ODVA SIG Proposed Timeline

Definition of the media is conducted in the ENIP Physical Layer SIG, which is focused on delivering 3 ESEs, pronouncing the cable and connector specifications, the SP Tap connectors and grounding specifications and the Media Planning and Installation Manual.

### EtherNet/IP Media for Constrained In-cabinet Application

We are proposing a mixed gauge 7 conductor cable:

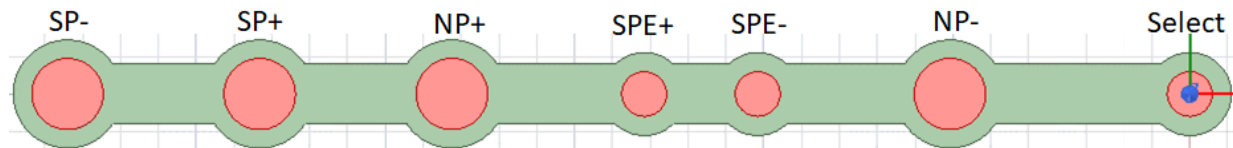


Figure 8 Conductor Cable

- Two conductors for Switched (Control) Power to actuate contactor coils
- Two conductors for Network Power to power device electronics
- Two conductors for SPE Signal Pair for T1S based PLCA Multidrop Ethernet Communication
- One conductor for Select Line for simple sequential network service delivery to discover linear nodal topology.

Wire gauge:

- 20AWG wires (19 strands) for NP-, NP+, SP+, SP-
- 24AWG wires (7 strands) for SPE+, SPE-, Select Line

Keying feature:

- SPE data pair and Select line conductors will be used as keying feature to minimize chance of wrong connector orientation.

Data pair Impedance: 100ohm, insulation voltage: 600V.

## Media Interface

- Interfaces with Standard 2.54 mm pitch Pin Header, 0.635 mm x 0.635 mm square pin (Vertical shown)
- 8 pin single row header, 8 pins populated, each pin  $\geq 2A$

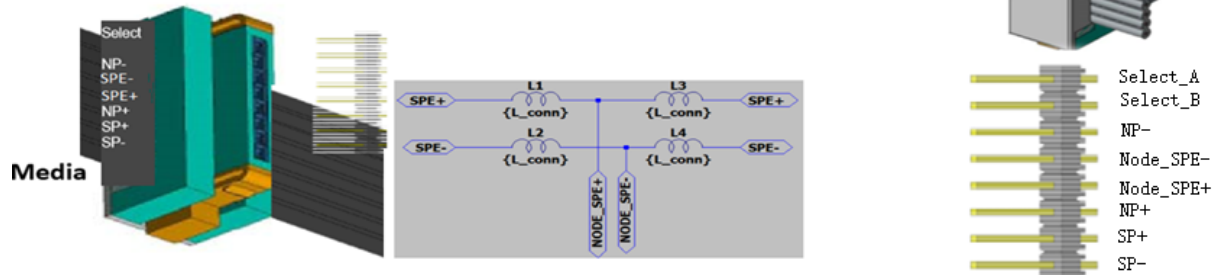


Figure 9 Media Interface

We have a node connector with 8-pin receptacle that interfaces with headers of the constrained devices. The pin assignment is shown above.

The pin header has standard 2.54mm pitch, 0.635mm X 0.635mm square pin.  
8 pin single row header, 8 pins populated, each pin can carry current greater than 2 Amps

- Connector shall be connected to and make an electrical connection with the media using standard or no tools
- Connector shall break Select line and then establish connections to Select\_A and Select\_B pins
- Connector may break both SPE+ and SPE- lines and add inline inductors for improved signal integrity.

## SPE 10BASE-T1S PHY Requirements

We worked with different semiconductor vendors for early 10BASE-T1S PHYs. Three options are presented here.

