Enhancements to EtherNet/IP for Constrained Devices and Networks

David D. Brandt
Senior Principal Engineer
Rockwell Automation, Inc.

Dayin Xu
Senior Research Engineer
Rockwell Automation, Inc.

Dr. Jörg Hähniche
Head of Development & Integration Services
Endress+Hauser Process Solutions AG

Matthias Dietrich
Software Engineer
Endress+Hauser Process Solutions AG

Presented at the ODVA
2018 Industry Conference & 18th Annual Meeting
October 10, 2018
Stone Mountain, Georgia, USA

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. Unfortunately there remain barriers to the single network vision. The mix of EtherNet/IP, fieldbuses, and hardwired nodes persists due to application constraints near the network edge. Fortunately, the open market is bringing new techniques to bear. Unprecedented IoT opportunities led IETF to create IP-stack optimizations for constrained devices and networks (RFC 7228). Enhancements are applicable to both low power wireless (6TiSCH) and wired networks, eliminating TCP overhead (UDP-only), compressing messages (6LoWPAN), expanding the address space (IPv6), optimizing security (OSCORE), and shrinking the Web server (CoAP). Numerous industries 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 1000 meter variant targets process plants and other large sites. A deterministic Ethernet bus variant targets very constrained devices, such as in-cabinet components. This paper proposes 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.

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,

Definition of terms (optional)

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 P802.3cg	-	Ethernet project, 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

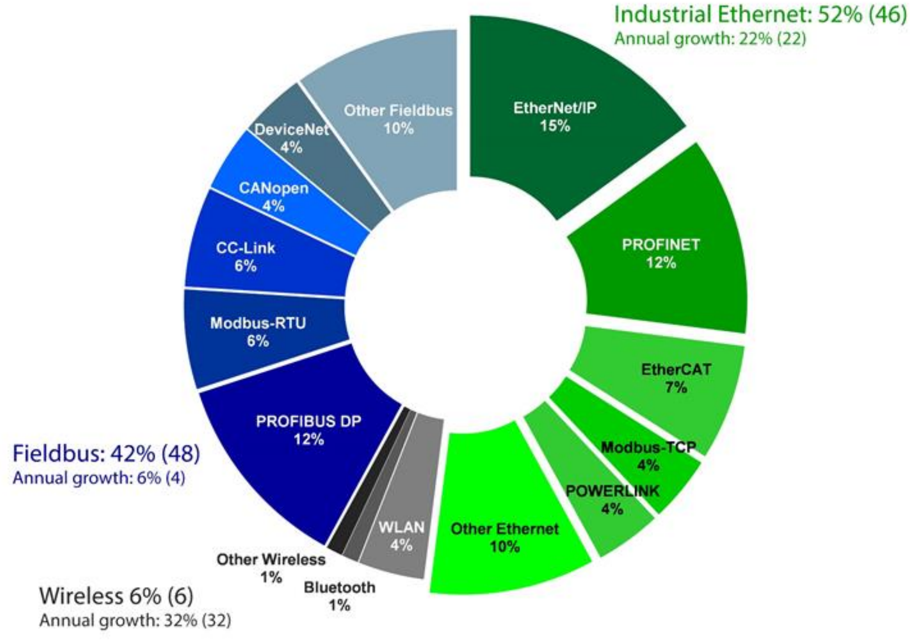
Trademarks

Purpose of Paper

This paper presents a set of proposed enhancements, many adopted from or inspired by IETF and IEEE, making it possible to use EtherNet/IP on constrained devices and networks, thus enabling the single-network vision - where all devices in an industrial plant can communicate with the same set of protocols.

It is assumed the reader had familiarity with EtherNet/IP implementation concepts.

Industrial Network Convergence



Source: HMS networks, Feb 2018
(Parentheses indicate 2017 numbers)

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. However, traditional fieldbus solutions and sensor networks still have advantages, retaining a large position. Additionally, many potential network nodes remain hardwired.

The Single Network Vision

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

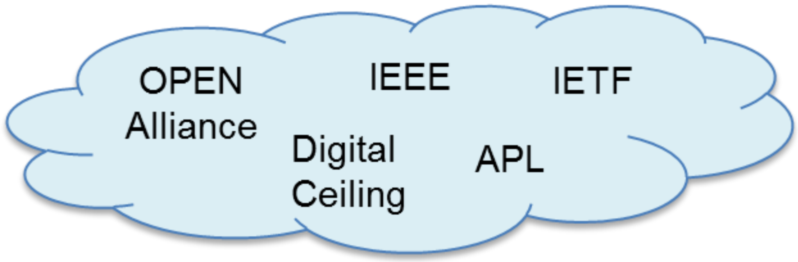


Figure 2: Organizations promoting expansion of Ethernet and/or IP at the edge

The Automotive industry has been working toward an all-Ethernet vehicle. Multiple, incompatible networks (including Ethernet) were added to vehicles, until finally the cable harness became the third heaviest component in a vehicle – adversely affecting the mileage. The industry formed the OPEN (One Pair EtherNet) Alliance to promote a variety of Single Pair Ethernet (SPE) solutions, first creating a specification around a proprietary solution and the later developing open standards solutions within the IEEE. Automotive continues to push SPE solutions to both higher rates (e.g., LIDAR and radar) and low bit rates (e.g., door switch and headlamp assemblies). Ethernet now pushes to the edge to displace other networks in the vehicle.

