european coordinating committee of manufacturers of electrical switchgear and controlgear

Networking opportunities with Single Pair Ethernet for CAPIEL manufacturers

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EXECUTIVE SUMMARY

Switchgear, controlgear and their assemblies are getting smarter thanks to more powerful embedded electronics. The emerging Single Pair Ethernet (SPE) technology enables these network components to interact with the control systems into which they are integrated. This whitepaper analyses the potential transformation of industrial communication networks from traditional fieldbus to SPE, as well as the associated challenges and benefits on the market.

The major business trend is the development of industrial internet of things using digital twin information models for increasing the effectiveness of the manufacturing and electrical distribution systems where the increased connectivity and interoperability of switchgear and controlgear plays a significant role, including the flexibility to adapt information exchanges in systems more rapidly. Challenges such as the carbon footprint reduction required by EU regulations and the required new skills should be managed.

Three use cases:

- manufacturing line,
- industrial in-cabinet automation panel and power distribution panel, and
- smart sensor

are analysed in terms of current challenges, appropriate SPE solution and potential benefits such as simplifying and reducing the cost of the control circuit wiring and increasing the communication speed and its cybersecurity level.

1 INTRODUCTION

In the 1980s, the Controller Area Network (CAN) bus, developed by the automotive industry and integrated into CAN controller chips, provided opportunities for a plethora of industrial applications. In a similar vein, new opportunities are emerging with the current rise of Single Pair Ethernet (SPE), already adapted in the automotive industry. In this paper, we will analyse this technological shift in the industry towards SPE specifications defined by the Institute of Electrical and Electronics Engineering (IEEE). It also provides typical use cases covering most of switchgear and controlgear (7.3) deployed within industrial control systems.

CAPIEL is the Coordinating Committee for the Associations of Manufacturers of low voltage (<1kVAC/1,5kVDC) Switchgear and Controlgear equipment for industrial use in the European Union. The objective of CAPIEL is to promote and to support the common technical, industrial, economic, environmental and political interests of the European low voltage switchgear and controlgear industry (products, systems and assemblies). CAPIEL plays an active role in driving emerging technologies and in supporting the values of ethical, environmental, health and safety, innovation for sustainability, quality and fair competition, in accordance with the imperatives of the Treaty of Rome.

CAPIEL members are national associations representing small, medium and large-sized companies that in total employ more than 100,000 people directly in Europe. Their scope covers all the equipment, products fittings, systems installed, and services required for operations of low voltage switchgear and control gear (products, systems and assemblies).

Our focus on switchgear, controlgear and assembly manufacturers dealing with electric power distribution, as well as on machinery and manufacturing processes in which fieldbus communication (7.9) is business critical. We will be covering market trends and needs such as cybersecurity, energy management and event monitoring. Moreover, we will look at technology trends impacting communication networks in switchboards.

A proposal for a unified internet protocol network architecture is included, too.

2 BUSINESS TRENDS AND IMPACTS

2.1 SMARTER AND MORE SECURED CONNECTED DEVICES

Remote monitoring and control are basic requirements in today's automation applications.

Some applications implement local monitoring and control through hardwiring of components. Pushbuttons, indicators, contactors, and motor protection devices are interconnected by discrete wiring for power and control. Any change in function entails rewiring and addition of components. These hardwired subsystems are sometimes interconnected back to PLCs (7.22) for remote monitoring and supervisory control.

Traditionally, only one or a few data values were communicated. Analog or digital values were converted into standard signals and transmitted to the control system (e.g., a PLC) in various ways aiming at:

- Transmitting the current status of the controlled element
- Transmitting commands to change the status and the controlled process

Most of the time, these signals were limited due to wiring effort for I/Os and consequently to cost per signal. The resulting complexity increased the risk of errors. On the level of the Programmable Logic Controller (PLC) (7.22), all individual signals controlling the machine or process were combined. Every single function needed to be programmed. If data was to be transmitted to higher levels (e.g., Manufacturing Execution System (MES) (7.19); Supervisory Control and Data Acquisition system (SCADA) (7.23), etc.), a mapping to another protocol as well as the communication process had to be programmed on the PLC. This not only elevated performance requirements but also increased engineering and commissioning efforts, as well as sources of errors.

With the advent of increasingly powerful microcontrollers, devices became smarter. Simple functions implemented in various components were merged and realised directly in-device. The need to program every basic function on the PLC became obsolete. Examples of additional functions integrated directly into devices include:

- Running control logic at the edge
- Executing more advanced algorithms to derive maintenance triggers from locally measured data
- Integrating features related to energy management
- Concentrating functions that were previously realised separately into fewer devices
- Offering flexible configurations to adapt to various industrial applications

Smart devices offer users higher levels of abstraction, presenting complete solutions for individual tasks. Furthermore, they provide a significantly higher number of signals and data that can be exchanged with higher-level systems. Such devices also allow access to more data without incurring additional costs, as the data is transmitted via communication system instead of separate digital and analogue signals. Moreover, smart devices are often not just integrated into higher-level devices, such as a PLC responsible for application control, but also into additional devices, responsible for process visualisations, asset management, and more.

Simultaneously, the usage of Ethernet communication protocols for more powerful automation devices and the associated security requirements have steadily increased. Single Pair Ethernet promises to utilise Ethernet based communication protocols for simpler devices where Ethernet has not been an option so far. This allows for easier device integration across different levels of the automation pyramid, reduction of wiring and I/O costs, reduction of likelihood of mistakes, as well as utilisation of inherent security features and best practices available in Ethernet-based communication protocols.

2.2 FIELDBUS MARKET TRANSFORMATION

With the first applications installed and used as early as the beginning 1970s, the fieldbus (7.9) market was established around 50 years ago. Standardisation, however, did not start until the mid-1980s.

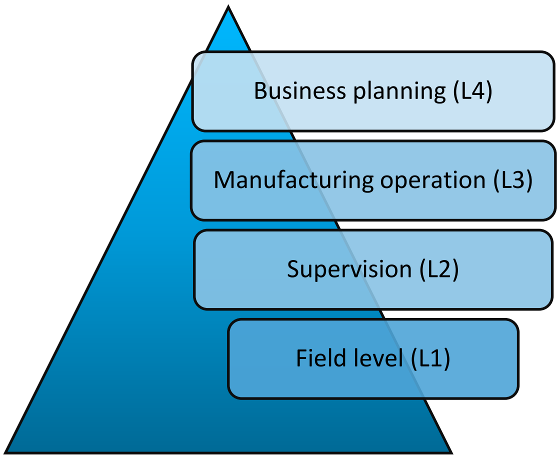


Figure 1 – IEC 62264-1 functional hierarchy

Referring to the ISA95/IEC 62264-1 functional hierarchy given in Figure 1, four different levels can be distinguished in a manufacturing process:

1. **The business planning (Level 4)** with Enterprise Resource Planning ERP (7.7) data collection, high-level supervisory systems and visual monitoring of plant status. On this level, PCs communicate via traditional cable networks.
2. **The manufacturing operation management (Level 3)** defines the activities of the work-flow, to produce the desired products. It includes the activities of maintaining records and coordinating the processes.
3. **The supervision (Level 2)** where PLCs (7.22) and other controllers receiving and processing sensing data and controlling the physical processes to the field level. Communication between devices using Ethernet-based protocols like EtherNet/IP or PROFINET takes place at this level, too.
4. **The field level (Level 1)** with sensors, actuators such as motor starters and other elements detecting or acting in the processes. We find a multitude of different fieldbus (7.9) protocols, cables, connectors, data packets or analogue signals here, all running in parallel. If these elements are exchanged, a gateway (7.10) active device must translate the information. This implies a greater inventory of spare parts, more specialists for different protocols and more difficult troubleshooting.

The field level is the only level of this automation pyramid, not usually based on Ethernet. On this level, we find legacy technologies that work for today's applications, but do not offer the bandwidth and integration capabilities for future infrastructures of the Industrial Internet of Things (IIoT) as shown in Figure 2.

Whether in buildings or industry, the emphasis on modern automation processes is growing and companies increasingly rely on intelligent solutions. With the help of smart infrastructure, environmental conditions can be monitored seamlessly and automatically adapted to user requirements at any time.

Intelligent solutions enable:

- Worldwide remote access to information, machines and plants
- Monitoring the health of equipment as a basis for predictive maintenance management
- Monitoring of consumption and efficiency (e.g. energy, water)
- Increased multi-levelled access security and protection against security hazards
- Customisable settings and profiling (e.g., light intensity or temperature balance)
- Fast updates and a clear overview to facilitate maintenance and troubleshooting

Figure 2 – IIoT architecture

IIoT applications require a new generation of sensors and actuators (7.1), communicating with each other in a network. Figuratively speaking, they need to see more, feel more and analyse more. However, traditional automation structures are encountering limits. SPE promises to overcome this limitation in the near future.

2.3 TRENDS IN INDUSTRY SECTORS

Across all industries, network installers and automation specialists are facing old and new challenges while implementing automation networks at the field level.

Current challenges can be divided into 2 main categories:

1. **Complexity of communication**
   A broad variety of different traditional fieldbus (7.9) protocols requires expert knowledge on each specific fieldbus. The management of different communication protocols, as well as the various cabling and connectivity constraints, results in high labour costs of intensive setups and network maintenance.

2. **Specific hardware**
   Today's field level communication does not support robust security features. It also requires fieldbus specific infrastructure (e.g. gateway (7.10), repeater) and it does not have the network capability in common, to integrate with the IT systems that sit above.

On top of that, network installers and automation specialists are facing new challenges. They can be divided into 3 main categories:

1. **Skill shortage**
   The foreseeable lack of traditional fieldbus experts requires reliable and simple network setups, installation, and maintenance. Specialist knowledge for a broad range of proprietary installation concepts demands skills that will be hard to find in the years to come. Common IT network skills and standardised components with easy-to-install connectivity and software will make the difference. See 2.5 "Economic and societal impacts".

2. **Monitoring the Corporate Sustainability Reporting Directive (CSRD)**
   The requirements for corporate sustainability reporting will be greatly expanded from 2024. Reporting of non-financial KPIs will include CO_2 corporate emissions necessitating a transparent network to access information on energy efficiency and resource conservation.

3. **Cyber Resilience Act**
   A low level of cybersecurity, reflected by widespread vulnerabilities in automation networks and the insufficient and inconsistent provision of security updates to address them, demands hardware with internet connectivity. The EU regulation on cybersecurity requirements for products with digital components, known as the Cyber Resilience Act, bolsters cybersecurity rules to ensure more secure hardware and software products across the entire automation pyramid.

Across the market, Ethernet has long worked as a backbone for networking in applications. However, the advent of digitalisation and the Industrial Internet of Things (IIoT) have led to rising sensor density and a corresponding demand in uninterrupted communication speed. This marks a shift in the role of Ethernet. The technology will no longer purely complement serial fieldbus communication protocols, but will extend and/or replace them in the future.