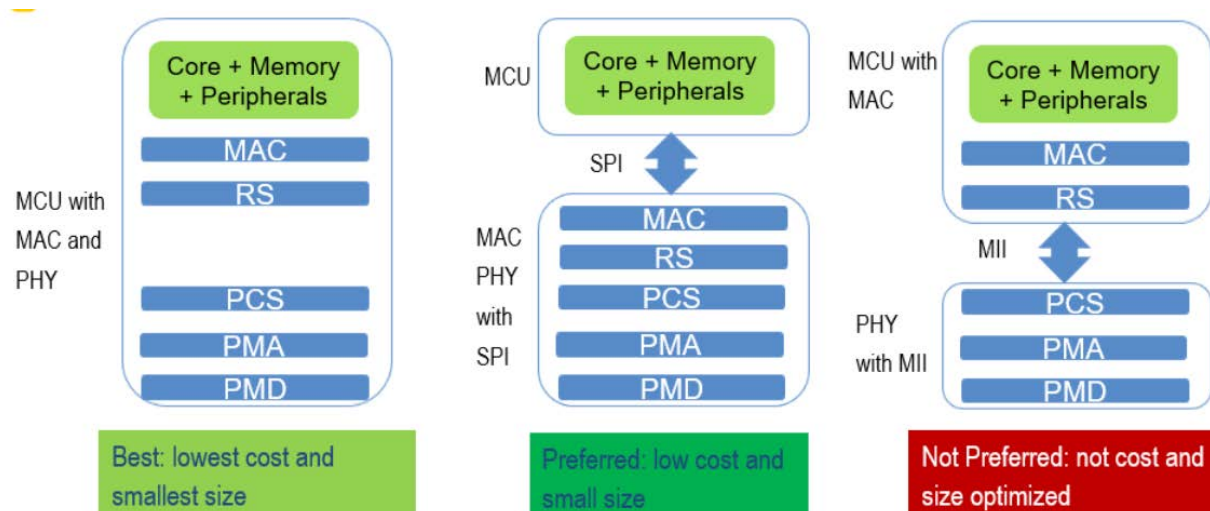


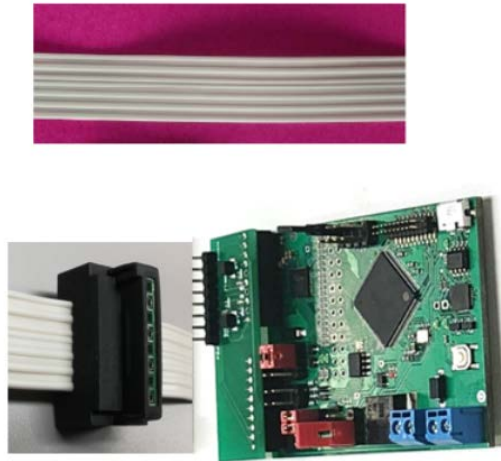
Figure 10 10BASE-T1S PHY Requirements

Option 1 is PHY with MII interface, which will require MCU with MAC and RS built in. This is not a preferred option since MCU with MII interface tend to be a lot more expensive than what the constrained in-cabinet device can afford. More than 16 signals need to be routed between PHY and MCU, therefore requires more board space.

Option 2 is PHY with SPI interface with integrated MAC and RS. This will only require a MCU with SPI interface. This is a preferred option since MCU with SPI interface tend to be a lot less expensive and is the target MCU for constrained in-cabinet devices. Some standard organization like Open Alliance is working on standardizing SPI interface for 10BASE-T1S PHY and we have learned from semiconductor vendors that the SPI PHY will be available in 2020.

Option 3 is PHY and MCU integrated on a single chip. This will greatly reduce the overall package size and could potentially offer the lowest cost option. The challenge is to come up with a part that has right mix of processor power, memory footprint and security features, which can be adopted by the mass market.

