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Single Pair Ethernet (SPE) System Architecture

Whitepaper

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Content

1. Introduction and scope

In the early stages of automation for factories, buildings, and processes, custom communication hardware architectures were often developed to address specific tasks. This approach led to the proliferation of application-specific communication buses, each requiring dedicated gateways to enable intercommunication and integration with enterprise IT infrastructure. As a result, wiring became increasingly complex, with distinct requirements for each communication system.

Today, the prevailing automation pyramid, which relies heavily on fieldbuses and analog signal transmission, presents several critical challenges. Although fieldbuses enable direct communication between sensors, actuators, and control systems, they are often constrained by limited bandwidth and range. These limitations create bottlenecks in data transmission and restrict the scalability and flexibility of automation systems. Furthermore, the diversity of fieldbuses complicates system maintenance and integration. Each type demands specialized knowledge and protocols, driving up costs and introducing complexity in both operation and expansion.

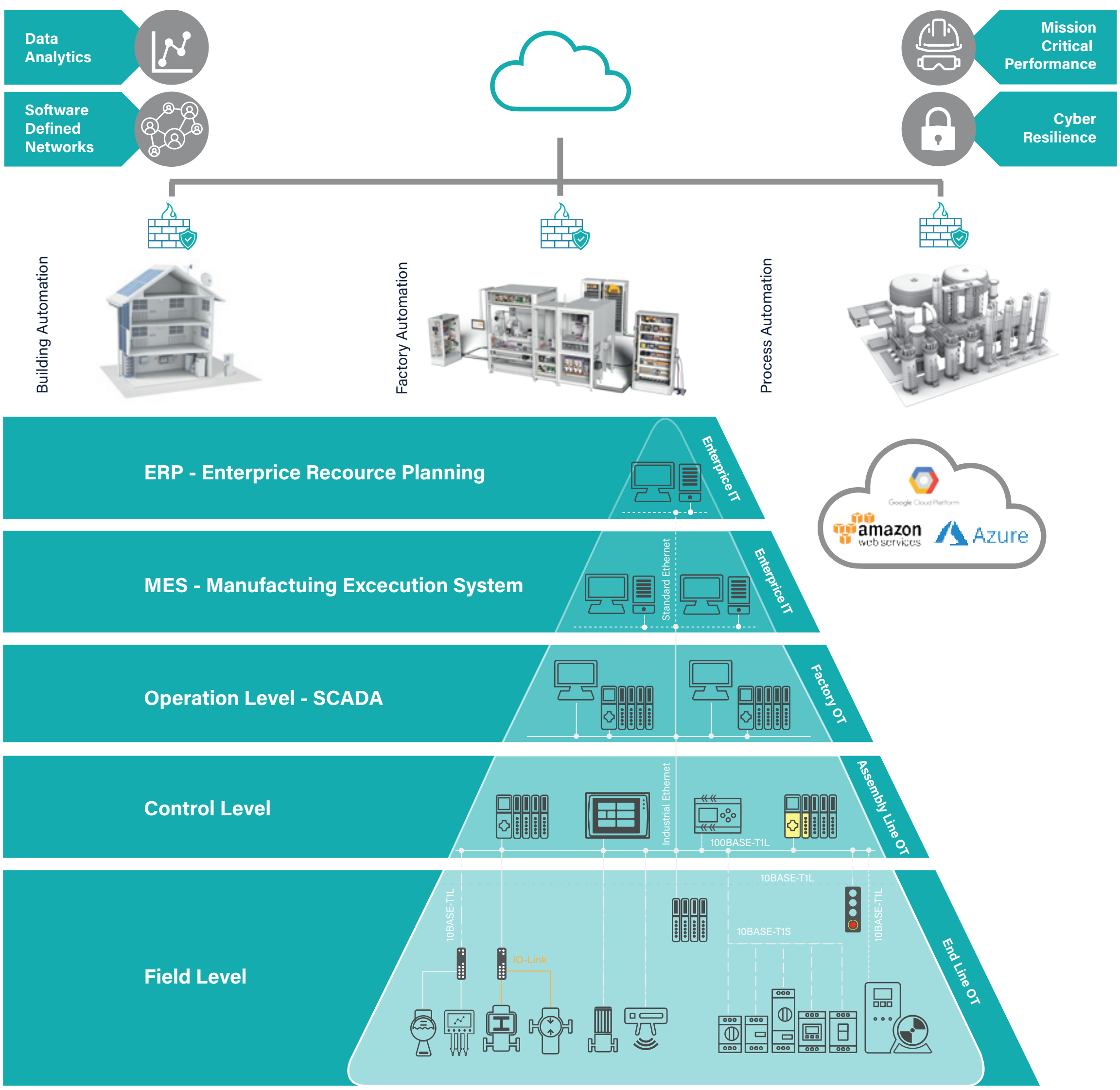


Illustration 1: The Automation Pyramid in Current Industrial Applications

A significant concern in the modern automation pyramid is cybersecurity. Many fieldbus systems and analog signal transmission methods were not designed with contemporary security standards in mind. Consequently, they introduce potential vulnerabilities, acting as gateways for cyber threats. Outdated protocols and unsecured communication pathways can expose systems to risks such as unauthorized access, operational disruption, or even threats to critical infrastructure. By adopting standardized security protocols and robust encryption techniques, organizations can significantly enhance the confidentiality, integrity, and availability of their automation systems, mitigating the risk of cyberattacks.

The integration of Ethernet into the sensor level, particularly with SPE, allows a seamless communications throughoutt the automation pyramid and provides the opportunity to implement state-of-the-art security mechanisms.

2. The All-Ethernet Approach

The current trend in industrial automation is shifting away from distributed, hardware-defined architectures toward more centralized, software-defined implementations. Rather than relying on domains of specialized communication protocols, this approach allows the creation of zones connected to a centralized computing environment.