The Digital Ceiling is a partner ecosystem promoting smart LED lighting and associated applications. The transition to LED enables recent Power over Ethernet to both power the lighting and to communicate with the lighting over a single cable. Once smart lighting is in place, sensors (occupancy, security, etc.) can be integrated, and wireless communication can be added, to service both the room and the occupants.

Process Automation end users from NAMUR promoted Ethernet (and IP-based automation protocols including EtherNet/IP) for instruments and related devices. Vendors have responded to deliver the technology, organizing in the Advanced Physical Layer organization, and involving ODVA and their peer organizations. Work in IEEE on Single Pair Ethernet (SPE) is anticipated to deliver Ethernet communication and power over cables as long as 1000 meters (including many installed cables) into intrinsically safe environments. See: https://www.slideshare.net/FieldCommGroup/press-conference-joint-fcg-odvapi-20171108-draft-201711041

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-specific 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

Barriers to the Single Network Vision

The mix of Industrial Ethernet, fieldbuses, and hardwired nodes persists due to application constraints near the network edge.

Many of the edge devices are constrained by very low cost. It does not make economic sense to have the network cost more than the rest of the device.

Some devices are constrained by size. They are very small (photo-sensors) and the network components must fit.

Other devices are constrained by power. They are either densely packed or battery powered. Low power consumption becomes a requirement.

Total system cost may be constrained by the amount of wiring, which includes running both communication and power wiring. Wiring cost may exceed the cost of certain devices. Delivery of adequate power plus communication over a single cable becomes a necessity. Certain applications are constrained by the disadvantages in having any wiring at all. Low power wireless solutions exist, but not as part of a harmonized system.

For other applications, long cable distances are required (1000 m or more for industrial fieldbus) and constrained by existing Ethernet length limitations. This may be associated with a requirement for compatibility with Intrinsic Safety for explosive environments.

Addressing the barriers

These barriers are in part addressed with the development of new constrained Ethernet and IP technologies, for wired and wireless usage, emerging from standards organizations such as IEEE and IETF.

This does not automatically imply that Industrial Ethernet protocols can be used on such technologies. The industrial Ethernet protocols have assumed operation over traditional platforms. Thus protocols such as EtherNet/IP must be adapted to match with new constrained devices.

IETF contributions

The IETF introduced "Terminology for Constrained-Node Networks" in https://tools.ietf.org/html/rfc7228. We adopt this terminology in this paper. The nodes and the networks have separate characteristics that make them constrained.

Constrained Node characteristics:

- Low cost
- Small size
- Limited memory [Flash, RAM], and processing resources
- Limited power and energy [battery size or scavenging]
- Limited upper layer services
- Low weight

Constrained Network characteristics:

- Low bitrate or throughput
- High packet loss
- Variability delivery rate
- Asymmetric traffic
- Small packet size
- Limited availability [device sleeps]
- Limited upper layer services

The IETF has introduced a number of related standards and drafts for constrained nodes and networks. These include RFC 7252 (CoAP), RFC 7400 (6LoWPAN), and derivative documents. Techniques are introduced and are applicable to both low power wireless and wired networks, and include:

- Elimination of TCP overhead (UDP-only)
- Compression of message headers
- Expansion of the address space (IPv6)
- Optimization of security (OSCORE)
- Shrinking the Web server (CoAP)

The IETF suite of IP standards is intended to solve IoT needs, but these needs are similar to Fieldbus needs.

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. A number of the standards are already complete, including 100BASE-T1 (100 Mb/s), 1000BASE-T1 (1000 Mb/s), and optional power known as PoDL.

Another family member, IEEE P802.3cg, is in development and has estimated completion in late 2019. The new standard will introduce 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 are contributing to the standard.