## SPE 10BASE-T1S Multidrop Media and Hardware



*Figure 11 Multidrop Media and Hardware*

Cable Sample: Impedance at 104ohm, Insertion loss of 6.7dB @40MHz for 25meter

Connector Sample: Insertion loss of 0.1dB@40MHZ return loss of 33dB@40MHz, breaking both SPE+ and SPE- lines ,36nH in-line inductors are built in.

T1S Hardware: Evaluation boards with T1S PHY compliant to IEEE 802.3CG draft 2.1, MII Interface Integrated PLCA functions

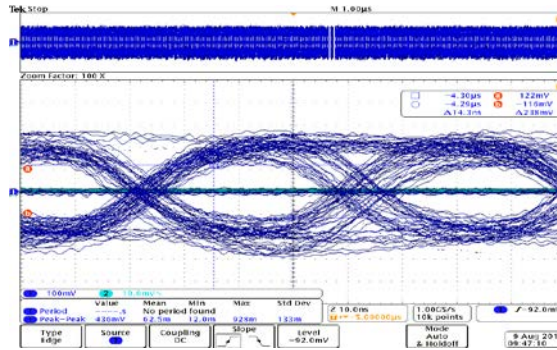
### **System Evaluation Results.**



*Figure 12 System Evaluation Results*

- Multiple setups were evaluated to determine the number of nodes that can be supported with T1S hardware, cable and connectors.
- 40 total nodes; master node 0 at the beginning of 25meter cable, node 1 in the middle of the cable, 38 nodes lumped at the end of the 25meter cable
- Conducted BER test with no bit errors.
- Measured eye height at nodes and matched simulation results.

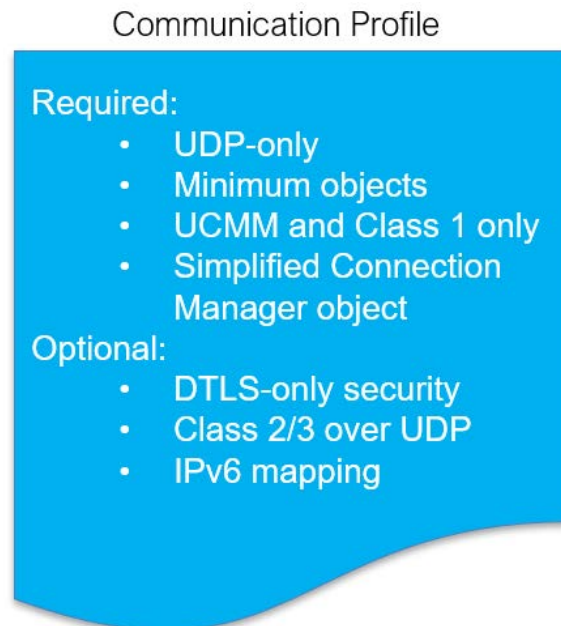




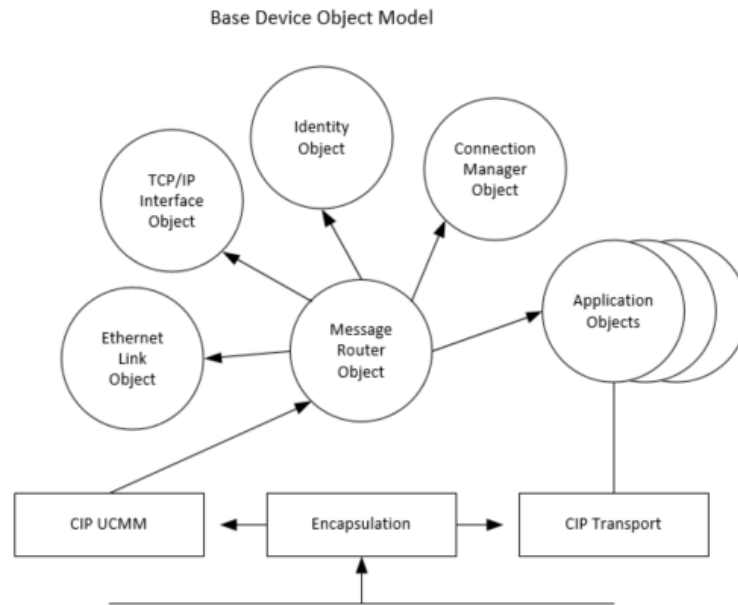
## Constrained EtherNet/IP Communication Profile and Stack Summary

Current EtherNet/IP communication does not support constrained device and network requirements.