The study from HMS Networks AB on industrial networks illustrates in Figure 3 the shift from fieldbus to Ethernet communication. The transition in recent years has been dramatic. In 2015, 66% of industrial communication was fieldbus-based, with Ethernet accounting for 34%. Only eight years later, we see fieldbus communication making up only 24% of all installed networks, while Ethernet represents 68% of overall communication, growing by 10% annually.

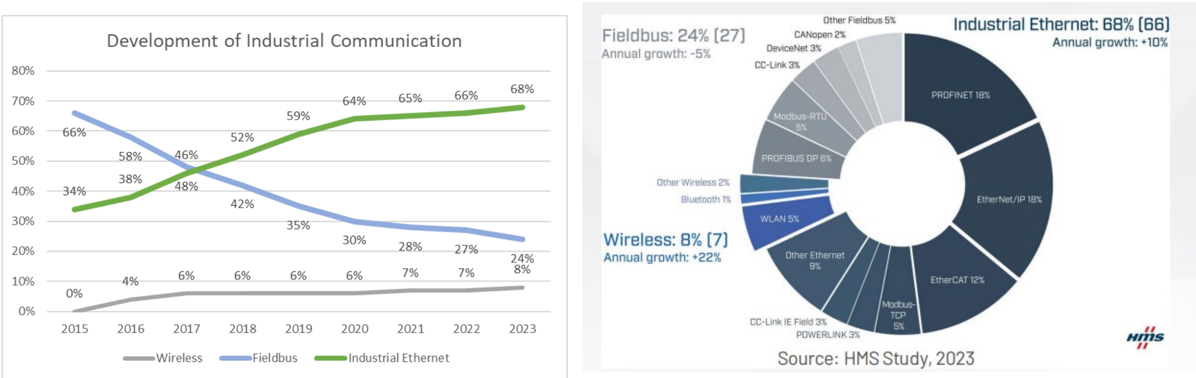


Figure 3 – Fieldbus transition to Ethernet

The development is best exemplified by the industrial plant. Historically, plants featured an Ethernet networking backbone alongside a collection of fieldbus systems at field level. The emergence of IIoT disrupted this established architecture as the new technology demands a more efficient communication sub-system.

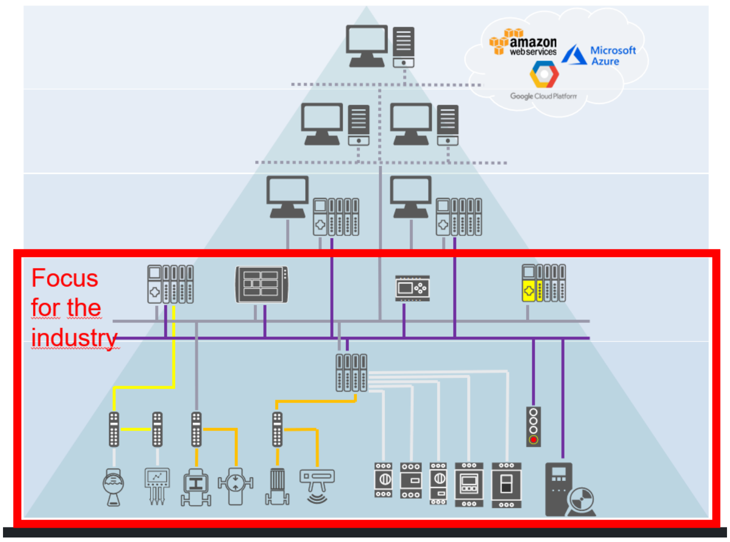


Figure 4 – Example of a current network infrastructure.

Fieldbus communication as shown in Figure 4 in modern industry is quite heterogeneous. Adoption of Ethernet-based networks promotes standardisation and provides an opportunity for intercommunication between fieldbus devices and the upper levels of the automation pyramid. Similar advantages apply to any market or application area involving communication at sensor and network levels. For all applications mentioned above, seamless communication is crucial. Single Pair Ethernet provides a great solution for all high-speed (1 Gbit/s) to low-speed (10 Mbit/s) IP networks.

The technology is ideal for applications where saving space, costs and extending long-distance communication are more important than maximum speed. While various application areas might require different hardware, buildings, or outdoor applications, all relevant industries will benefit from SPE. With Single Pair Ethernet, a new standard has been established, enabling the necessary miniaturisation and long cable runs. With Ethernet technology suitable for industrial use, a seamless link from the sensor to all upper levels of automation, including the cloud, can be established.

Moreover, SPE supports the entire spectrum of modern cybersecurity. It enables installers to create multiple network domains, segments or sub-networks connected by firewalls or gateways (7.10) where cybersecurity policies can be enforced. Therefore, SPE enables continuous connections from sensor to cloud; but connections may also be “segmented”, e.g. for cybersecurity purposes.

Another major advantage of the technology is the possibility of supplying power to connected peripherals via Power over Data Line (PoDL). This way, the sensor system can be supplied with both power and data through a single pair of conductors in the cable and a single connector even in extremely compact environments, eliminating the need for additional, separate power supply lines.

Different industries have different SPE requirements. Figure 5 gives an overview of these various requirements.

	Automotive	Building Automation	Process Automation	Factory Automation
Application Focus	**Wiring harness in the automobile**	**Switch cabinet wiring Field cabling (e.g. KNX)**	**Field cabling sensors**	**Ind. switch cabinet wiring Field cabling Field cabling sensors**
Transmission rate Transmission distance	10 MBit/s - 1 GBit/s 15-40 m	10 MBit/s - 1 GBit/s < 1000 m	10 MBit/s < 1000 m	10 MBit/s - 1 GBit/s ≤ 100 m
Conductor cross-section	AWG 26-22	AWG 26-22	AWG 22-18	AWG 26-22
Mech. / electr. robustness	medium – high	low – medium	high (+Ex)	medium – high
Current connectors	Automotive-specific connectors	Individual wiring, terminal, EIB, RJ45	Terminal, plug connector, M12	RJ45, single wiring, terminal, M8/12

Figure 5 – Different industry requirements for single pair Ethernet

2.4 TYPICAL USE CASES IN INDUSTRIAL AUTOMATION

The value for the industrial automation market, has some common themes which are identified below.

2.4.1 Incentive

When examining automation panels and industrial cabinets, the question arises as to how Single Pair Ethernet can provide benefits in this area. Within these environments, there are many devices – for the most part complex ones such as servo drive controllers (7.24) or PLCs (7.22) – already equipped with traditional Ethernet connectivity (10BASE-T, 100BASE-TX or 1000BASE-T).

SPE's transformative impact is most pronounced in devices that currently lack communication capabilities or only support legacy technologies like serial communication, fieldbuses, or proprietary systems. SPE can extend Ethernet connectivity to simpler, in-cabinet devices, bridging a critical gap in continuous, transparent machine communication and facilitating digital transformation in plant automation.

The ongoing digital transformation in plant automation highlights the importance of processing and utilizing structured data. Industrial equipment has in general more valuable data available internally than currently exposed on the communication interface. Continuous communication across industrial networks, which SPE enables, is vital for leveraging this data. SPE supports scalable, time-sensitive networking throughout the entire automation pyramid.

As the number of intelligent terminal devices grows, the available space in industrial settings is shrinking. At the same time, sensor technology is becoming increasingly integral to industrial machines and systems. SPE addresses these challenges by providing compact, simply designed cabling suitable for industrial use, aligning with the evolving needs of the industry.

2.4.2 Challenges

Expanding globalization places increasing cost pressures[1] on panel builders and machine manufacturers alike. This extends beyond component costs to include assembly, installation, commissioning and maintenance expenses.

Another challenge is energy efficiency. Figure 6 illustrates the distribution of greenhouse gas (GHG) emissions across various sectors. From the total impact, 21% is attributed to industrial processes and industrial energy consumption. A more detailed breakdown into specific industries and applications reveals that the majority of emissions occur in sectors where machine manufacturers sell their products. Consequently, these manufacturers face heightened demands to reduce the carbon footprint of their machines. The situation necessitates insights into their processes and strategies for optimizing energy efficiency.

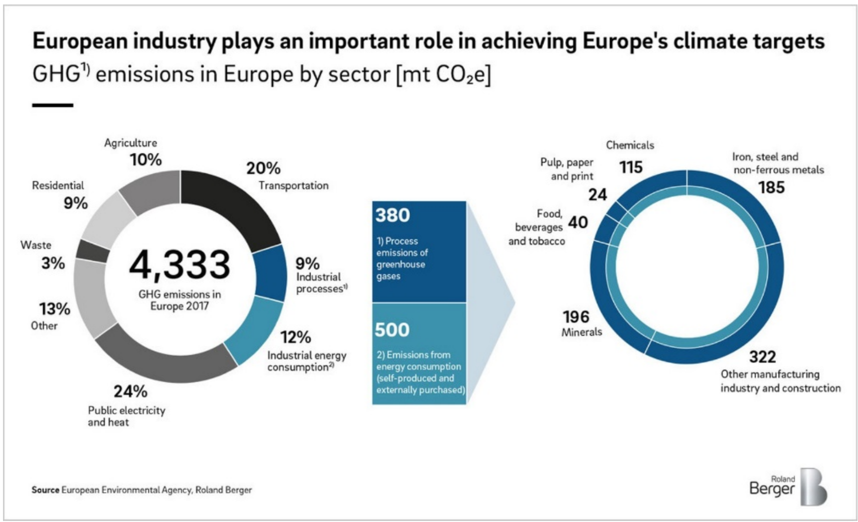


Figure 6 – Carbon footprint reduction trends in the EU

Similarly, machine manufacturers face the need to differentiate themselves from their competitors. In an increasingly digitalized world, this requires the incorporation of new product features and the exploration of new business models. All of which rely on data from machines and subsequently, the components within those machines. Increased complexity, in automation systems and reporting requirements, calls for a more data-driven approach towards asset management and tracking, a need that cannot be fulfilled without products capable of effective communication.

Alongside the growing demand for data, there is an increasing number of cybersecurity[2] threats that cannot be countered effectively by legacy communication systems. Legislative action is taken to enforce the appropriate protection and intended use of data. Consequently, manufacturers and users alike require communication systems that can leverage well-established security mechanisms to protect their data.

These challenges can only be met by a standardized, transparent and open communication system that is easy to install, commission and use. As we have seen, Ethernet presents all of these advantages. For the specific use case within the industrial automation panel, however, such a communication system must also be competitively low-cost, space-efficient and energy-efficient. Providing the necessary benefits for this environment, SPE promises to extend the reach of Ethernet to in-cabinet devices.

2.4.3 Manufacturing line

Modern production lines as illustrated in Figure 7 consist of intelligent machine modules communicating with each other. Until now, automation engineers have grappled with the challenge of different manufacturers using a multitude of communication networks. With SPE, a uniform and completely transparent IP based network can be set up. This not only facilitates data acquisition and process visualisation but also allows for complete freedom when setting up and adapting production lines, enabling "plug-and-produce".