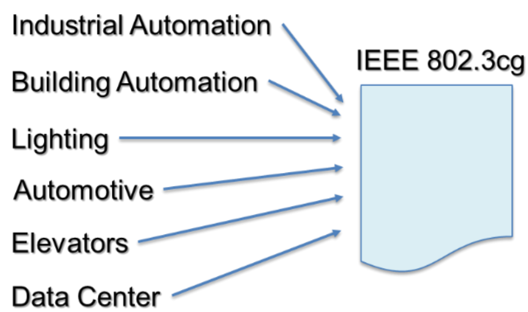


Figure 3: Industries seeking Ethernet enhancements to help displace other edge networks

IEEE P802.3cg 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.

One important application area is Process Automation. Users are requesting Ethernet to the instruments. Constraints include achieving long distance communication and power over single pair cables while maintaining compatibility with intrinsic safety.

A related application area is Low-power Wireless. This is complementary for Process Automation, but has wider usage in Discrete and Batch. The constraints are related to achieving long battery life and the related constraint of fitting into small packet sizes.

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

Another potential application area is On-machine components. The challenge is to reduce the number of cables, while delivering adequate power. Often the component constraints are low cost and small size. Higher performance SPE may be applicable. This application is not discussed further in this paper.

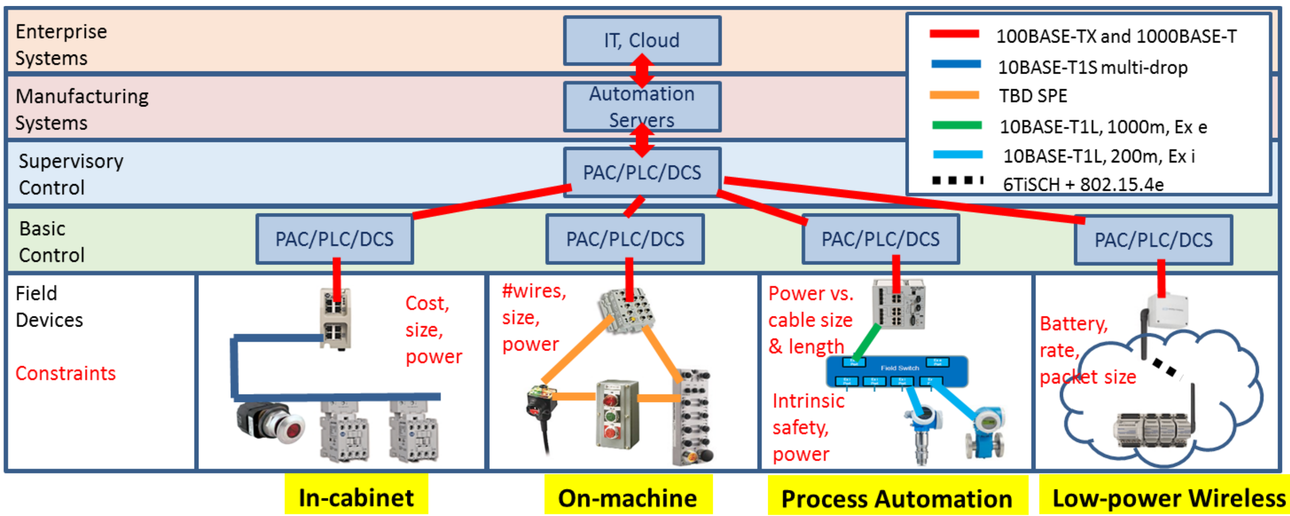


Figure 4: Candidate constrained application areas for EtherNet/IP

UDP-only option

EtherNet/IP currently requires the use of both TCP and UDP in the network stack of a device. While TCP does have advantages e.g. when it comes to the guaranteed delivery of messages, it also adds additional resource requirements. TCP being connection-oriented, the stack needs to keep track of each single client connected to the device and needs to buffer messages in case packets are lost on the network and need to be retransmitted. This means TCP needs additional memory and processing compared to UDP.

Using UDP-only can result in a substantial reduction in stack complexity and messages. A UDP-only prototype demonstrated about 30% savings in Flash and RAM in a constrained device. Such a reduction can mean a device uses one size smaller MCU, reducing cost, size, and power.

Figure 5 shows the elimination of TCP-based connected messages. It also shows the elimination of the associated encapsulation session. Besides the reduction in stack size, the reduction in messages benefits low power wireless applications by extended battery life.