It is proposed to develop a constrained EtherNet/IP communication profile as shown. Note that this differs from the concept of a device profile.



The minimum device object model uses the same base objects for constrained EtherNet/IP but minimizes the implementation of the base objects. There are minimized CIP transports over UDP, supporting only UCMM + Class 1.



*Figure 15 Base Device Object Model*

As part of reducing the overhead in a device, the objects are minimized by limiting the optional features. The Connection Manager is shown as an example. Attributes and services are minimized. The communication methods are minimized. The simplifications still retain the required interoperability.

Original Definition in EtherNet/IP Specification	Simplified Implementation for Constrained Devices
Object level simplifications	
20 optional attributes	Zero attributes
4 common services	Zero common services
8 object specific services	2 object specific services (Forward_Open and Forward_Close)
Service level simplifications	
Class 0 and 1 I/O connection	Class 1 I/O connection
Unicast and multicast	Unicast
Class 2 and 3 explicit connection	No explicit connection, UCMM only
CIP Routing	No CIP Routing
Listen-only or redundant owner	No redundancy

*Table 1 Constrained Devices Differences*

The application profiles that a device supports are reported via the Application Profiles attribute 25 of the Identity object. Chapter 11 has been proposed for Volume 2, EtherNet/IP Adaptation of CIP to define the EtherNet/IP Transports Application Profile. The new EtherNet/IP Transports Application Profile defines the “Full” and “UDP-Only” transport profiles.



The Full EtherNet/IP transport profile specifies the use of TCP and EtherNet/IP encapsulation sessions for CIP connection management and connected explicit messaging, and UDP transport protocols for implicit message transmission.

The UDP-Only EtherNet/IP transport profile specifies the exclusive use of UDP for the transmission of all CIP messages. This profile, since TCP is no longer required, results in a simplified EtherNet/IP stack.

A new “EtherNet/IP Capability” CPF item is propose, this new CPF item will use the EtherNet/IP Transports application profile data. The EtherNet/IP Capability” CPF item has been added as a valid item to the ListIdentity response. This allows discovery of a constrained device’s EtherNet/IP capability using ListIdentity. Paired with this is a new EDS entry [ApplicationProfiles Assembly], to describe constrained device’s EtherNet/IP Capability. The following is the define on the new EtherNet/IP Capability” CPF item:

Field	
Type ID	EtherNet/IP Capability (0x87)
Length	Number of bytes = 4
EtherNet/IP Transports Application Profile	Bit 0 = UCMM over TCP Bit 1 = UCMM over UDP Bit 2 = Class 3 Connections via TCP Bit 3 = Class 3 Connections via UDP Bit 4 = Class 2 Connections via TCP Bit 5 = Class 2 Connections via UDP Bit 6 = Class 1 Connections Bit 7 = Class 0 Connections