[1] Total Cost of Ownership Data from ODVA, 2023

[2] European Cybersecurity Resilience Act 2023

Next-generation mechanical engineers will ask questions such as:

- How much time do we have to spent on interfacing and maintaining individual bus systems?
- Where can we save costs in construction when machines become increasingly modular?
- How can we efficiently attain data from sensors and devices that can be used for predictive maintenance?

In terms of building up the necessary infrastructure, Single Pair Ethernet will become significantly more cost-effective than all of today's standard bus and Ethernet components put together. The technology's two-wire construction offers considerable installation advantages. PoDL optimises power distribution by supplying intelligent sensors and data over a single pair of wires. Commissioning, maintenance and changeover costs are reduced. Continuous reprogramming, due to exchanges between machines, can be executed much faster.

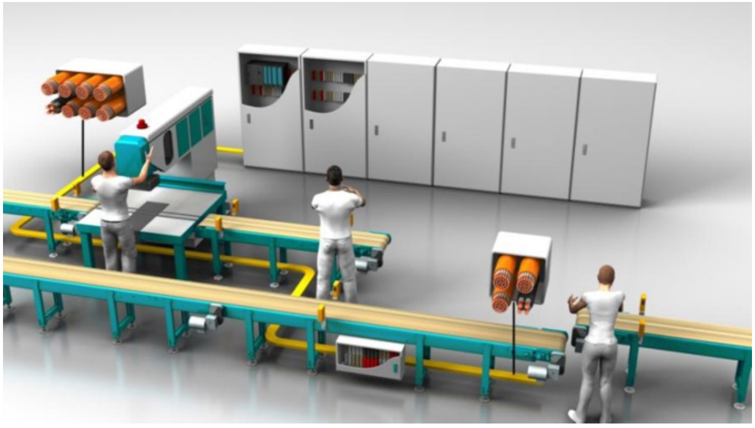


Figure 7 – conventional manufacturing line

2.4.4 Use cases for industrial in-cabinet automation panel and power distribution panel

SPE is not intended to replace traditional Ethernet but rather to complement it and enable new applications, such as using Micro- or Nano-PLCs (7.22) as edge controllers in small, remote cabinets. However, the transformative power of SPE for cabinets lies in devices that currently lack communication capabilities (hard wired) or only support legacy communication technologies like serial communication, fieldbuses, or proprietary systems. The following section is written with these low-complexity, in-cabinet devices in mind, emphasising why and how SPE can extend Ethernet to the lowest level of the automation pyramid, addressing a longstanding gap in continuous, transparent machine communication.

Industrial components significantly benefit from the simplicity, compactness, cost reduction and inherent cybersecurity offered by SPE[1] inside the cabinet. This is particularly evident in variants that support Multi-Drop technology, such as 10BASE-T1S.

To estimate the cost of assembly as illustrated in Figure 8 and Figure 9, using six minutes per wire termination[3] (approximately one Euro per wiring termination). As an example, a direct-on-line motor starter wired with three-wire control requires 13 physical blue wire terminations.

Figure 8 – Wiring of a conventional panel

Figure 9 – Conventional control panel wiring

[3] Total Cost of Ownership Data from ODVA, 2023

1

The situation is exacerbated by a growing shortage of skilled workers in most countries.

2.4.5 Smart sensors

Seamless and direct connection to IIoT sensor data without special gateways (7.10) and protocol translation is essential for all aspects of machine digitalisation. This approach provides easy-to-access sensor-based information, e.g., for environmental measurements or condition monitoring. Sensor design can now benefit from all advantages Ethernet offers such as:

1. Running web servers, e.g., for parametrisation
2. Information servers based on OPC Unified Architecture (OPC UA), MQ Telemetry Support (MQTT) (7.20) or JSON REST APIs (7.15)
3. Network management such as Simple Network Management Protocol (SNMP) (7.27)
4. Standard security mechanisms

Even time sensitive networking capabilities for low-time latency applications can be implemented. Sensors will be designed to host these services autonomously at the edge.

In the field of the conveyor industry or in container crane applications, sensors need to be connected over long distances without expensive extenders or repeaters. SPE with 10BASE-T1L is the best solution for a robust communication combined with PoDL power supply. If the power consumption exceeds PoDL capability, a hybrid SPE connection (two-wire SPE 10BASE-T1L with two-wire power supply) is the best one-cable solution. Today’s device design will only have to change for the connector.

For devices operating in an explosive atmosphere (7.8), a long-distance point-to-point communication intrinsically covering safety issues is required. With APL providing 10 Mbit Ethernet communication, device designs can now support full Ethernet-based functionality. Sensors can be designed to leverage their full capabilities, providing powerful data services for diagnostics and monitoring. In addition, fast updates of software, e.g., in case of security issues, will be possible.

2.5 ECONOMIC AND SOCIETAL IMPACTS

Digital technologies have advanced more rapidly than any innovation in our history. Within just two decades, they have reached approximately 50 percent of the developing world's population, bringing about transformative changes in societies. By enhancing connectivity and access to services, digital technology can strike a great economic and societal balance. The anticipated shift from fieldbus (7.9) to internet protocol-based technology will contribute to this progress.

As with other major technological changes, people, companies and institutions experience the profound impact of the transformation, often feeling overwhelmed by it out of sheer ignorance of the effects. The media aggravate the resulting distorted perception by focussing on alarming reports based on anecdotal observations and biased commentary. In practice, digitalisation opens up new opportunities for businesses and entrepreneurs to reach customers and markets they would never have had access to before. Therefore, enhanced connectivity and the associated business advantages entail a skill transformation among the work force.

Due to its numerous functionalities and services, the design of Ethernet-based systems requires more education effort compared to one particular fieldbus. It significantly reduces operational costs, however, particularly regarding access to data (implicit data, protocol convertors, etc.), as well as maintenance and change management costs (reliability, high availability, diagnostic services, interoperability (7.14)).

The industry faces challenges such as labour shortages, making it difficult to find personnel for the job. Even more pressing is the skill shortage, a scarcity of skilled professionals able to read ladder diagrams (7.16) and electrical line diagrams essential for tracing and troubleshooting. SPE addresses these pain points, rendering the hiring process smoother for panel builders. These advantages also extend to maintenance, the replacement of devices and the extension of systems.

Single Pair Ethernet for in-panel networks offers an optimised set of services compared to Ethernet networks utilised in information technology systems. Consequently, understanding of how to assign, configure and troubleshoot IP addresses for switchgear and controlgear (7.3) is currently limited, but the relevant knowledge can be acquired more rapidly.

3 TECHNOLOGY

3.1 OVERVIEW

3.1.1 Internet protocol (IP) everywhere

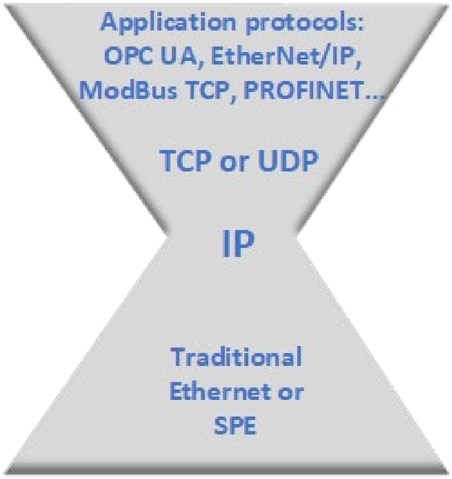


Figure 10 – The pivotal role of the IP layer.

The network strategy illustrated in Figure 10 is based on the "IP everywhere" concept providing the following benefits:

- Ensuring a **maximum of data continuity** from sensor to edge processing or higher up the IP layer. Even if the IP network may be made of isolated segments, for instance due to cyber-security reasons, the data payload can be conveyed across every layer of the automation pyramid. Data continuity promotes simplification by eliminating the need for data format translation across various gateways (7.10).
- **Protocols interoperability** (7.14)**:** IP naturally enables multiple protocols in parallel on the same medium, such as OPC-UA, EtherNet/IP, IEC 61850, Modbus TCP or PROFINET. Protocol cohabitation improves interoperability between different vendors, as physical medium can be shared, and administration software can manage different devices from different vendors with different protocols in the same network. Interoperability between different device generations of a given vendor is an important topic as well: as a means of combatting obsolescence consequently improving sustainability. Interoperability will enable all IP-based protocols, old and new, in the same network and with same administration software, therefore allowing a smooth transition and avoiding obsolescence for older devices. Consequently, it greatly simplifies integration into higher-level systems like MES (7.19), ERP (7.7) or cloud infrastructures.
- **Information exchange based on semantic**: Communication networks in industry are very often heterogeneous, interconnecting different devices with different functions and constantly changing over time. The challenge is to maintain the performances of networked systems while allowing enough flexibility in their evolution. Semantic based data models of the device and network functions consist of describing digital twins (abstracts) of systems. These data models simplify the change management of systems including the interactions between devices. For example, OPC UA FX "field exchange" standardises the semantics and behaviours of controllers and field devices from different manufacturers. Another example, MQTT (MQ Telemetry Transport) (7.20), is a client server 'publish/subscribe' messaging transport protocol. It is light-weight, open, simple, and designed to be easy to implement. These characteristics make it ideal for use in many situations, including constrained environments such as for communication in Machine to Machine (M2M) and Internet of Things (IoT) contexts where a small code footprint is required and/or limited network bandwidth is at a premium. These protocols offer the flexibility of meshing with other communication protocols, ensuring streamlined communication.
- **Services**: IP protocol distinguishes many network-orientated services from business-orientated ones. For instance, **auto-discovery** (with e.g., DHCP (7.5)) **and cyber-security** ((D)TLS (7.32) and SYSLOG (7.25)) pose complex challenges addressed by other players with more experience in information technology. By utilising IP protocols, equipment vendors can leverage existing solutions

for most non-business, network-orientated challenges. The benefits include reduced R&D effort, more reliable designs, and vendor interoperability (7.14) for cybersecurity and auto-configuration/discovery, for example.

- **Auto-negotiation of features:** This functionality is utilised to coordinate between different Physical Layers (PHYs) (7.21), ensuring that devices can communicate efficiently without the need for additional configurations. It is well established for standard Ethernet and should be extended to field devices.
- **Large Ecosystem:** Industrial Ethernet benefits from common, certified standards and widespread vendor support. It utilises the transport layer and protocols of traditional Ethernet and IP, found in many off-the-shelf components. This allows for the design of reliable, cost-effective hardware and firmware with a vast selection of parts and stacks.

3.1.2 Physical Layer: the role of Single Pair Ethernet

Table 1 gives an overview of the IEEE specifications of SPE.