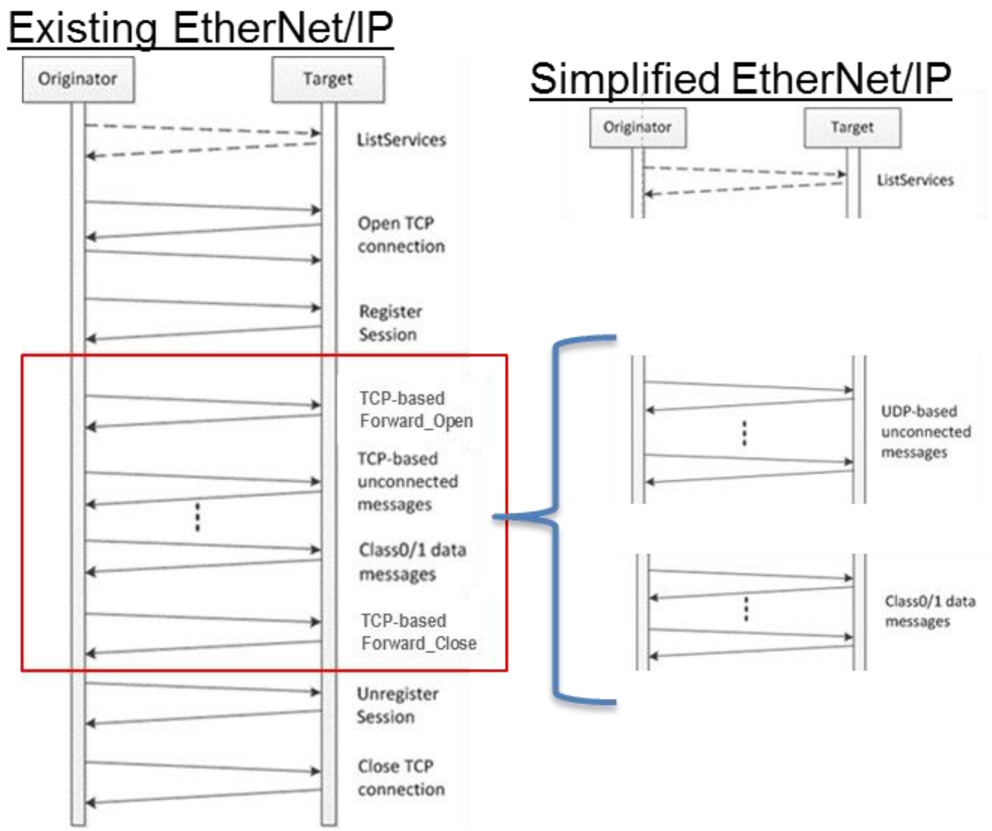


Figure 5: Simplification of EtherNet/IP messaging

Note that other constrained stacks, such as CoAP from IETF, also implement and rely on UDP exclusively. Support of UDP-only would align EtherNet/IP with IoT requirements and evolution.

We propose to add optional support into the EtherNet/IP adaptation for 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 Figure 6. It is also proposed that ListServices be extended to identify the capabilities of UDP-only, TCP+UDP, or both.

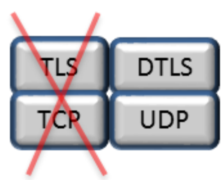


Figure 6: Simplification of EtherNet/IP stack by optional UDP-only and related DTLS-only

A number of implementation options exist. One option is to base the solution on the existing Volume 8 - Secure UDP-only. Extension would be necessary to support both secure and standard UDP-only, and to support a more complete set of services via UCMM. It would also be beneficial to support a unified capability discovery method. Figure 7 shows an example stack for this implementation option.

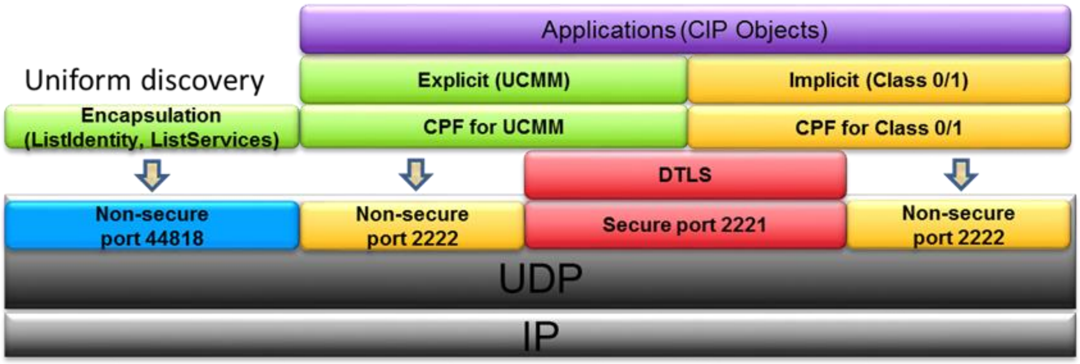


Figure 7: Example UDP-only stack

Encapsulation and CPF Header Compression option

In relation to typical CIP application payloads, the encapsulation and CPF headers create a significant overhead in EtherNet/IP messages. Low power wireless networks, such as IETF 6TiSCH, have constrained packet size, which is not able to carry the existing encapsulation header in a single wireless packet. Extra messages (multiple per message) substantially reduce battery life.