*Table 2 CPF Item*

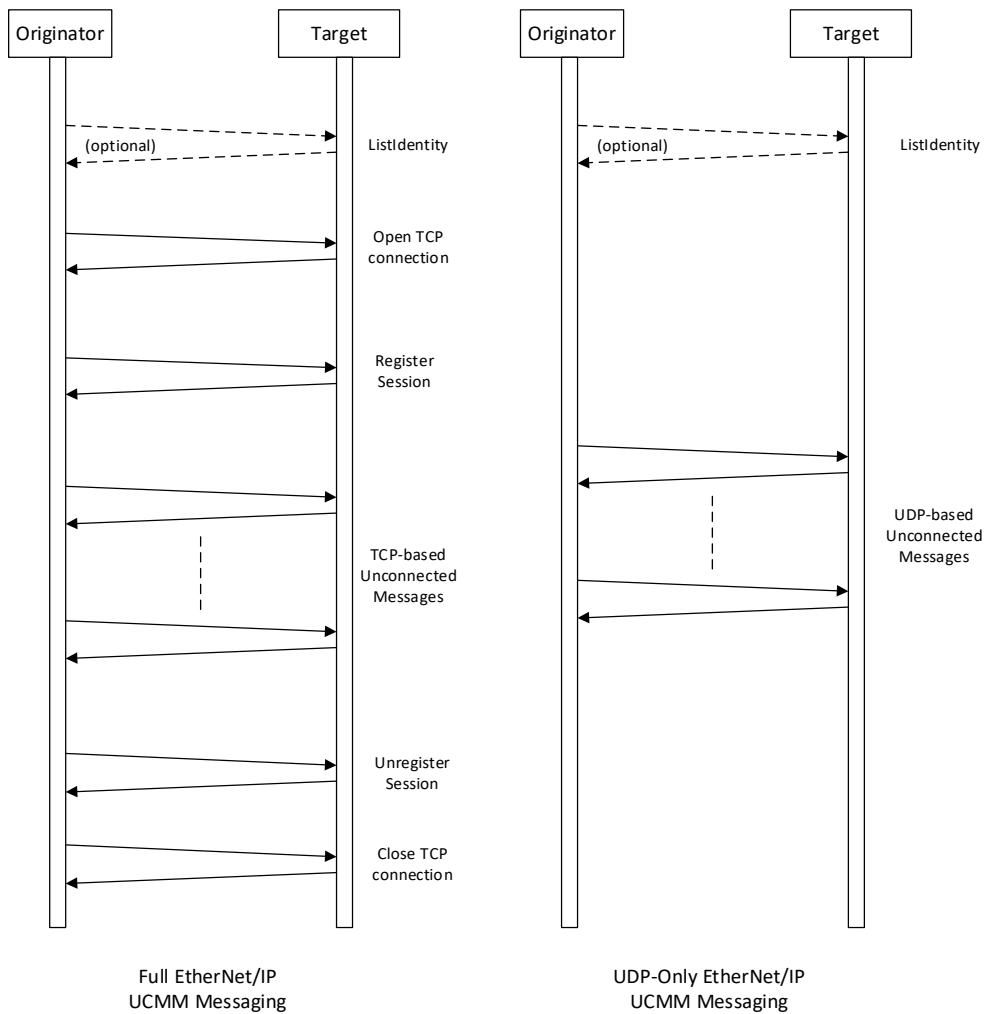
The new EtherNet/IP Transports Application Profile definition allows the combinations of supported features:

Features	Full EtherNet/IP Transport Profile	UDP-Only EtherNet/IP Transport Profile
UCMM over TCP	Required	Not Supported
UCMM over UDP	Not Supported	Required
Class 3 over TCP	Optional	Not Supported
Class 3 over UDP	Not Supported	Optional
Class 2 over TCP	Optional	Not Supported
Class 2 over UDP	Not Supported	Optional
Class 1 over UDP	Optional	Optional
Class 0 over UDP	Optional	Optional

*Table 3 Transport Application Profile Definition*

The simplification of the communication of an UDP-only device eliminates the TCP connections and the encapsulation sessions and this will reduce the complexity of the communication stack. Some examples if the simplification will be described in the following figures.

The following figure show a comparison of Full EtherNet/IP vs. UDP-Only UCMM messaging.



*Figure 16 Sequence Diagram UDP-only*

The following figure show a comparison of Full EtherNet/IP vs. UDP-Only Implicit messaging.