An IP-based architecture that utilizes Ethernet throughout simplifies the establishment of these zones. With Ethernet technologies, such as Virtual LANs (VLANs), it becomes possible to separate zones for improved security, reliability, and optimized bandwidth usage. This approach also accommodates varying distance requirements, ensuring flexibility while maintaining a streamlined and cohesive network infrastructure.

The Transition from Fieldbus to Ethernet

The adoption of Ethernet in industrial settings is accelerating rapidly. According to a study by HMS Industrial Networks, 64% of industrial communications in 2016 relied on fieldbus technologies, with only 30% using Ethernet. By 2024, these figures have reversed dramatically: 71% of industrial communication systems now use Ethernet, while the share of fieldbuses has dropped to 22%. Wireless solutions, meanwhile, have remained constant at around 7%.

This shift highlights a significant and ongoing transition from fieldbus-based to Ethernet-based communication. Ethernet's superior scalability, bandwidth, and support for modern security standards make it the preferred choice for future-proofing industrial communication systems.

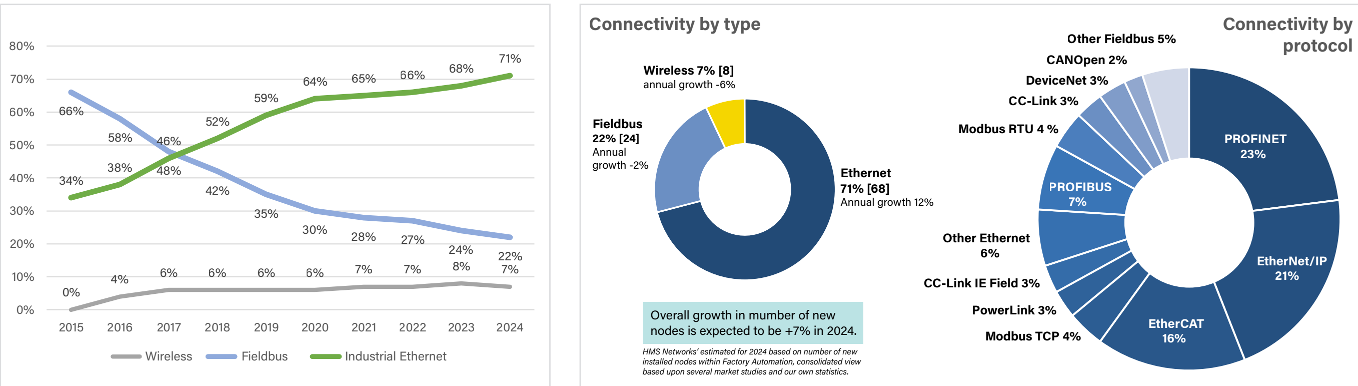


Illustration 2: Transition from fieldbus to Ethernet communication (Source: HMS-networks.com)

Vision of OT and IT Integration: The Future of Industrial Control Systems

The following diagram illustrates a modern industrial control system (ICS) enabled by the full implementation of Single-Pair Ethernet (SPE) technology. But how does this future ICS differ from today's systems?

In this SPE-based architecture, all field-level devices are directly connected to Ethernet, eliminating the need for the variety of heterogeneous legacy networks and protocols currently used in industrial environments. The complex and expensive gateways previously required to connect these legacy networks to Ethernet are replaced by simpler and more efficient Ethernet switches. Single-Pair Ethernet enables seamless connectivity for field devices—such as sensors, actuators, and other IIoT devices—directly to Ethernet. Using a simple twisted-pair cable, SPE supports communication over distances of up to 1 km, delivers data rates of at least 10 Mbit/s, and provides up to 50 W of power. This innovation simplifies network infrastructure, enhances scalability, and establishes a unified foundation for the integration of OT and IT systems.

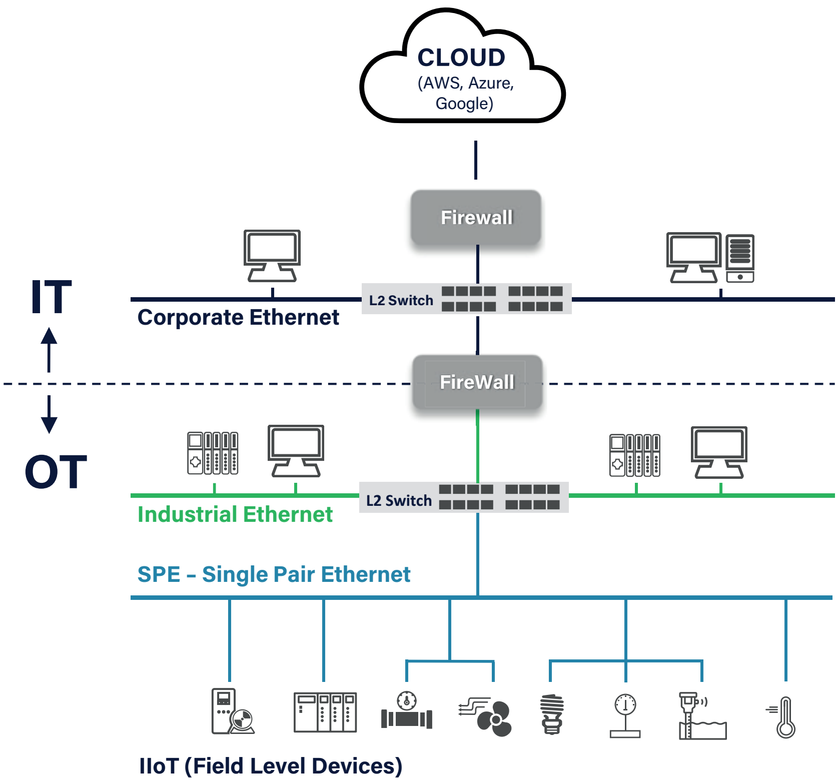


Illustration 3: Connecting the IT and OT environments

SPE is a key enabling technology for Industry 4.0, offering several significant advantages:

1. End-to-End Ethernet:
   - Unifies legacy networks into a single Ethernet-based infrastructure.
   - Reduces costs (CapEx / OpEx).