The EtherNet/IP encapsulation and CPF headers can be compressed by adopting the same technique as is used in 6TiSCH. The process is called “eliding”. Many of the header fields are options that rarely change. Addition of bit fields to indicate the optional presence of byte or word fields allows a compression on the order of 8 to 1. Eliding is lossless in function and backward compatible.

Prototyping (Figure 8) has shown excellent compression for ListIdentity, ListServices, General UCMM, and Class 0/1. Note the ability to compress multiple headers in a single message.

			ListIdentity	ListService	General UCMM	Class0/1
Header Compression and Command (HCC)		Word Value	0xB763	0xBF04	0xB76F	
	15	Header Comp. Flag	1	1	1	
	14	Reserved	0	0	0	
	13	Options	1	1	1	
	12,11	Sender Context	2	3	2	
	10	Status	1	1	1	
	9	Session Handle	1	1	1	
	8	Length	1	1	1	
	Bit7-0	Command	0x63	0x04	0x6F	
CPF Compression&Item Count (CCIC)		Word Value			0x8052	0x8092
	15	CPF Comp. Flag			1	1
	14	Message Type			0	0
	13,12	Reserved			0	0
	11,10	T->O Socketaddr			0	0
	9,8	O->T Socketaddr			0	0
	7,6	Data Item			1	2
	5,4,3	Address Item			2	2
	2,1,0	Item Count			2	2
Before compression (byte)			24	24	40	18
After compression (byte)			4	2	8	10

Multiple Items

Figure 8: Prototype header compression results

Existing Volume 8 - Secure UDP-only introduced the “CPF for UCMM” to replace and reduce the Encapsulation header from 40 bytes to 16 bytes. The proposed compression could reduce this even further.

It is proposed to evaluate compression options for:

- Encapsulation header
- CPF for Class 0/1
- CPF for UCMM
- CPFs used within CIP services

Constrained EtherNet/IP physical layers

EtherNet/IP does not support appropriate physical layers for several constrained domains:

- Process Automation wired instruments for APL
- Process Automation companion wireless instruments
- In-cabinet components

We suggest to reference and extend 3 new PHYs:

- IEEE P802.3cg 10BASE-T1L PHY for Process Automation wired instruments
- IEEE P802.3cg 10BASE-T1S PHY for In-cabinet component usage
- IEEE Std 802.15.4-2015 PHY for Process Automation wireless instruments

Constrained EtherNet/IP Communication Profile

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.

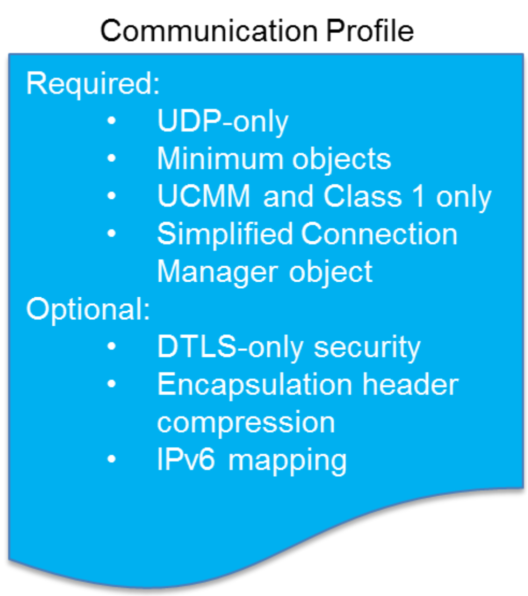


Figure 9: EtherNet/IP Communication Profile for constrained nodes

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

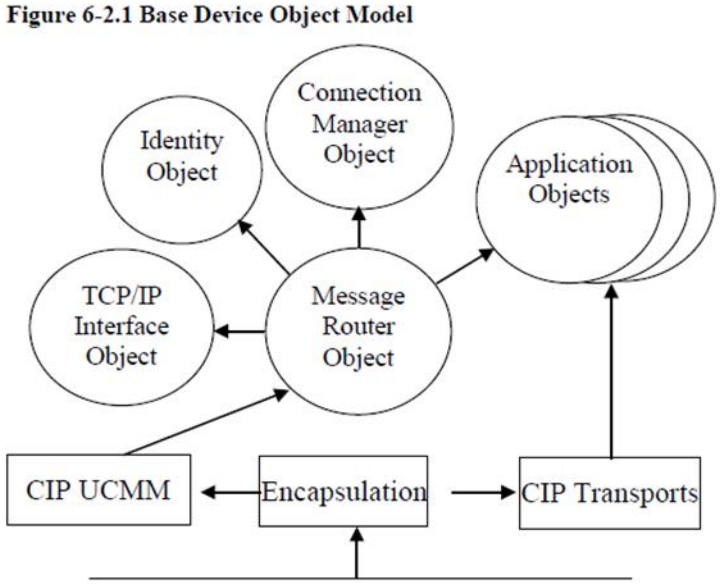


Figure 10: EtherNet/IP Base Device Object Model

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

Figure 11: Object minimization example for Connection Manager

A new “Constrained EtherNet/IP Capability” CPF item is proposed. This allows discovery of a constrained device’s EtherNet/IP capability using ListIdentity. Paired with this is a new EDS entry [Constrained EtherNet/IP Capability], to describe constrained device’s EtherNet/IP Capability.