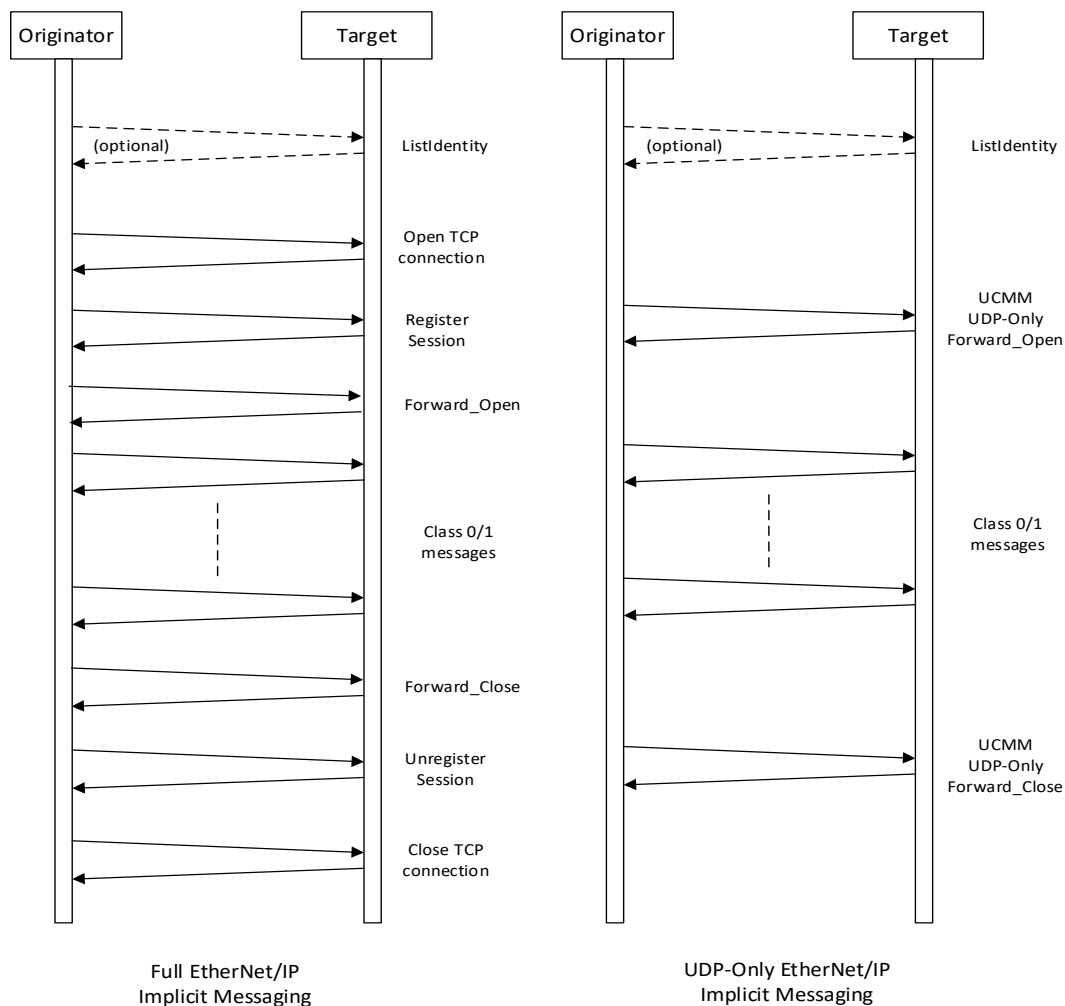
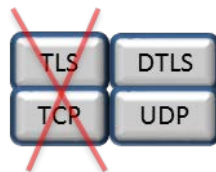


Figure 17 Full EtherNet/IP vs UDP-only

Since CIP Security requires both TLS and DTLS, we also propose to add optional support for into the EtherNet/IP adaptation for DTLS-only. This is illustrated in the Figure below.