Table 1 – IEEE 802.3 SPE specifications

<table>
<tr><th>IEEE Designator</th><th>Data rate</th><th>Intended application</th><th>Distance</th><th>Topology</th><th>Nb. nodes</th><th>Power</th><th>Status [c]</th><th>Use case [d]</th></tr>
<tr><td>1000BASE-T1 Type A</td><td>1 Gb/s</td><td>Automotive</td><td>15 m</td><td>Point to point (p2p)</td><td>-</td><td>PoDL</td><td>pub</td><td>-</td></tr>
<tr><td>1000BASE-T1 Type B</td><td>1 Gb/s</td><td>Industrial</td><td>40 m, shielded</td><td>p2p</td><td>-</td><td>PoDL</td><td>pub</td><td>-</td></tr>
<tr><td>100BASE-T1</td><td>100 Mb/s</td><td>Automotive</td><td>15 m</td><td>p2p</td><td>-</td><td>PoDL</td><td>pub</td><td>-</td></tr>
<tr><td>10BASE-T1L</td><td>10 Mb/s</td><td>Industrial, process</td><td>1000 m</td><td>p2p</td><td>-</td><td>PoDL</td><td>pub</td><td rowspan="2">M. Line, P. Sensor</td></tr>
<tr><td>100BASE-T1L</td><td>100 Mb/s</td><td>Industrial, process</td><td>500 m [a]</td><td>p2p</td><td>-</td><td>PoDL</td><td>dev</td></tr>
<tr><td>10BASE-T1S</td><td>10 Mb/s</td><td>Automotive, Industrial</td><td>15 m [b]</td><td>p2p or multidrop</td><td>≥ 8</td><td>PoDL, for p2p only</td><td>pub</td><td rowspan="2">Cabinet, M. Sensor</td></tr>
<tr><td>10BASE-T1M</td><td>10 Mb/s</td><td>various</td><td>50 m at least</td><td>Multidrop</td><td>≥ 16</td><td>Enhanced PoDL</td><td>dev</td></tr>
</table>

[a] 100m with low latency

[b] 15 m point to point, 25 m multidrop

[c] IEEE specification status either “pub” published or “dev” under development

[d] Most suitable IEEE specification for the use cases “M. line” manufacturing line (3.2.1), “Cabinet” Industrial Automation in-cabinet or power distribution cabinet (3.2.2), “M. Sensor” smart sensor for machinery or “P. sensor” smart sensor for processes (3.2.3).

The most ubiquitous wired technology family supporting IP is Ethernet. This extensive family covers a broad spectrum of usage, ranging from the super-high performance segment based on optical fibre down to the low-cost segment based on Single Pair Multi-Drop or SPMD (7.26) (see below).

The technology has become ubiquitous and represents the largest communication eco-system today. Switches, connectors, cables and more are available with all kinds of performance and cost options, spanning from super low-cost commodities to high-performance customisable devices. Besides its ubiquity, Ethernet offers the best software support options.

Automotive found that the cable harness had become the third heaviest single component in a vehicle and weight reduces performance. They also found that as many as eight different specialized networks were needed in the same vehicle for dedicated purposes. These were bundled in the cable harness. Upcoming autonomous vehicle demands only threatened to worsen the situation. SPE was seen as a possible way to optimize the harness. Ethernet is known to be scalable in performance, and a single network could potentially solve the existing applications and scale into the future. Less wires in SPE meant less copper and less weight. The eventual transition to a zoned switch system can bring additional benefits. Redundant networking is one aspect. Transparent interconnection across systems is another aspect (wheel speed sensor can augment GPS in tunnels for example). Security has also become an issue. Recently, CAN headlights have been used to hijack cars.

What is more, Ethernet variants may provide means of delivering power over the data line(s); i.e. combining power and data on same electrical pair. This brings obvious simplification in cabling and connectors: When power and data are conveyed in separate pairs, devices must rely on either larger cables and high-pin count connectors, or separate cables and connectors. All SPE variants support delivering power over data line, using either point-to-point topology (with so called PoDL technology), or multi-drop (so called Multi-drop Power over Ethernet technology, MPoE for short; whereby the available power is shared between all nodes).

Furthermore, a given network can comprise multiple segments, each based on different Ethernet variants. Each variant corresponds to the segment's physical challenges and offers the best local compromise between cost, range, throughput, Electromagnetic Compatibility EMC (7.6) resilience etc. All these diverse variants can be linked together using simple hardware (typically simple adapters or switches), forming a single network at the IP level. Consequently, Ethernet is generally recommended for switchgear and controlgear (7.3) equipment.

The main drawback of Ethernet so far has been the cost incurred in final, simple devices, which is somehow higher than that of non-IP wired technologies such as CAN or RS485. This is where SPE especially the SPMD (7.26) variant, comes into play. SPE variants are a recent addition to the Ethernet portfolio. Essentially, there are three main sub-branches in the SPE category each focusing on overall system and device cost:

- High speed (100/1000BASE-T1)
- Long range (10/100BASE-T1L)
- Multi-Drop (10BASE-T1S/T1M)

These variations of SPE are compatible up through to the IP Protocol, as an adaptor or switch enables continuity of communication between them. In detail, they are compatible at the Ethernet frame format (switch/bridge) level. The Ethernet frame allows multiple Ethertypes, including IP.

Adopting SPMD (7.26) for network segments where cost is the main criteria and throughput, or range may be expendable is the appropriate solution. SPMD is currently defined in the 10BASE-T1S standard (IEEE Std 802.3 cg-2019) and is being improved in the T1M follow-up standard (IEEE P802.3da).

Main benefits of SPMD include:

- **Lowest overall cost:** Individual devices only need one connector, one transceiver and no internal switching capability. At sub-system level, SPMD reduces the overhead for switches. In details, the reduction is achieved from 2 or 4 pairs to 1 pair. Multiple magnetic coupling (isolation) components are reduced to a single capacitor pair. EMC components are reduced by a factor of 2 to 4.
- **Medium speed:** 10 Mbit/s shared between all devices in the same network segment is often sufficient, especially in low-voltage switchgear.
- **Real-time applications:** Guaranteed delivery time of approximately 10 ms.
- **Passive connection:** Often sufficient for reliability purposes. When a device fails, other devices are not impacted, as opposed to point-to-point daisy chain (7.4) topology, for example.
- **Reduced use of copper material:** Being based on a single-pair unshielded cable UTP (7.30), SPMD minimises the use of copper material in the assembly for connectivity.
- **Smaller connectors:** Compared to traditional multi-pair Ethernet ones.
- **Adjustable cable length:** Easily adjusted to relevant needs without the requirement for special tools.
- **Optional communication and limited power supply:** Can be both supported by two wires, either in the future (T1M) or today with proprietary extensions (T1S).

The drawbacks of SPMD are mainly:

- Its short range (25-50 m maximum).
- Absence of explosive atmosphere (7.8) compliance
- Not easily scalable at high-speed rates

On the other hand, 10BASE-T1L enables very long reach (up to 1 km) and compliance with explosive atmosphere regulations (thanks to APL) but each point is more expensive because of higher complexity PHY and its star topology. Ongoing work will provide 100 Mbit/s support with length up to 500 m through 100BASE-T1L.

3.1.3 Technology summary

As illustrated in Figure 11, the network strategy can be summarised as follows:

1. Multiple application-level protocols interoperability (7.14)
2. IP everywhere
3. Multiple application optimized variants of Ethernet (especially SPE and SPMD (7.26))

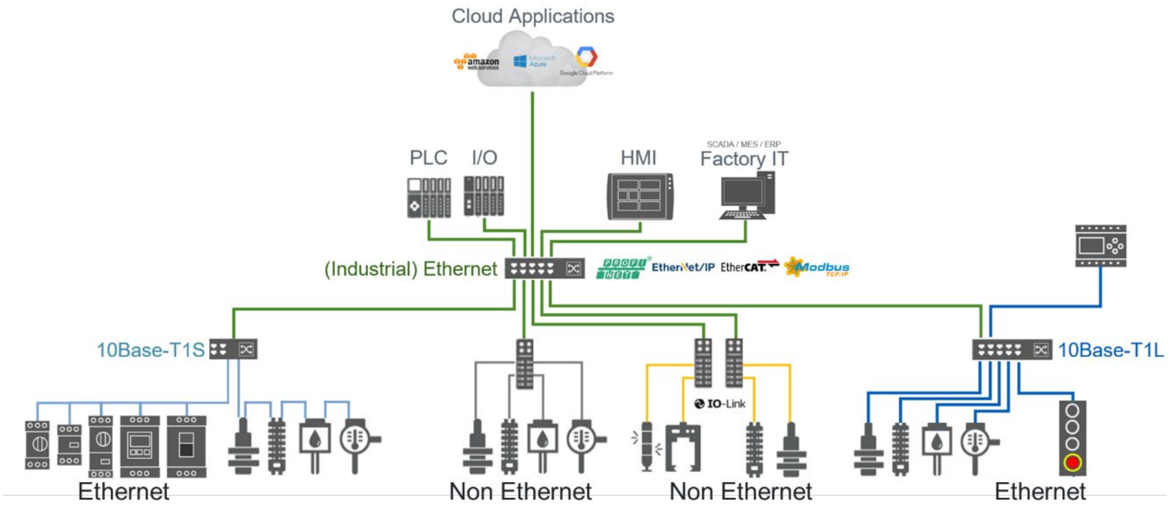


Figure 11 – Draft of an IP everywhere network architecture.

The strategy achieves the following goals:

- Using multiple Ethernet variants together allows selecting the right alternative for each local sub-system. Given the span of the Ethernet spectrum, this ensures optimal network performance at optimum cost in almost every case. Whatever the physical constraints, one member of the Ethernet family will offer the optimal trade-off between cost and performance.
- User complexity is minimised by utilising the same high-level, IP-based protocols from administration software (SCADA system (7.23) etc.) down to cost-optimised devices, consequently providing data continuity. Furthermore, at the Physical Layer (PHY) (7.21), all Ethernet variants are compatible with regards to routing, therefore achieving network continuity.
- Only standard items are considered: Ethernet PHY, IP stack, application protocols etc. all follow existing standards. This standards-based approach, as well as protocol openness and an optimal physical cost/performance trade-off, enable large volumes and subsequently lower costs.
- Most application Software protocols are supported down to the end devices, such as EtherNet/IP, OPC UA, Modbus TCP, PROFINET etc.
- Reliability/safety can be added on top of any IP-based communication, e.g., using the black channel (7.2) safety concept. For instance, Common Industrial Protocol (CIP) safety provides fail-safe communication between nodes on any Ethernet layer.
- Thanks to IP support, cybersecurity can be managed as an option at the session (Transmission Control Protocol TCP (7.28), User Datagram Protocol UDP (7.29), level using encryption protocols such as Transport Layer Security TLS (7.32) or Datagram Transport Layer Security DTLS (7.33). While PHY encryption could be considered (based on, e.g., Media Access Control Security; MACsec (7.18)), using session level instead provides more flexibility for large sites without decryption/encryption at intermediate points.
  For example, HTTP (7.11) can be retrofitted with TLS (7.32) to constitute HTTPS (7.12) protocols.
- Lastly, Ethernet variants keep evolving while preserving backwards compatibility. This mitigates the risk of obsolescence in two ways: by providing a roadmap for every Ethernet branch and by ensuring that older devices based on outdated Ethernet variants can still be connected, preventing them from becoming obsolete.