Field	
Type ID	Constrained EtherNet/IP Capability
Length	
Link Type	0 = Ethernet 1 = 802.15.4e
TCP/IP Type	TBD (future compression or feature reduction capabilities)
Encapsulation & CPF Compression	WORD1: ENCAP Header Compression Profile WORD2: CPF Compression Profile
CIP Transport Type	Bit 0 = UCMM Bit 1 = Class 1
CIP Application Type	Bit 0 = Active Report Manager

Figure 12: EtherNet/IP Capability CPF Item for constrained nodes

Constrained EtherNet/IP over 6TiSCH network

Quoting the EtherNet/IP adaptation of CIP:

> *9-2 Data Link Layers*
> *Though this specification is called "EtherNet/IP", Ethernet is technically not required. The EtherNet/IP protocol may be used on any media that supports the transmission of the Internet Protocol.*

Wired EtherNet/IP for Process Automation (under APL) calls for a complementary low power wireless solution. Best suited is IETF 6TiSCH with its open UDP support. EtherNet/IP over 6TiSCH requires constrained features and 802.15.4 link support. EtherNet/IP lack of IPv6 complicates 6TiSCH solutions, and precludes other usage.

We suggest to specify necessary enhancements for EtherNet/IP over 6TiSCH. We can leverage the Constrained EtherNet/IP enhancements:

- Add 802.15.4 MAC and PHY
- Add 6TiSCH router and network management
- IPv4/6 mapping to integrate 6TiSCH devices into IPv4

A full support of IPv6 requires substantial changes. Hence we suggest revisiting full IPv6 EtherNet/IP enhancements and security additions at a future date.

There is good motivation for adopting the IETF 6TiSCH stack (Figure 13) for EtherNet/IP. It is an open (not industry specific) wireless standard, supporting IP-based communication. It provides a self-organizing mesh network that is robust, reliable, and reduces engineering. Furthermore it is based on IEEE Std. 802.15.4 radio hardware, which leads the market.

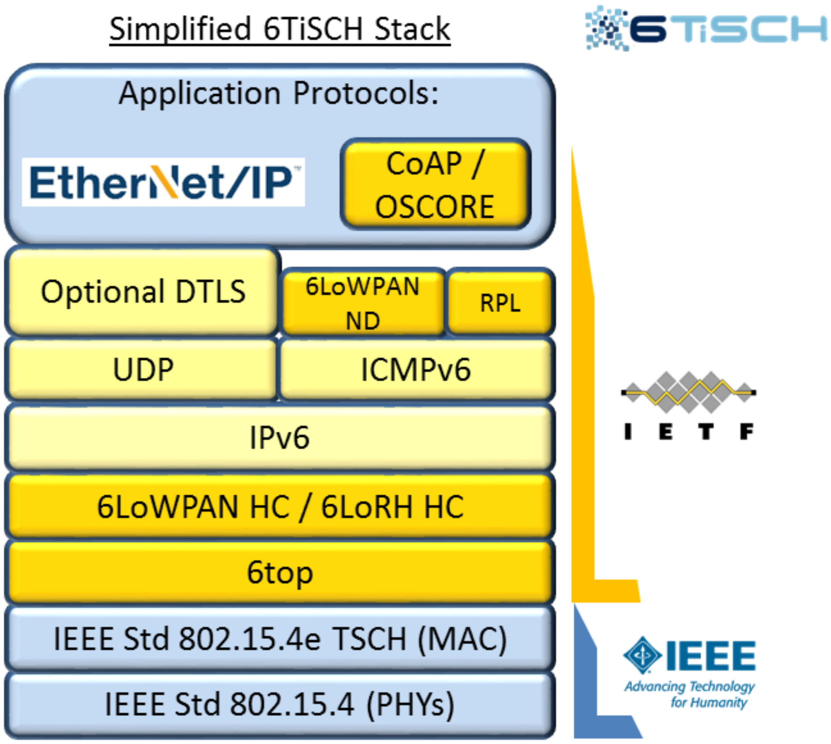


Figure 13: IETF 6TiSCH stack supporting EtherNet/IP

Several enhancements are important for integration of constrained EtherNet/IP over 6TiSCH. These are illustrated in the Figure 14. The physical layer needs to be converted between Ethernet and 802.15.4e. The network and transport layers need to be converted between IP/UDP and 6LoWPAN. The addressing needs to be converted between IPv4 and IPv6.