Proposed additions to Volume 8 CIP Security will allow devices implementing the UDP-only EtherNet/IP transport application profile, DTLS is used for all CIP communications sent in a CIP Security context. The following figure illustrates the (simplified) sequence of messages needed to exchange EtherNet/IP unconnected messages over DTLS

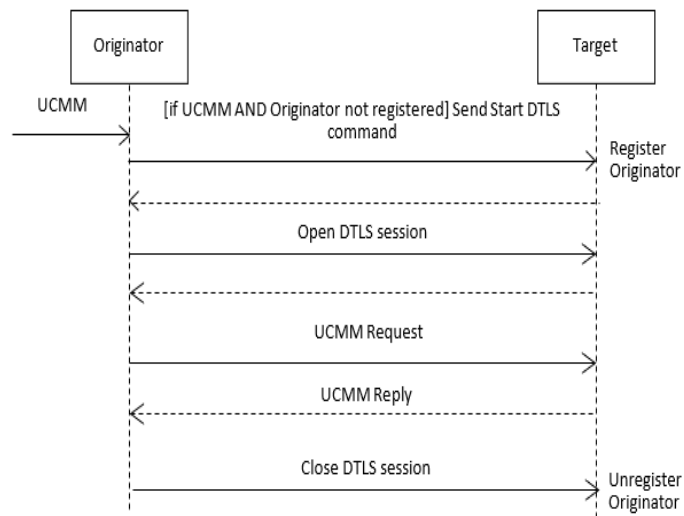


Figure 18 Unconnected messaging over DTLS

The following figure summarizes the constrained EtherNet/IP proposal. Features shown in red are eliminated. Features shown in green are new additions. Features shown in yellow are modified (reduced).

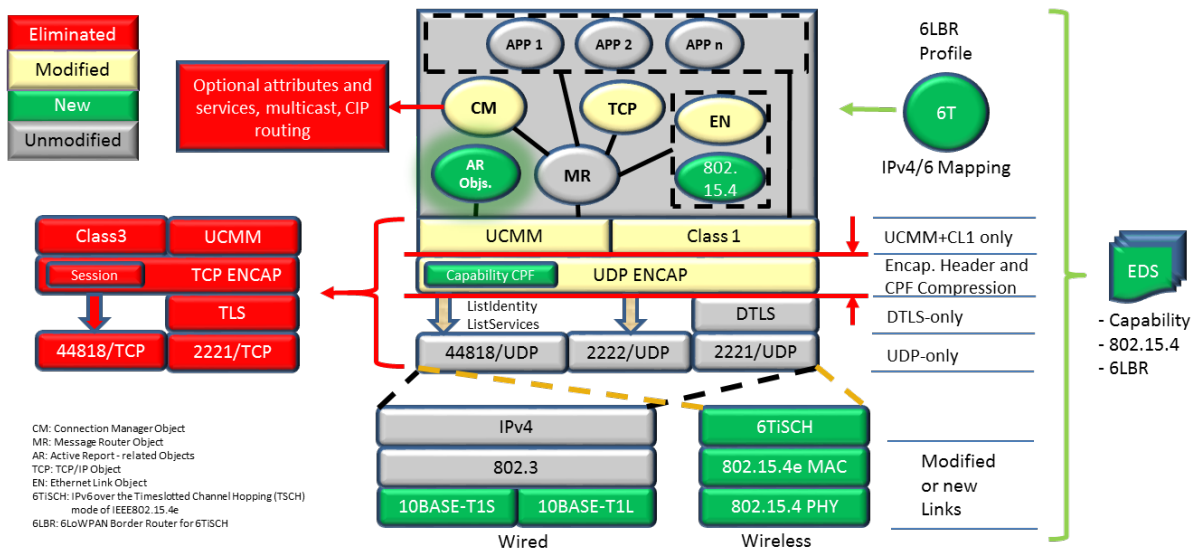


Figure 19 EtherNet/IP Proposal

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