2. Secure Cloud IIoT connectivity:
   - Enables secure, bidirectional communication between devices and the cloud.

3. Enhanced Cybersecurity:
   - Delivers security at the device level.
   - Integrates seamlessly into existing cybersecurity frameworks.
   - Utilizes proven network security methods.

4. Predictive maintenance and use of artificial intelligence and machine learning
   - Increased reliability, decreased cost.

5. Industry 4.0 Protocol Support:
   - Fully compatible with control protocols like OPC UA and others.

Migration of SPE into existing industrial networks

Plant-specific fieldbuses are still widely used for factory, process, and building automation. While Ethernet has become the standard communication protocol between the plant control system and higher-level management systems, RS485 serial interfaces are often found at the field level. Protocols such as Profibus, CAN, Modbus, BACnet, and various proprietary protocols are commonly used to enable communication between the control system, sensors, and actuators. While this setup may appear straightforward, it requires expert knowledge of the specific fieldbus technologies. Furthermore, these different protocols are not compatible with each other, necessitating the use of gateways. This results in increased costs for cabling and the installation and maintenance of gateways.

This is where SPE comes in and provides an effective solution for upgrading fieldbus systems for the IIoT. SPE can solve the latency problems of serial systems that communicate at significantly lower transmission rates than 10BASE-T1S and T1L offer. SPE cables are 2-wire and therefore just as easy to install as cables for serial fieldbuses. 10BASE-T1L also allows PoDL, the transmission of up to 50 W power (See IEC 61156-12 Table G1) to a sensor or actuator. Other types of PoDL exist for different SPE speed variants. A homogeneous Ethernet system architecture also increases the reliability and administrability of the systems, as well as cybersecurity throughout the entire system.

3. Status Quo of Today's Ethernet Standards

The IEEE 802.3 series includes several Ethernet standards at the physical layer, each designed for specific applications and environments. These standards were created for wireless, copper, and fiber-based Ethernet, as well as SPE.

In recent years, the data rate for standard Ethernet in industrial applications has been extended, ranging from 10 Mbit/s to 10 Gigabit per second. The transmission length is limited to 100 meters for all speeds. SPE on the other hand, offers longer distances while supporting the most common data rates (10 Mbit/s to 1 Gigabit).

IEEE Standardization of SPE Channels

The following diagram shows the current SPE communication channels, sorted by bandwidth (10 Mbit/s to 25 Gbit/s) and cable length. The cable length is defined as "at least up to xx meters" according to the IEEE specification (further details in the section "Applications Beyond the Specification").

The areas of application are determined by the combination of speed and cable length: high speeds and short lengths dominate the automotive sector, while longer lengths and lower bandwidths are designed for the automation segments.

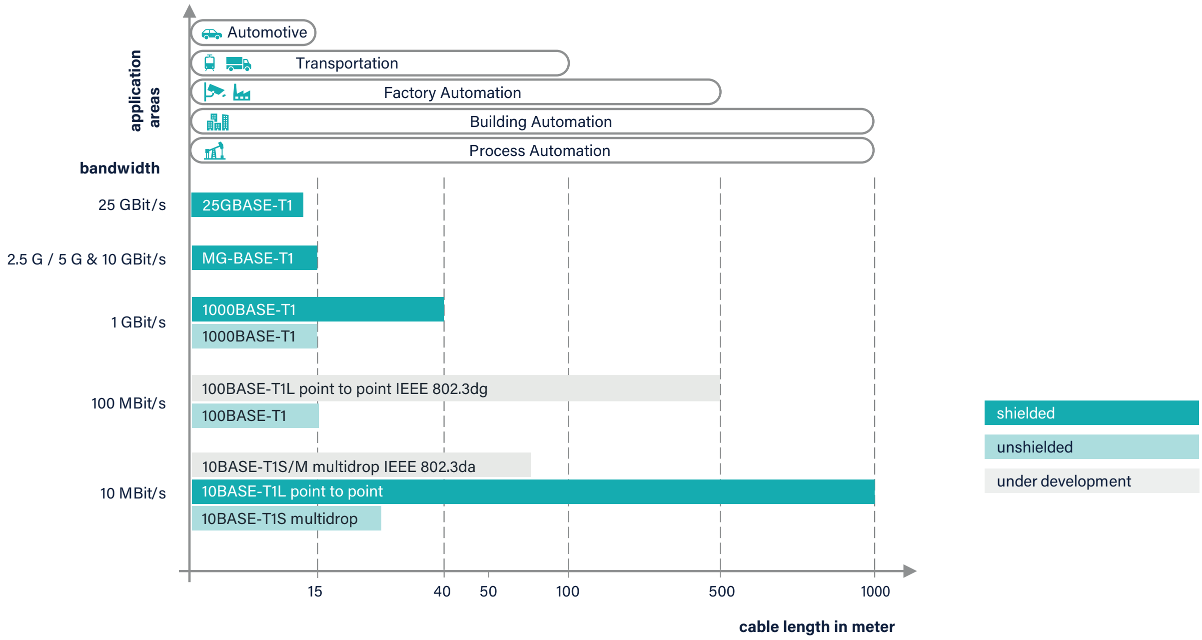


Illustration 4: Different SPE Channels sorted by Bandwidth and Cable length

IEC Standardization of SPE Connectors

The RJ45 connector is widely used in communication technology but is not optimal for industrial applications, as it is only contacted on one side, and contact issues may arise under harsh environmental conditions. Industrial SPE connectors according to IEC 63171 offer improved safety, lower contact resistance, vibration resistance, and better pull strength under load, thanks to electrical contacts on both sides, such as the tulip contact.
The IEC 63171 standard series not only covers the various mating face variants but also includes electrical and transmission properties. The subclauses of IEC 63171 define the different mating faces of the connectors, which fulfil all the general technical requirements of the basic standard IEC 63171. The following figure shows the structure of the entire standard. Some IEEE specifications mention specific variants of IEC 63171, but all variants comply with the defined electrical transmission characteristics.