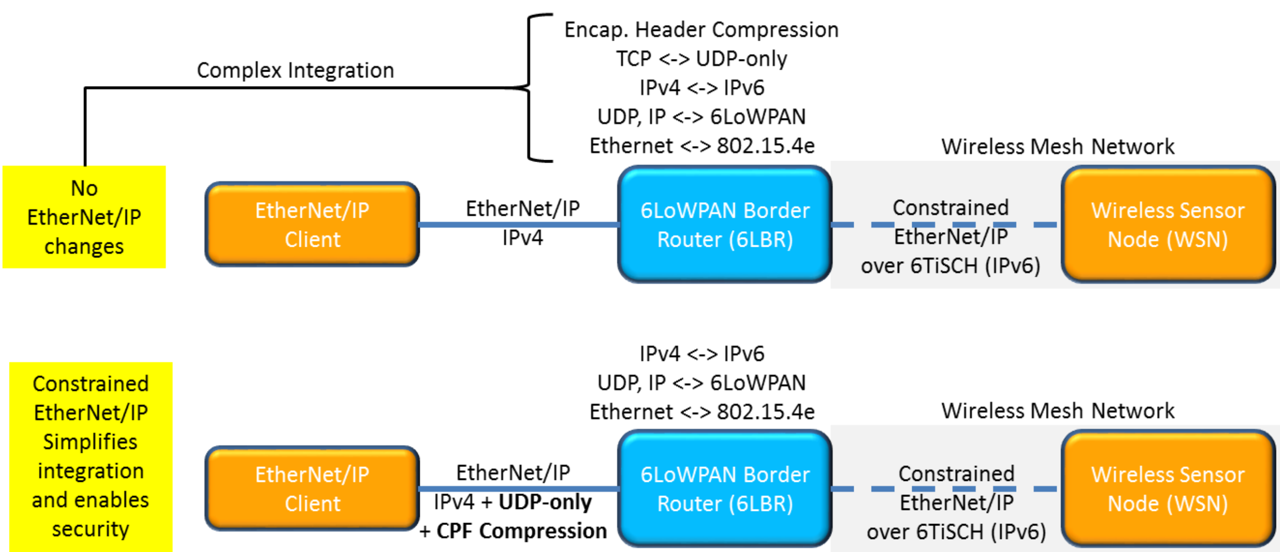


Figure 14: Enhancements simplifying integration of EtherNet/IP over 6TiSCH

Security is required for constrained EtherNet/IP over 6TiSCH. Figure 15 illustrates security options for 6TiSCH.

One option is to utilize two separate security systems. Link layer security is mandatory for 6TiSCH. Additionally, 6TiSCH requires IETF OSCORE security for network join. CIP Security can provide optional security terminating at the 6LBR. Note that CIP end-to-end security is precluded by any 6LBR processing of the application layer (Encapsulation Layer compression).

While CIP Security could operate end-to end, DTLS increases the wireless node overhead. Double processing would have a negative impact on battery life.

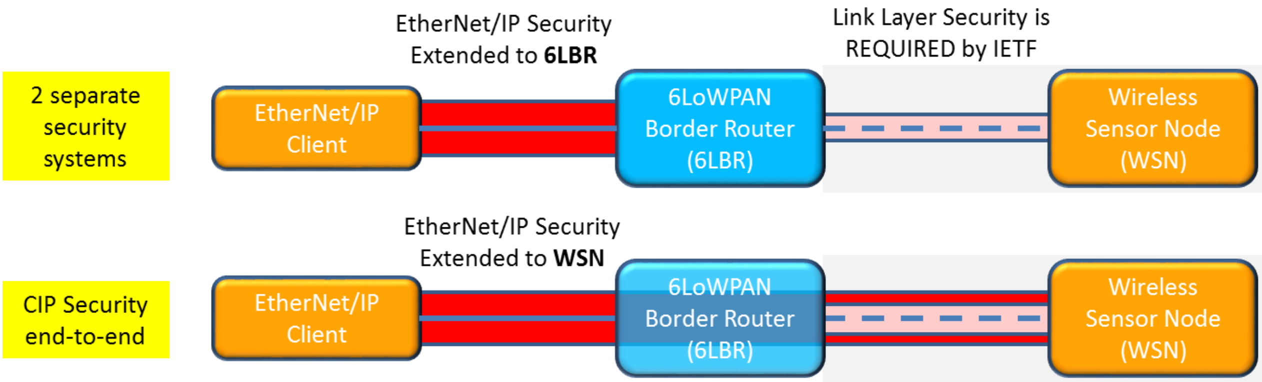


Figure 15: Security options for EtherNet/IP over 6TiSCH

Two new objects are required for support of 6TiSCH networks.