3.2 MAIN ADVANTAGES COMPARED TO EXISTING TECHNOLOGIES

Advantages of the SPE technology covers multiple use cases in industrial automation.

SPE technology transforms process automation by merging diverse data types such as process variables, asset health, and secondary parameters, facilitating seamless integration with control layers and cloud systems. This integration unlocks new opportunities for comprehensive data analysis and operational insights, potentially paving the way for integrating artificial intelligence, thereby significantly boosting productivity through a unified Ethernet network.

SPE technology substantially simplifies operational processes by reducing sensor size and complexity, thereby boosting efficiency and increasing the cybersecurity footprint within these devices resulting in a secure by design communication. It eases the integration of automation systems into higher-level frameworks like MES (7.19), ERP (7.7), or cloud infrastructures, negating the need for complex data-mapping gateways (7.10). This simplification is particularly advantageous for machine builders and integrators, enhancing process control and easing integration challenges.

Addressing critical industry challenges, SPE technology plays a key role in mitigating labour and skill shortages, particularly in panel building and system maintenance. By reducing the need for highly specialized skills in reading complex diagrams and troubleshooting, SPE streamlines the hiring process and facilitates more efficient maintenance, device replacement, and system expansion.

3.2.1 Manufacturing line

Figure 12 – A modern modular machine

10BASE-T1L Single Pair Ethernet provides a shared power and high bandwidth data architecture, where 10 Mbps data and power are shared on a low-cost 2-wire cable over 1000 meters distance. This simplifies communication from sensor to local server or cloud, eliminating the need for additional gateways (7.10) or interfaces. This makes it easier to integrate sensors without additional gateways or interfaces.

By solving these challenges for both brownfield upgrades and new greenfield installations, 10BASE-T1L SPE will enable new insights that were previously unavailable, such as combining process variables, secondary parameters, asset health feedback, and seamlessly communicating them to the control layer and to the cloud. These new insights will awaken new possibilities for data analysis, operational insights, and productivity improvements through a converged Ethernet network from the field to the cloud.

The launch of Single Pair Ethernet, 10BASE-T1L physical layer solutions will provide long reach ethernet connectivity to edge nodes making them directly IP addressable. This will drive productivity improvements and process optimization.

In conclusion, the 10BASE-T1L SPE offers numerous benefits for sensor-to-cloud applications. It simplifies communication, reduces sensor size and complexity, improves operational efficiency, solves challenges in process automation, enables new insights, and provides long reach ethernet connectivity to edge nodes. These benefits make it a promising technology for the future of sensor-to-cloud applications.

The IEEE consortia is currently working on the 802.3 dg standard that will allow 100 Mbit speed at a maximum distance of 500m. This will allow Manufacturing lines to communicate at much higher speed and increasing the length significantly as traditional Ethernet provides 100Mbit communication at a maximum length of 100m. Many Manufacturing lines and the communication between Manufacturing lines require longer distances that 100m. So with this new upcoming standard, the 2 wire SPE technology can beneficially be used for longer length segments and extend todays Ethernet distance by 5 times. This will reduce the implementation costs for Networks with longer length requirements where repeaters or fibre optics are usually needed.

3.2.2 Industrial automation in-cabinet or power distribution cabinet

The first benefit of using SPE in a control panel or a switchboard is the elimination of traditional parallel control wiring. Not only does this approach enhance efficiency but also accelerates panel production, ultimately boosting productivity.

For machine builders and integrators alike, added connectivity as explained in 3.1.1 represents a significant advantage in terms of flexibility and interoperability (7.14) within the manufacturing line or the electrical distribution system of the building. In the current version of the IEEE 802.3 specification, PoDL is limited to point-to-point topologies for 10BASE-T1S and will be extended to Multi-Drop for T1M currently under development. The technology may initially appear to be a convenient option for in-cabinet transformations, but it comes with its own set of challenges. PoDL (Power over Data Line) may fall short in providing adequate support for higher-current products, an essential feature in many industrial settings that often demand separate wiring for such devices. Nevertheless, the technology presents a valuable solution for lower-rated products. As cabinets often have pre-existing power wiring, adopting PoDL could be considered redundant.

Despite its potential for reducing installation complexity, inclusion of two extra wires for a 24V supply may be seen as incremental cost. Most modern devices are designed with this provision, however, making setup easier and less time-consuming compared to other alternatives. By carefully considering these factors, decision-makers and engineers alike can make well-informed choices, optimising both current requirements and future adaptability for in-cabinet transformations.

3.2.3 Smart sensor

SPE offers advantages for different kinds of smart sensors and small actuators (7.1). For instance, devices for field applications are compliant with environmental protection provided by enclosure IP66 or IP67 and typically connected to control units point-to-point via an I/O box, switch, or gateway (7.10). Currently, these sensors feature multiple connectors for power supply and communication, alongside special connectors for digital switching signals. The different connectors raise costs and require extra space as shown in Figure 13. Using SPE with PoDL reduces costs and space for connectors. SPE, as a one-cable solution, fits into space-constrained devices enabling device miniaturisation. Moreover, SPE provides Ethernet communication capabilities in smaller sensors, supporting the “IP everywhere” approach.

Figure 13 – Device space savings using SPE connectors.

Unified connectors and cables supporting speeds ranging from 10 Mbit to 1 Gbit will reduce device variance and enable seamless connections from the factory floor to the enterprise level or from the factory field to building automation.

Sensors based on 10BASE-T1L can be connected in a 1 km range from the switch, serving perfect long-distance applications in logistics automation. As a one-cable technology, Advanced Physical Layer (APL) Ethernet proves suitable for connecting sensors even in intrinsically safe areas, dramatically accelerating the communication speeds today of Highway Addressable Remote Transducers (HARTs), typically used in process automation. Standardisation and usage of SPE hybrid connectors (Ethernet communication combined with power supply) enables a one-cable solution for higher power-demanding actuators).

4 HOW TO PREPARE THE FIELDBUS TRANSFORMATION?

Before integrating Single Pair Ethernet (SPE) technology, it's crucial for system integrators to thoroughly assess their current network infrastructure. This includes identifying potential points for SPE integration and necessary upgrades to ensure compatibility. The goal is to create a clear plan for incorporating SPE technology seamlessly into the existing network setup. Ensuring this compatibility is the first step towards a successful transition to SPE.

For effective SPE deployment, a well-trained workforce is essential. System integrators should invest in training their teams through workshops, webinars, and specialized sessions to deeply understand SPE technology and its benefits. This preparation is vital for skilful deployment and utilization of SPE. A phased implementation approach, starting with pilot projects and then moving to full-scale implementation, is recommended. This methodical progression allows for smoother integration, enabling early identification and resolution of potential issues. Additionally, securing the necessary tools and equipment is vital for installation and maintenance, necessitating new hardware or software as needed.

Collaboration with SPE experts and consultants is crucial for navigating the transition process. Seeking guidance from organizations like ODVA and PI, and working closely with product manufacturers and machine builders, can significantly enhance the implementation process. These experts can provide invaluable insights, especially in educational campaigns and workshops demonstrating SPE systems and use cases. Furthermore, with the introduction of SPE, updating cybersecurity measures to meet industry standards is paramount to protect the network's integrity. Strengthening these security protocols ensures a secure and reliable SPE network post-integration.

Switchgear and controlgear using legacy fieldbuses (7.9) like PROFIBUS, CAN, ASI or DeviceNet can be converted to Ethernet by:

- Unifying Physical Layer adaption to SPE for point-to-point or daisy chain (7.4) topology
- Integrating a power supply solution with PoDL or hybrid power cables for high-power demanding devices
- Auto-negotiation for 10 Mbit/100 Mbit/1 Gbit

For intrinsically safe applications, the transformation is already underway with Advanced Physical Layer (APL) replacing HART communication or PROFIBUS PA. Devices with an SPE interface will be capable of utilising safety or real-time protocols as well as the full spectrum of digital services or data servers Ethernet offers.

5 STANDARDISATION LANDSCAPE

5.1 TRADITIONAL FIELDBUS STANDARDS AND ORGANISATIONS

The following standards and organisations are related to Fieldbus communication networks used traditionally in control cabinet and power distribution board.

CAN (Controller Area Network bus) is a network designed for use in automotives. It uses a single terminated twisted pair cable; is multi master; maximum signal frequency used is 1 Mbit/sec; length is typically 40M at 1Mbit/sec up to 10KM at 5Kbits/sec; it has high reliability with extensive error checking; typical maximum data rate achievable is 40KBytes/sec; maximum latency of high priority message <120 µsec at 1Mbit/sec.

Profibus (usually written as *PROFIBUS*, is an abbreviation for Process Field Bus) is a standard for fieldbus communication in automation technology and was first promoted in 1989. Two variations of PROFIBUS are in use today; the most commonly used PROFIBUS DP, and the application specific, PROFIBUS PA for process automation.

RS-485 (also known as TIA-485) is a TIA/EIA standard for serial communication systems, which defines only the electrical characteristics of drivers and receivers. RS-485 is typically 3 (half duplex) or 5 wire (for full duplex operation) cable. Compared to single pair Ethernet multi drop, RS-485 also supports multi-drop topology; but it does not enable delivery of power over the data line; and the throughput is much lower. Critically, RS-485 does not support cyber-security nor the IP protocol. However, RS-485 does support long range, similar to 10Base-T1L reach. There are many SW protocols which use RS-485 as physical layer, such as ModBus-serial and PROFIBUS. All in all, RS-485 is very wide-spread, highly mature, but frozen and somehow obsolete technology, mostly due to its low throughput, lack of cyber security and lack of IP support.

The **Common Industrial Protocol** (CIP) is an industrial protocol for industrial automation applications. It is supported by ODVA. CIP encompasses a comprehensive suite of messages and services for the collection of manufacturing automation applications – control, safety, synchronization, motion, configuration and information. It allows users to integrate these manufacturing applications with enterprise-level Ethernet networks and the Internet.

DeviceNet is a network protocol used in the automation industry to interconnect control devices for data exchange. It utilises the Common Industrial Protocol over a controller area network media layer and defines an application layer to cover a range of device profiles. Typical applications include information exchange, safety devices, and large I/O control networks.

The HART Communication Protocol (Highway Addressable Remote Transducer) is an open digital industrial automation protocol. It communicates over legacy 4–20 mA analogue instrumentation current loops, sharing the pair of wires used by the host systems. HART operates in point-to-point (analogue/digital) mode, and multi-drop mode. The transmission rate of is 1200 bits per second.

Profibus (usually written as *PROFIBUS*, ais an abbreviation for Process Field Bus) is a standard for fieldbus communication in automation technology and was first promoted in 1989. Two variations of PROFIBUS are in use today; the most commonly used PROFIBUS DP, and the application specific, PROFIBUS PA for process automation.