The PROFIBUS & PROFINET International (PI) automation community, with over 1,800 members, including many companies from the Single Pair Ethernet System Alliance, presented a uniform mating face for SPE at SPS 2024 and submitted it for international standardization. As a pioneer of open technologies such as PROFIBUS and PROFINET, PI drives market-leading standards for all areas of industrial production. The agreement on a SPE mating face is a crucial milestone towards future-proof communication.

Numerous manufacturers have signalled their support and are actively driving implementation.

Illustration 5: Example of IEC 63171-7 compliant connectors

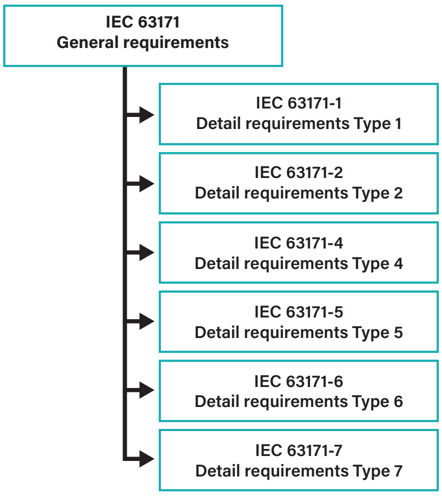


Illustration 6: The IEC 63171 series of connector standards.

Illustration 7: Example of the IEC 63171-2/5 connectors.

For applications with a transmission of 10BASE-T1, the requirements for connectors and cables are less demanding than to 100BASE-T1 and 1000BASE-T1.
However, the requirements for shielding and symmetry are just as demanding as for 100BASE-T1 and 1000BASE-T1. The terminals and connectors used must comply with the requirements defined in Table 1:

Spezification	**Min**	**Max**
Current per Contact	4 A @ 60°C	
Rated voltage contact to contact	50 V DC	
Isolation voltage contact to shield	1500 V AC	
Insertion loss (IL)		0,02 ×√ f 0,1 to 20MHz (Whenever the equation results in a value less than 0,1 dB, the requirement shall revert to 0,1 dB.)
Return loss (RL)		48 – 20 log(f) 0,1 to 20MHz (Whenever the equation results in a value greater than 30 dB, the requirement shall revert to 30 dB.)
Coupling Attenuation E3		120 - 20 log(f) 0,1 to 20 MHz (Whenever the equation results in a value greater than 75 dB, the requirement shall revert to 75 dB.) When coupling attenuation meets or exceeds the values of 105 - 20 log(f), the PS ANEXT and the PS AFEXT limits are met by design.
DC resistance per contact		0.025 Ω

Table 1: Electrical requirements for terminal blocks and connectors acc. to IEC 63171 Edition 2.

IEC Standardization of SPE Cables

The international standardization of SPE cables is governed by the IEC 61156 series and the channel definitions of IEEE 802.3 for SPE. The IEC 61156-11 to IEC 61156-14 standards classify SPE cables, define materials and cable constructions, as well as transmission characteristics and tests.

Standard	Description
IEC 61156-11	Multicore and symmetrical pair/quad cables for digital communications - Part 11: Symmetrical single pair cables with transmission characteristics up to 1,25 GHz - Horizontal floor wiring - Sectional specification
IEC 61156-12	Multicore and symmetrical pair/quad cables for digital communications - Part 12: Symmetrical single pair cables with transmission characteristics up to 1,25 GHz - Work area wiring - Sectional specification
IEC 61156-13	Multicore and symmetrical pair/quad cables for digital communications - Part 13: Symmetrical single pair cables with transmission characteristics up to 20 MHz - Horizontal floor wiring - Sectional specification
IEC 61156-14	IEC 61156-14: Multicore and symmetrical pair/ quad cables for digital commu-nications - Part 14: Symmetrical single pair cables with transmission character-istics up to 20 MHz - Work area wiring - Sectional specification

Table 2: SPE cable standards extract from the IEC 61156 standard.

Four main SPE cable standards are relevant for the different IEEE applications:

IEEE Application	Cable Standard	Bandwidth acc. to IEEE	Length acc. to IEEE
10 BASE-T1 (802.3cg)	IEC 61156-13, IEC 61156-14	20 MHz	T1L: 1000 m T1S: 25 m
100 BASE-T1(802.3 bw)	IEC 61156-11, IEC 61156-12	66 MHz	40 m (500m in development)
1000 BASE-T1(802.3 bp)	IEC 61156-11, IEC 61156-12	1,25 GHz	40 m

Table 3: SPE cable standards extract from the IEEE 802.3.standard.

Applications beyond the Specification

IEEE standards sometimes mention connectors or other physical components, but they are only examples. The technical specifications focus on channel characteristics such as insertion loss, return loss and mode conversion loss. Specific cable distances and number of nodes are not normative. they represent initial minimum targets that practical implementations frequently exceed. For example, the 10BASE-T1S mixing channel is defined in clause 147.8 of the 802.3cg-2019 standard:

"A mixing segment is specified based on cabling that supports up to at least 8 nodes and 25 m in reach. Larger PHY count and/or reach may be achieved provided the mixing segment specifications in 147.8 are met."

This means cabling should support at minimum "up to at least" a certain number of nodes and distance, but any mixing medium that meets the specifications defined in the respective clause is acceptable. High-quality cables and connectors often significantly exceed these minimum requirements. Public demonstrations, for instance, have shown 50 nodes connected over 100 meters of cabling, with oscilloscope measurements displaying well-defined eye diagrams of the signals.