804.15.4 Link Object

- Utilized in both 6LBR and WSNs
- Similar to Ethernet: Interface Speed, Flags, Counters, State, Label, Capabilities, Physical Address…
- New: RF characteristics

6TiSCH Wireless Network Management Object

- Utilized in 6LBR
- Includes:
    - Network status information
    - Network topology information
    - Network routing information
    - Device join and leave

Stack Summary

Figure 16 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).

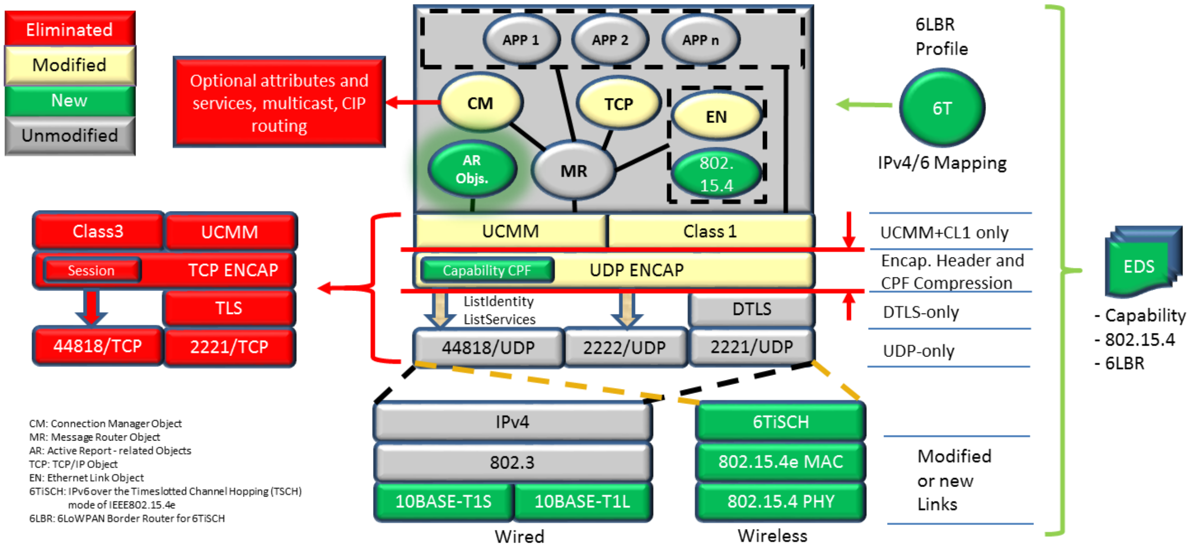


Figure 16: Stack modification summary for EtherNet/IP for constrained nodes and networks

References

NAMUR, “Position paper An Ethernet communication system for the process industry”, http://www.namur.net/fileadmin/media_www/Dokumente/Anforderung_Ethernet-NAMUR_2016-02-25_EN.pdf

IEEE 802.3 CFI, “10 Mb/s Extended Reach Single Twisted Pair Ethernet PHY”, http://www.ieee802.org/3/cfi/0716_1/CFI_01_0716.pdf

IEEE 802.3 SG, “10SPE” (10 Mb/s Single Pair Ethernet), http://www.ieee802.org/3/10SPE/index.htm

IEEE 802.3cg (10SPE) – 10 Mb/s Single Pair Ethernet Meeting Industrial Automation Objectives : 2017-ODVA-Conference_Brandt Xu Haehniche_IEEE-802-3cg-10SPE_R0_FINAL

DeviceNet of Things - Use Cases, Value Proposition and Status of Specification: 2017-ODVA-Conference_Caspers_DOT_FINAL

Resource-constrained Industrial Things - Proposal for the Adaptation of CoAP to EtherNet/IP: 2017-ODVA-Conference_Green Otterdahl_CoAP_FINAL

EtherNet/IP to the Edge – A Concept for "Low-complexity Ethernet” : 2017-ODVA-Conference_Alsup_Weingartner_Low-complexity_Ethernet_FINAL

Extending EtherNet/IP™ to Resource-Constrained Industrial Things: 2015_ODVA_Conference_Xu-Brooks_Extending-EtherNetIP-to-Resource-Constrained-Industrial-Things-FINAL

CIP over 6LoWPAN: Expand CIP to IPv6-based Field Wireless Network: 2014_ODVA_Conference_Xu_Brooks_Yu_Brandt_CIP_over_6LoWPAN_FINAL