5.2 ETHERNET STANDARDS AND ORGANISATIONS

The following standards and organisations are related to Ethernet communication networks in industrial applications are the following:

IEEE 802.3 (Institute of Electrical and Electronics Engineering) is a working group and collection of standards defining the PHY and data link layer's MAC address of wired Ethernet. In February 2019, specifications on 10BASE-T1S and 10BASE-T1L covered under IEEE 802.3cg were released. The group is currently working on 10BASE-T1M (Multi-Drop with longer reach and power delivery) under file IEEE P802.3da.

Advanced Physical Layer (APL): A two-wire Ethernet for process automation and hazardous locations, based on IEEE and IEC standards Ethernet-APL deploys one standard from SPE (10BASE-T1L) and adds definitions for physical layer attributes that meet the needs of process users.

OPC-UA (Open Platform Communication - Unified Architecture) is an information exchange standard for Industrial Automation and related systems created by the OPC Foundation. The OPC-UA standard provides an Addressing and Information Model for Data Access, Alarms, and Service invocation layered over multiple transport-level protocols

ODVA (Open DeviceNet Vendors Association) is a standards development organisation and membership association comprising the world's leading Industrial Automation companies. ODVA works to advance open, interoperable information and communication technologies in Industrial Automation.[4] It has shared all the intellectual property on the non-IEEE SPE in-cabinet solution, providing benefits and detailed impact information to users since 2019.

PROFINET International (PI) is a leading international industry association for the standardization and dissemination of industrial communication and information technologies. PI standardized APL technology and works on SPE as an open interoperable standard.

Open Alliance is a special interest group (SIG) primarily composed of automotive industry and technology providers collaborating to promote wide-scale adoption of Ethernet-based communication as the standard in automotive networking applications. Open Alliance provides PHY specification for Ethernet communication, complementing standards such as IEEE, in particular for the automotive industry and its technology partners.

Profinet (usually styled as *PROFINET*, as a abbreviation for Process Field Network) is an industry standard for data communication over Industrial Ethernet, designed for collecting data from, and controlling equipment in industrial systems, with a particular strength in delivering data under tight time constraints.

IEC 6063-7 An **RJ45** connector, standing for Registered Jack 45, is a type of connector commonly used for Ethernet networking. It was initially devised for telephones but is now widely used to connect to the Local Area Network (LAN) and is most commonly used in wired Ethernet networks. The RJ45 connector is defined by the TIA-968 standard, as well as the IEC 60603-7 publication. These standards define both the RJ45 connector wiring sequence, as well as the physical dimensions.

IEC 61850 series standardises the communication networks, data models and systems in electrical transport substations. It also includes an XML-based language (Substation Configuration description Language - SCL) offering a vendor-independent method of describing devices and their configurations.

5.3 SINGLE PAIR ETHERNET CONNECTORS AND CABLES

5.3.1 Introduction to SPE Connectors

Undoubtedly, the RJ45 stands out as the most successful connector in communication technology based on twisted pair cabling. However, from an industrial point of view, it still presents a technical disadvantage: in plugged state, contact is only made on one side at a defined contact point. Consequently, under extreme circumstances such as strong vibrations or shocks, contact interruptions may occur. A more secure and suitable option for industrial applications involves the use of a two-sided electrical contact, such as a tulip contact. The design of industrial SPE connectors, as defined in the IEC 63171 standard, meets industry requirements and offers advantages such as safer contacting, lower contact resistance, vibration resistance and improved behaviour when pulling under load.

Moreover, SPE offers fundamental advantages due to the use of one-pair cables compared to standard Ethernet with two- or four-pair cables.

These specific advantages include:

- Easier connection/installation with only 2 wires instead of 8
- Smaller connector interfaces compared to RJ45

Smaller cable diameter, more flexible cable, tighter bending radii and lower cable weight. These advantages are particularly significant in the field (sensor/actuator level), and will lead to increased adoption of SPE in the future.

[4] ODVA Website - https://www.odva.org/

5.3.2 IEC Standardisation of SPE Connectors

In the IEC 63171 series of standards not only extends to the individual variants of mating faces but also encompasses the electrical and transmission properties. These properties are described in IEC 63171 "Connectors for electrical and electronic equipment – Shielded or unshielded free and fixed connectors for balanced single-pair data transmission with current-carrying capacity – General requirements and tests". The subclauses of the IEC 63171 standards define the different mating faces of the connectors; however, they all have to comply with the general technical requirements of the IEC 63171 basic standard. The structure of the entire series of standards follows:

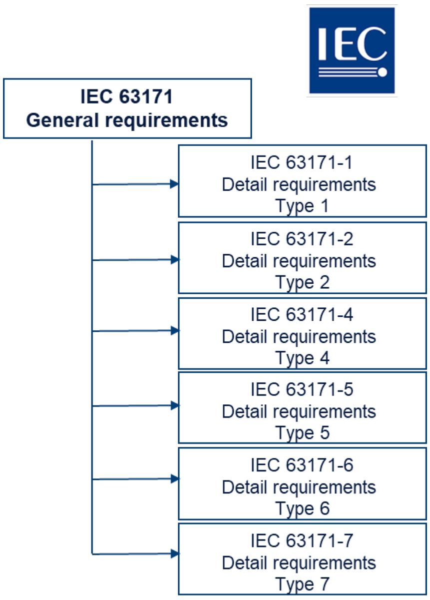


Figure 14 – The IEC 63171 series of connector standards.

Out of the different connector solutions of IEC 63171-X standard, two stand out as particularly suitable for industrial applications:

Figure 15 – Connectors according to IEC 63171-2 and -5

Figure 16 – Connectors according to IEC 63171-6

5.3.3 IEC Standardisation of SPE Cables

The international standardization of Single Pair Ethernet cables is governed by the IEC 61156 series and the channel definitions from IEEE 802.3 for SPE.

The IEC 61156-11 to IEC 61156-14 standard classifies SPE cables and defines Material and cable constructions as well as transmission characteristics and Tests. For the different IEEE applications 4 major SPE Cable standards are relevant.

IEEE Application	Cable Std	Bandwith acc. to IEEE	Length acc. to IEEE
10 BASE-T1 (802.3cg)	IEC 61156-13, IEC 61156-14	20 MHz	T1L: 1000 m T1S: 15 m
100 BASE-T1(802.3 bw)	IEC 61156-11, IEC 61156-12	66 MHz	15 m
1000 BASE-T1(802.3 bp)	IEC 61156-11, IEC 61156-12	1,25 GHz	40 m

Figure 17 – The IEC 61156 series of SPE cable standards.

5.3.4 Point to Point SPE connection

In applications like small-size electronic assembly machines or cabinet mountings, the need to minimise sensors combined with full communication capabilities arises. By using SPE instead of standard Ethernet, device design can be more space-efficient eliminating the need for extra power supply connectors. PoDL enables power supply over two wires using a small size connector. These minimised connectors open the potential for optimising sensor enclosure design and reduce the space required for mounting.

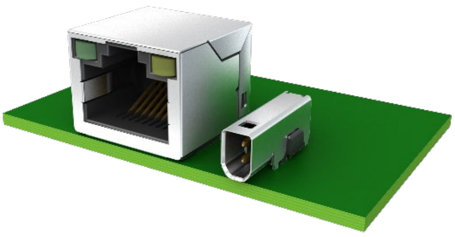


Figure 18 – A space comparison of a SPE connector to a RJ45 connector

For instance, SPE connectors already offer the possibility of terminating the two wires very easily leveraging the so-called insulation displacement connection IDC (7.13). Consisting of only two parts, these connectors can be handled intuitively: simply strip the cable, insert it into the cable manager, cut off any protruding cable ends and press the two connector parts together. This allows Single Pair Ethernet to be easily routed to the device on-site without the need for special tools.

Another example is to simply use two dual-terminal pluggable or snap-on connectors for easy daisy chaining in multi-point topologies, where Unshielded Twisted Pair UTP (7.30) is cost-effective compared to electromagnetic interference constraints.

Figure 19 – Example of a field-attachable SPE connectors for on-site assembly

SPE connector solutions should deliver long cable length support, present a compact, simple, robust and vibration-proof design and remain insensitive to electromagnetic influences (EMC).

These connectors are characterised by:

- A robust metal housing with metal snap-in hooks
- Safe industrial double contacting compared to single-sided contacting RJ45
- Shock and vibration resistance according to IEC 60068
- Stable latching with lateral forces

In an industrial environment, EMC (7.6) requires:

- The EMC coupling attenuation at 600 MHz according to IEEE 802.3
- An additional burst test according to IEC 61000-6-2
- Optimum shield connection on the Printed Circuit Board (PCB) due to four symmetrical legs
- PCB connectors for environments up to pollution degree 2
- Impulse voltage strength of 2.25 kV according to IEEE 802.3
- Optimum contact distance for 100 Ohm systems

Several manufacturers have developed user-friendly connectors for industrial use, according to IEC63171-2. With a pitch of 7.62 mm the compact connector system saves up to 50 percent space compared to RJ45 interfaces. The vertical arrangement of the two contacts allows very high packing density enabling device manufacturers to save valuable space on the PCB and construct smaller devices.

Miniaturisation is a key criterion for SPE connectivity. Consequently, connector manufacturers need to realise high packing density. These connectors should allow:

- Doubling the packing density compared to RJ45 connectors
- Doubling the amount of communication interfaces while maintaining the same device housing
- Providing a significantly lower volume compared to a RJ45 jack

In the construction of industrial devices, smaller connectors enable significantly reduced installation space. Thanks to highly compact SPE connectors, substantial space savings can be achieved compared to existing connection technologies. For instance, devices can be built with twice the port density, as SPE connectors require only half the installation space of an RJ45. While maintaining the housing dimensions, doubling the number of Ethernet ports on a device can significantly reduce the cost per Ethernet connection.

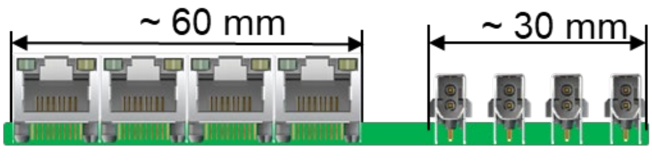


Figure 20 – Space comparison of an IEC 63171-2 connector with RJ45.

Field devices need IP67 interfaces. Combining small packaging density and IP67 requirement, the circular M8 and M12 connectors are the best choice for this application. The connector should be integrated into standard M8 and M12 housings, a solution that is already available today.

These connectors should provide:

- M8 connectors with male and female contacts available
- Front and rear panel mounting with support of male and female contacts
- Simple integration into M8 and M12 sensors

Additionally, using the same connector within M8 and M12 housings eases commissioning and maintenance by allowing direct connection of a IP67 device to an IP20 switch.