4. Reference architectures with SPE

All-Ethernet architecture regardless of the Physical Layer

Once an Ethernet architecture is implemented, a variety of physical layers can be used to optimize data rates for different applications. An Ethernet switch can easily switch between different data rates. Different PHYs can be connected to each switch port. For example, data entering at 10 Mbit/s can be output at a different speed. This flexibility is valuable as simpler devices may not handle high data rates. Slower streams can be aggregated and transmitted over faster links in higher-level systems. The figure below illustrates a potential Ethernet deployment.

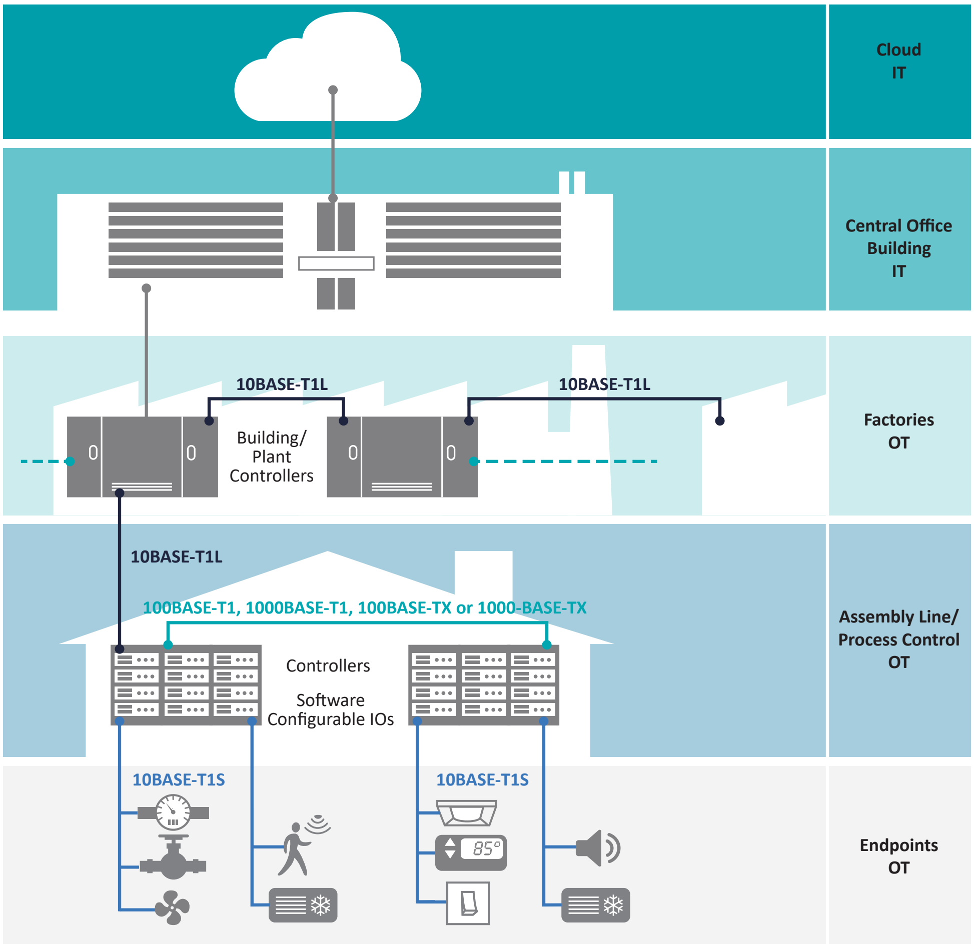


Illustration 8: Potential Ethernet deployment

At the edge between the digital and physical world, most sensors and actuators can operate with a 10 Mbit/s datalink. 10BASE-T1S and 10BASE-T1L Ethernet provide a good interface into the OT system of the enterprise that in turn can talk to a higher-level IT system. 10BASE-T1S is for shorter distances and offers multidrop capabilities that allow multiple devices to be connected to a single wire. This reduces the number of PHYs needed in each implementation and simplifies wiring. 10BASE-T1L is point-to-point, but allows for much greater distances, up to 1 km, between a sensor or actuator and the Ethernet switch it connects to.

The diagram below illustrates the Open Systems Interconnect (OSI) reference model. An all-Ethernet architecture allows all layers in one device to use a unified framework to communicate with corresponding layers in another device. Within this model, only the physical layer (1) and parts of the data link layer (2) change when switching between Ethernet speed grades, while the network layer (3) and higher layers remain unaffected.

Protocols that SPE can transport

As the previous section shows, IP-based protocols can be easily transmitted in an all-Ethernet architecture. These include protocols such as MQTT, OPC-UA, EtherNet/IP, Modbus TCP, UDP, BACnet/IP and KNX/IP, which are also supported via the 10BASE-T1S and 10BASE-T1L standards. However, these non-deterministic protocols do not guarantee real-time communication, which is not critical for many applications.

Deterministic protocols such as PROFINET (IRT), EtherCAT, SERCOS III or POWERLINK are used for time- or angle-synchronous positioning and often require higher bandwidths or deterministic latencies. Time-Sensitive Networking (TSN) also enables scalable, deterministic communication on 10BASE-T1S and 10BASE-T1L, so that future extensions of existing protocols could enable their use via SPE. One example is OPC-UA via TSN, which already enables open, deterministic communication in an industrial context.