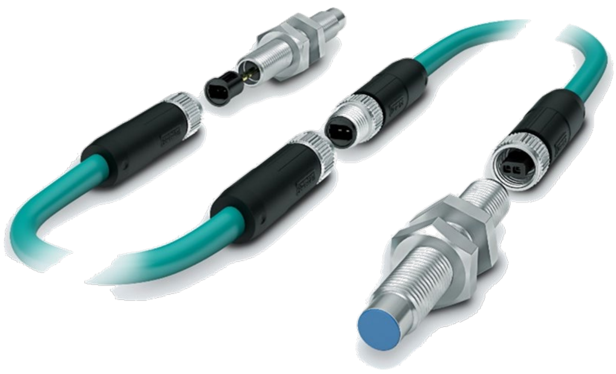


Figure 21 – Examples of IEC 63171-5 connectors available with M8 and M12 interface.

5.3.5 Multidrop SPE connection

Multidrop networks integrate many network nodes in a small space. These networks offer advantages for in Cabinet applications as well as in industrial and building automation.

Multidrop topologies start as soon as a cable gets a branch without an active component that allows a device to communicate with several other devices simultaneously. This is called a T- or Y-branch. They are often implemented in IP67 with circular connectors. True multidrop refers to a continuous cable that is branched off as needed using insulation displacement technology (IDC). This means that the branch can be placed at any point. Likewise, the cable can be cut at any point and a branch can be realized there with the help of a connector. SPE in-cabinet use cases demonstrate the benefits outlined in 2.4.4. The media is instrumental in delivering value for the integrator by reducing wiring time for all the wires connected to the components inside the cabinet, specifically for power and control wiring.

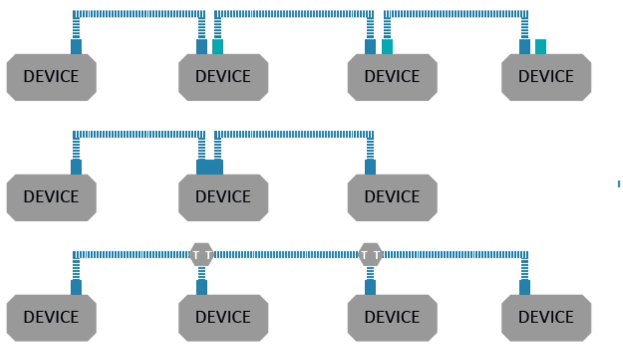
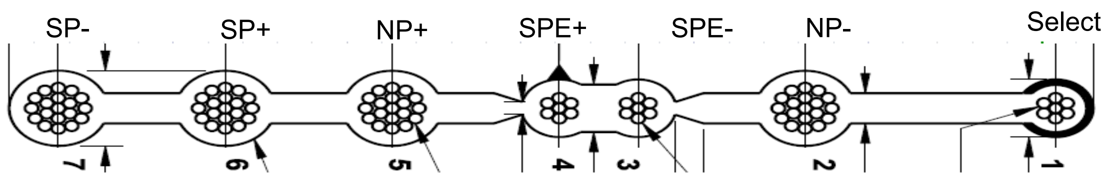


Figure 22 – Examples of multidrop implementations

5.3.5.1 SPE in-cabinet cable options

When dealing with an in-cabinet use case, it is imperative to consider all the wiring connections to the device in order to reduce wiring time. This implies that power and especially control wiring simplification would have the biggest impact in wiring time reduction. One approach to such a solution is the SPE in-cabinet wiring utilising a seven-conductor flat cable solution[5] suggested by the ODVA. This solution efficiently interconnects communication, power, and discrete signals between devices in a bus.

Network Power (NP) and Switched Power (SP) conductors are 20 AWG (19 strands); the data (SPE+, SPE-), select line conductors are 24 AWG (7 strands).



NP and SP lines are rated at four Amps. The unique cable design, featuring an asymmetrical arrangement of conductors, prevents incorrect connector orientation.

With this cable solution, a 24V-DC-4A configuration can be characterised as a "power bus". The advantages of this approach are manyfold. It offers a continuous bus, eliminates loose connecting, significantly reduces wiring as users can simply tap off the bus, and allows for disconnection without affecting the rest of the network [6]. Additionally, consistent power quality is ensured.

While a daisy chain (7.4) power topology may pose a risk of losing downstream devices due to a single connection issue, and the point-to-point method can result in increased wiring and a greater probability of mistakes, the power bus approach with SPE in-cabinet media mitigates these downsides for in-cabinet applications.

In summary, this cabling structure is optimised for in-cabinet use cases by grouping the network power and switched power into a single cable.

Alternatively, the power supply can be wired individually, resulting in a reduction in control wiring only. In this scenario, a standard 2-conductor SPE cable could be employed, preferably with 10BASE-T1S to make use of Multi-Drop functionality, thereby minimising the number of required switch ports to only one for multiple devices. This not only lowers the overall system cost but also significantly reduces the amount of different cables and connectors a panel builder has to stock. Only different lengths of patch cable would be required, which could be used both for T1S and T1L devices.

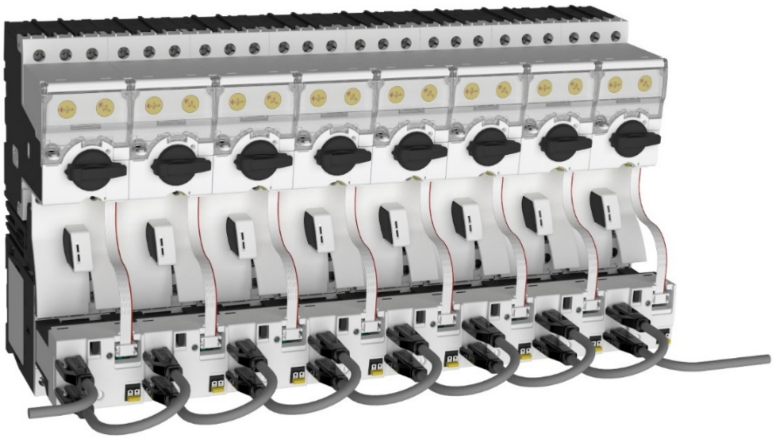


Figure 24 – A Multi-Drop application concept with motor starters using standard SPE cables and connectors. Power supply via terminal (wires not shown here).

This approach also avoids the need to integrate specific components for power feed to the cable when the system's maximum current draw is exceeded. It allows for the setup of supply voltage zones, providing simple means to switch off individual devices or groups of devices, such as in an emergency stop situation. This also eliminates the SEL line, which is used to determine relative device location. The trade-off is the need to individually connect power supply wires to the devices. Depending on the terminals used, this increases wiring efforts, screw terminals being more time consuming than, for example, snap-in terminals, which do not even need wire termination with ferrules.

5.3.5.2 SPE in-cabinet connectors option

The connectors for the flat-cable variant shown above complement the cable and core, aiming to reduce the unit cost per device by extending the cost across a maximum number of devices within the cabinet. These connectors feature unique passive electronics designed to extend the IEEE-specified SPE for in-cabinet applications[7]. This passive electronic component is the key to enable integrator value by avoiding an impact on component costs.

Plug connectors interconnect signals between a bus cable and a device jack connector. These connectors are applied to a flat cable using a tool that closes the connector housing. This causes insulation displacement or piercing connections to penetrate the cable insulation, providing electrical connection to all the cable signals. Cable connectors are easily installed using standard pliers, with no need for special installation tools. When installed, the connector will sever the SPE and select line, while inline inductors compensate for node capacitance.

[6] Enhancements to Single-pair Ethernet for Constrained Devices ODVA Inc. whitepaper

[7] ODVA Single Pair Ethernet (SPE) for in-cabinet constraint devices, March 2020

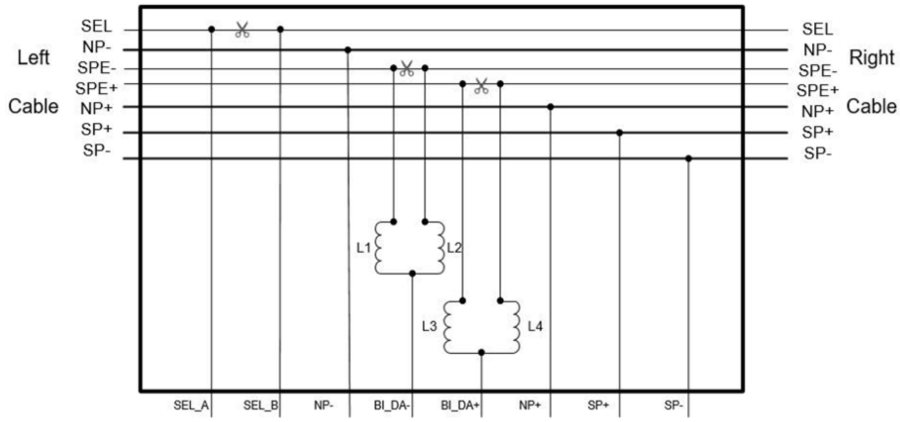


Figure 25 – Plug connector P1 circuit.

For Multi-Drop applications utilising standard SPE cables, standard SPE-connectors, as shown in Figure 24, can be employed. This requires two SPE sockets on the device. Alternatively, specific Multi-Drop connectors can be used. They utilise the same connector design and mating faces on the device but handle the Multi-Drop wiring internally. This approach still represents a plug-and-play solution while reducing the number of required sockets on the device to one, ensuring the network continuity, and lowering costs even further.

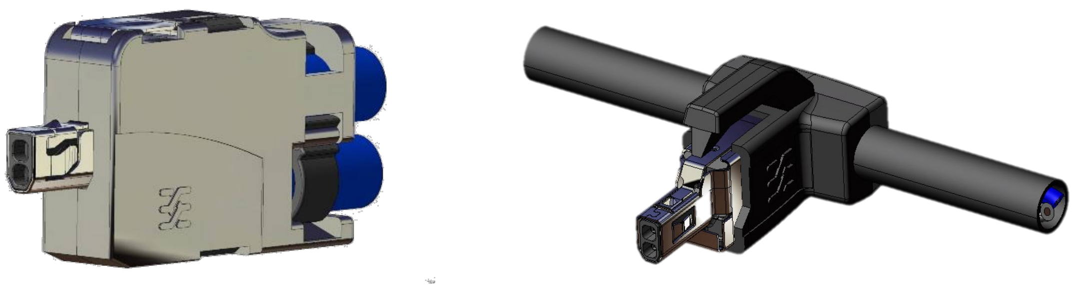


Figure 26 –Industrial Multi-Drop connectors based on IEC 63171-2 interface.

5.3.6 Miniaturisation with SPE cables and connectors

Single Pair Ethernet Point to point or multidrop connectors offer many advantages for new applications, combining compact dimensions with an industrial-grade contact system, easy installation and future-proof transmission rates. These connectors make it easy to integrate complex sensor technology into existing Ethernet networks. The connection technology has been accepted for years and has been used millions of times. The new, compact SPE connectors therefore enable sensors to be connected directly to the cloud. This takes Ethernet to the next communication level and is predestined for future compact digital communication interfaces.