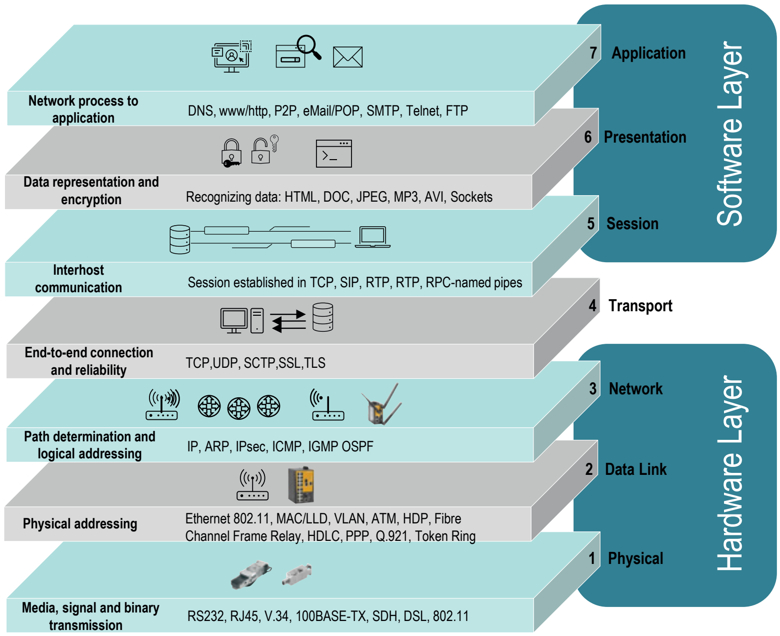


Illustration 9: OSI Model Picture

Sensor to cloud communication

Sensors generate various types of data, including measurements and diagnostic/monitoring information. This data is crucial for optimizing factories or plants through both local and remote services. For these services, seamless data transmission is key. SPE enables smooth connectivity from Ethernet-based data sources in the field to IT systems. Devices using 10BASE-T1S or T1L SPE, for example, can run services and servers directly on sensors, such as OPC UA servers or other web services like HTTP or MQTT, supporting any information transport architecture.

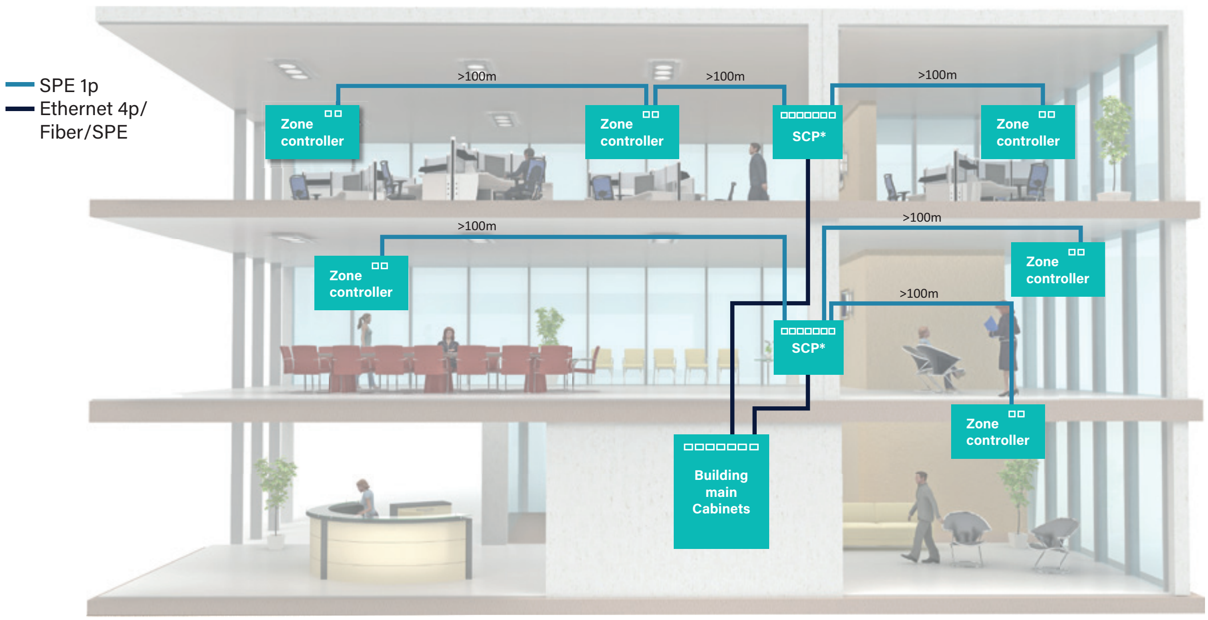
An Ethernet-based sensor becomes an integral part of a flexible information network, capable of sharing data directly with other sensors. This all-IP approach enhances traditional communication by enabling smart data management across smart factories.

Illustration 10: Sensor to IIot

Gateways for protocol conversion are not required, resulting in a cost-effective and lean communication architecture. Proven IT security standards ensure the cyber security of the sensor network. SPE is the future-proof interface for sensors that can be integrated into any IP-based network and is the enabler for wired IIoT communication.

Reference Architecture for Building Automation

Building automation is evolving too, and SPE technology offers many benefits for commercial and industrial buildings - from simplified 2-wire cabling to enhanced flexibility and scalability.



SCP* (Service Consolidation Point) enable SPE Connectivity

Illustration 11: Description of a Building with SPE

SPE provides long-distance connectivity, extending network reach without costly or complex infrastructure. It supports both star-topology and daisy-chain cabling, offering flexibility and scalability to meet the diverse needs of commercial buildings. The daisy-chain topology allows devices to be connected in series, simplifying network expansion and reconfiguration, making it ideal for dynamic environments.
With daisy chaining, new devices can be easily added without complex cabling or extra equipment, enabling seamless scalability for increasing IP connectivity demands. By reducing expansion costs and effort, SPE allows organizations to integrate new devices and technologies while maintaining a high-performance network infrastructure.
For commercial buildings, this innovation maximizes efficiency. The connectors and cables specific to SPE enable denser devices and more efficient network configurations, crucial in environments where every centimeter counts. Thanks to SPE, network cabinets become more discreet and easier to integrate, without compromising performance and reliability. The zone controllers on the second floor, as shown in illustration 11, are installed in a daisy-chain.

SPE also simplifies cable management and reduces network infrastructure costs. By requiring fewer cables, it cuts installation complexity and lowers material and labor costs.