6 CONCLUSIONS

Despite the challenges involved, the anticipated transformation from fieldbus (7.9) communication networks to SPE within machines and distribution boards holds great promise. The technology offers numerous advantages, notably fit-for-purpose performance (speed, distance, etc.), Ethernet interoperability (7.14), improved cybersecurity, cost savings and simplified wiring. As the number of connected devices and functions in applications continues to grow, this shift becomes paramount, particularly in areas where end users demand safe, resilient, efficient, and sustainable control systems.

Future work will focus on embedded software in individual devices, with a view to ensuring seamless connection throughout the entire control system. More precisely, the protocols required by higher level entities such as SCADA system (7.23) (e.g. ModBus TCP, PROFINET, OPC UA …) will be made available at individual, final devices; effectively eliminating the need for protocol-conversion gateways (7.10). In addition to cost-optimized IP connectivity enabled by SPE, this objective requires trimmed-down versions of the afore-mentioned protocols, able to fit into the limited memories available inside even basic end-devices. This is made possible by continuous improvements in micro-controlled manufacturing processes, in which memory density has become sufficient to accommodate optimized versions of the protocols mentioned above even in mid-end microcontrollers. Further work will show successful integration of such protocols into e.g., basic sensors; effectively fulfilling the promise of a seamless, end-to-end control system.

Lastly, future work is also needed to provide a complete, interoperable cyber-security scheme. Indeed, IP protocols will most likely rely on TLS (7.32), DTLS (7.33) or equivalent IT standards, which themselves incur cyber-security certificates and roles as a way to establish trust and authentication of users and machines. While the format of those certificates and roles are already specified and standardized, the question remains about how to install and configure them in the first place. There are many technical alternatives to choose from, but direct reuse of IT and public internet methods, based on third party certificate authorities, is probably not appropriate for the business of switchgear and controlgear. Thus, a cybersecurity configuration and commissioning process is an important topic to be addressed; as it may have significant impact not only on the level of security, but also on customer experience and interoperability.

7 GLOSSARY

7.1
actuator
device that causes a machine or another device to operate

7.2
black channel
parts of a communication channel which are not designed or validated according to the IEC 61508 series

Note 1 to entry: See: 7.4.11.2 of IEC 61508-2:2010.

[SOURCE: IEC 61131-6:2012, 3.6]

7.3
controlgear
product family composed of electromechanical and electronic control circuit and signalling devices, including position switches, proximity switches, push-buttons, pilot lights

7.4
daisy chain
bus where each passive network interface connects two trunk sections and provides a DC coupling between those sections

[SOURCE: IEC 61918:2018, 3.1.30]

7.5
dynamic host configuration protocol
DHCP
communication protocol which allows the assignment of a network configuration to a client by a server, making manual configuration unnecessary

[SOURCE: RFC 2131:1997]

7.6
electromagnetic compatibility
EMC
ability of equipment or a system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment

[SOURCE: IEC 60050-161:2018, 161-01-07]

7.7
enterprise resource planning
ERP
planning function that includes inventory transaction, cost accounting, order fulfilment and resource tracking

Note 1 to entry: The planning methodology uses material requirements planning and master production schedule to calculate requirements for materials and to make recommendations to release replenishment orders when due dates and need dates are not in phase.

[SOURCE: ISO 16100-1:2009, 3.11]

7.8
explosive atmosphere
mixture with air, under atmospheric conditions, of flammable substances in the form of gas, vapour, or dust, which, after ignition, permits self-sustaining propagation

[SOURCE: IEC 60050-426:2020, 426-01-06]

NOTE In Europe, ATEX are two EU directives describing the minimum safety requirements for workplaces and equipment used in explosive atmospheres.

7.9
fieldbus
communication system based on serial data transfer and used in industrial automation or process control applications

[SOURCE: IEC 61784-3-1:2010, 3.1.1.11]

7.10
gateway
device that typically connects two industrial communication networks and facilitates data exchange between them by handling differences in data format and protocols, hence providing some form of translation (in contrast to switching or routing on lower levels).

EXAMPLE 1 Modbus to Modbus TCP or Modbus to OPC-UA.

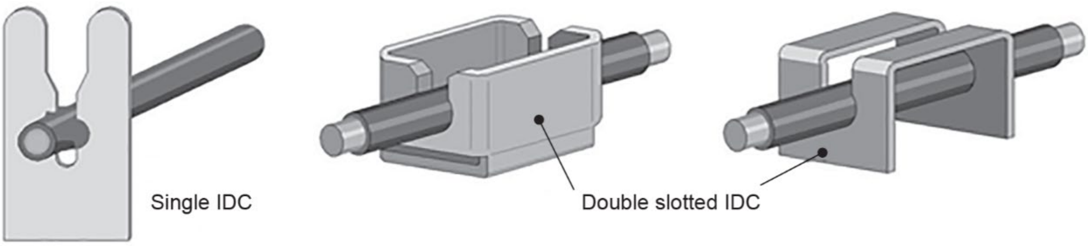
7.11
hypertext transfer protocol
HTTP
stateless application-level protocol for distributed, collaborative, hypertext information systems

[SOURCE: RFC 9110:2022, Abstract]

7.12
hypertext transfer protocol secure
HTTPS
extension of the hypertext transfer protocol (HTTP) using encryption for secure communication

[SOURCE: RFC 2818:2000]

7.13
insulation displacement connection
IDC
solderless electrical connection made by inserting a single wire into a precisely controlled slot in a termination such that the sides of the slot displace the insulation and deform the conductor of a solid wire or the strands of a stranded wire to produce a gas-tight connection



IEC

[SOURCE: IEC 60352-3:2020, 3.3]

7.14
interoperability
capability of two or more entities to exchange items in accordance with a set of rules and mechanisms implemented by an interface in each entity, in order to perform their respective tasks

EXAMPLE 1 Examples of entities include devices, equipment, machines, people, processes, applications, software units, systems and enterprises.

EXAMPLE 2 Examples of items include information, material, energy, control, assets and ideas.

[SOURCE: ISO 18435-1:2009, 3.12]

7.15
java script object notation representational state transfer
JSON REST
compact, human-readable, text-based data format used for the data exchange between applications and systems

[SOURCE: RFC 8259:2017]

7.16
ladder diagram
one or more networks of contacts, coils, graphically represented functions, function blocks, data elements, labels, and connective elements, delimited on the left and (optionally) on the right by power rails

[SOURCE: IEC 61131-1:2003, 3.4]

7.17
media access control address
MAC address
hardware address that uniquely identifies each node of a network

[SOURCE: ISO 17532:2007, 3.3]

7.18
media access control security
MACsec
protocol allowing authorized systems that attach to and interconnect LANs in a network to maintain confidentiality of transmitted data and to take measures against frames transmitted or modified by unauthorized devices

[SOURCE: IEEE 802.1AE:2018, 1.1]

7.19
manufacturing execution system
MES
system for producing the desired products or services, including quality control, document management, plant floor dispatching, work-in-process tracking, detailed product routing and tracking, labour reporting, resource and rework management, production measurement and data collection

[SOURCE: ISO 16100-1:2009, 3.14]

7.20
message queuing telemetry transport
MQTT
client server publish/subscribe messaging transport protocol

Note 1 to entry: The protocol runs over TCP/IP, or over other network protocols that provide ordered, lossless, bi-directional connections.

[SOURCE: OASIS MQTT V5:2019, Abstract]

7.21
physical layer entity
PHY
portion of the physical layer between the medium dependent interface (MDI) and the media independent interface (MII)

Note 1 to entry: The PHY contains the functions that transmit, receive, and manage the encoded signals that are impressed on and recovered from the physical medium.

[SOURCE: ISO/IEC/IEEE 8802-3:2021, 1.4.391]

7.22
programmable logic controller
PLC
solid-state control system which has a user programmable memory for storage of instructions to implement specific functions

[SOURCE: IEC 62279:2015, 3.1.20]

7.23
supervisory control and data acquisition system
SCADA system
type of loosely coupled distributed monitoring and control system commonly associated with electric power transmission and distribution systems, oil and gas pipelines, and water and sewage systems

Note 1 to entry: Supervisory control systems are also used within batch, continuous, and discrete manufacturing plants to centralize monitoring and control activities for these sites.

[SOURCE: IEC TS 62443–1–1:2009, 3.2.122]

7.24
servo drive controller
controller for motion coordination of a servo axes.

EXAMPLE With the multiuse of these controllers, it is possible to realise complex multi-axis motion sequences with high precision and minimum response times.

7.25
system logging protocol
Syslog
protocol utilising a layered architecture, which allows the use of multiple transport protocols for transmission of system event notification messages

EXAMPLE A wide variety of devices (e.g. printers, routers...) use the syslog standard.

Note 1 to entry: It is used for system management and security auditing.

[SOURCE: RFC 5424:2009, Abstract]

7.26
single pair multi-drop
SPMD
multi-drop capable variants of single pair Ethernet

EXAMPLE Only one example for term 2 – no numbering.

Note 1 to entry: 10Base-T1S and (future) 10Base-T1M are the two SPMD technologies available or under definition in 2024.

7.27
simple network management protocol
SNMP
protocol for collecting and organizing information about managed devices on internet protocol networks

EXAMPLE Only one example for term 2 – no numbering.

Note 1 to entry: Only one note for term 2 – still needs to be numbered.

[SOURCE: ISO 16100-1:2009, 3.14]

7.28
transmission control protocol
TCP
connection-oriented, reliable delivery byte-stream transport layer communication protocol

Note 1 to entry: Differs from UDP in that TCP is acknowledged and connection oriented.

[SOURCE: RFC 9293:2022]

7.29
user datagram protocol
UDP
internet protocol that provides connectionless datagram delivery service to applications

Note 1 to entry: Unlike TCP, UDP provides connectionless communication, i.e. UDP does not require prior communication to set up communication channels.

[SOURCE: ISO/IEC 24775-2:2021, 3.1.68, modified with the note 1 to entry]

7.30
unshielded twisted pair
UTP
electrically conducting cable, comprising one or more pairs, none of which are shielded

EXAMPLE It's used for transmitting Ethernet data due to its suitable frequency range, and it's cost-effective as it requires less maintenance and no grounding cable.

[SOURCE: ISO/IEC/IEEE 8802-3:2021, 1.4.500, modified with an example]

7.31
shielded twisted pair
STP
electrically conducting cable, comprising one or more elements, each of which is individually shielded

EXAMPLE This makes it suitable for industrial environments with potential interference, and while it's more expensive than Unshielded Twisted Pair (UTP) cables, it can support higher transmission rates over longer distances.

Note 1 to entry: Only one note for term 2 – still needs to be numbered.

[SOURCE: ISO/IEC/IEEE 8802-3:2021, 1.4.450, modified with an example]

7.32
transport layer security
TLS
cryptographic protocol designed to provide communications security over a computer network.

Note 1 to entry: TLS relies on a stateful connection, above the TCP protocol.

7.33
datagram transport layer security
DTLS
cryptographic protocol closely related to TLS

Note 1 to entry: Unlike TLS, DTLS is meant for UDP datagram messages.

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