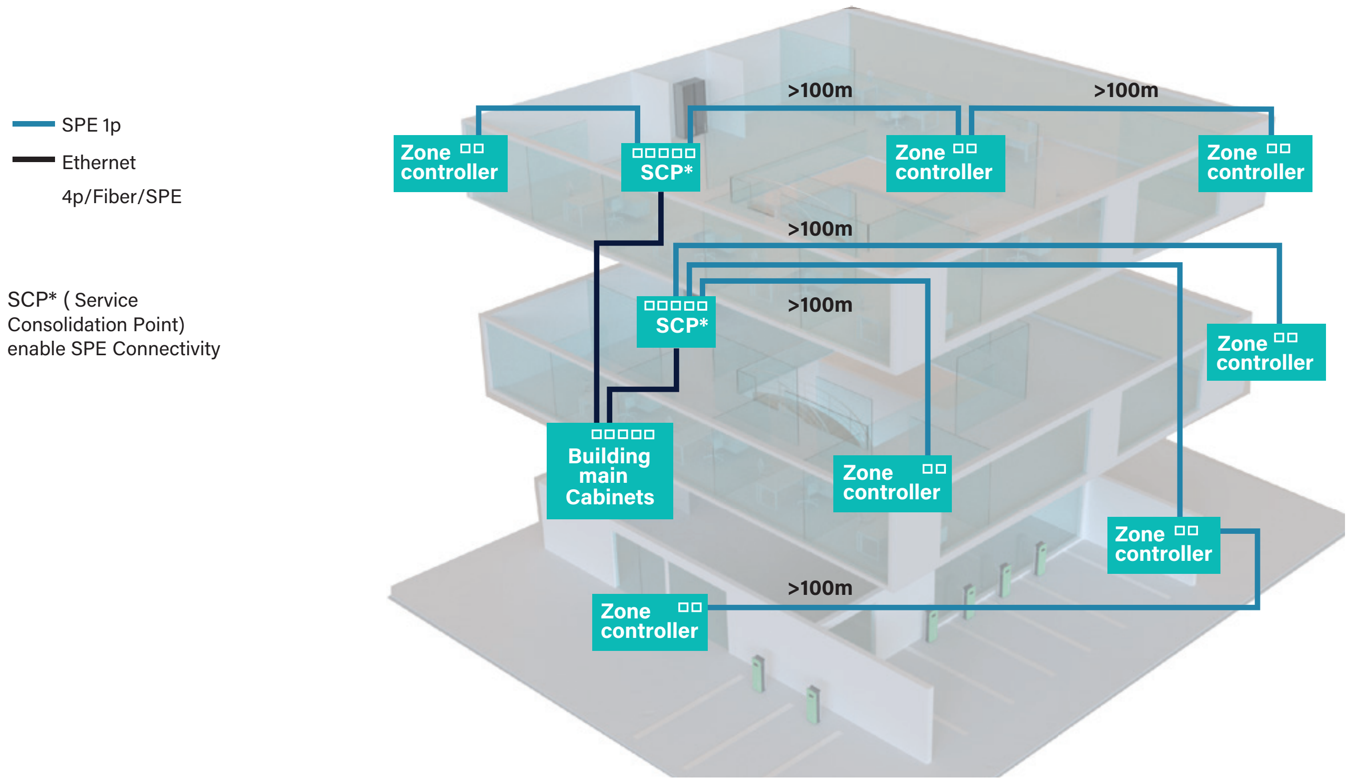


Illustration 12: SPE - The Future of Networking for Commercial Buildings

Power over Ethernet (PoE), standardized in 802.3af, requires 4-8 wires to transmit power to devices. However, some buildings may benefit from Power over Data Line (PoDL), standardized in 802.3bu. PoDL uses the 2 wires of a SPE connection to deliver up to 50 watts of power.
That simplifies the power distribution infrastructure within a building and is particularly useful in scenarios where PoE is not already in place or where PoE is not feasible due to existing wiring constraints.

By deploying SPE switches or routers at strategic points, organizations can create a reliable, high-performance network infrastructure that meets current needs and easily adapts to future expansion and innovation. SPE reduces installation costs with simplified cabling, allowing more IP devices, including IPv6-compatible components, to be connected.

SPE switches offer several key benefits. They simplify installation by reducing cabling complexity, requiring only one pair of wires for connectivity. This leads to faster, easier installations and lowers labor and material costs.

SPE scalability and adaptability make it an ideal solution for dynamic commercial environments. As organizations adopt SPE, they can expect lower installation costs, increased device connectivity, and a future-proof infrastructure that keeps them competitive and agile.

Reference Architecture for Factory Automation

In today's industrial applications, especially at the sensor and actuator level (within the automation pyramid), there is a highly heterogeneous interface landscape, leading to a media discontinuity that prevents continuous Ethernet communication all the way to the field level. Currently, various interface designs such as 4-20mA, HART, EtherCAT, IO-Link, CAN, CC-Link, and others are in use.

This results in the need for multiple gateways, significantly increasing the planning and implementation effort, especially regarding cabling and networking.

The introduction of SPE technology provides the foundation for end-to-end Ethernet communication at the physical layer, all the way to the field level. With SPE, Ethernet communication at the field level becomes a reality, enabling the seamless transmission of critical process values from sensors and actuators to all participants in the automation pyramid, with the appropriate authorization.

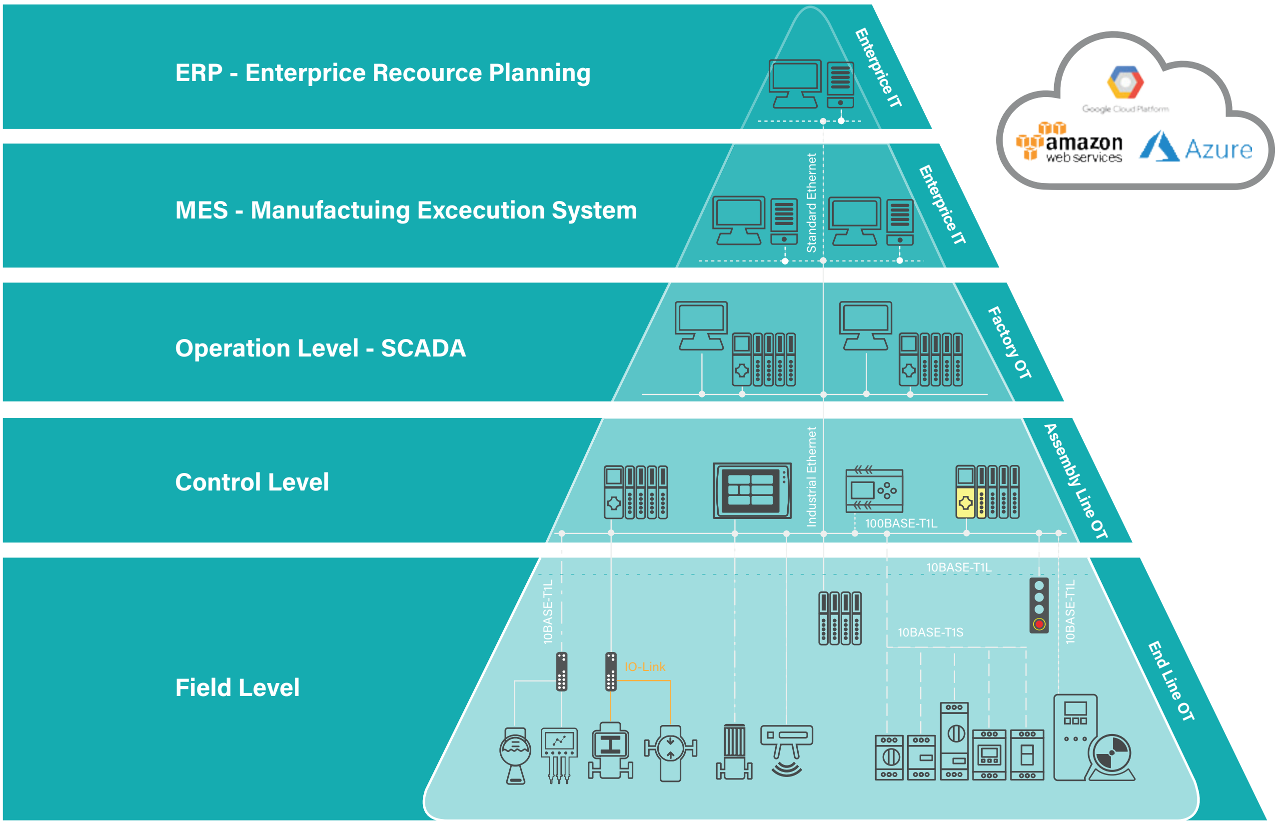


Illustration 13: Consistent Ethernet communication across all layers of the automation pyramid

This means that IT and OT converge all the way down to the field level where the sensors are installed, eliminating media disruptions. Consistent Ethernet communication is now available for the first time, enabling the implementation of Industry 4.0 at the field level.

Reference Architecture for Process Automation

Ethernet-APL, also known as 2-WISE (2-Wire Intrinsically Safe Ethernet), is an enhanced physical layer for single-pair Ethernet (SPE) based on 10BASE-T1L. It supports communication over cable lengths of up to 1000 m at 10 Mbit/s, full-duplex, which is more than 300 times faster than current fieldbus technologies.

Ethernet-APL is set to transform the process industry by offering extended reach and robust communication. It aligns perfectly with industry standards, providing deterministic communication for critical applications, while enhancing diagnostics and maintenance. Its adaptability to existing systems, flexibility in network topology, and compliance with industry-specific challenges make it a game-changing technology that optimizes performance and efficiency in industrial processes.

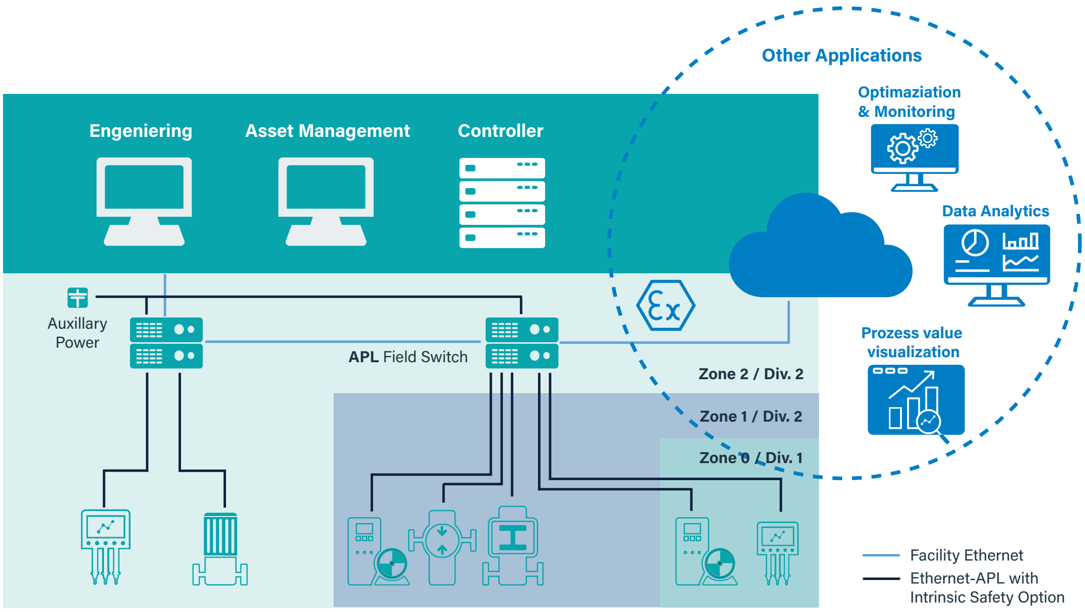


Illustration 14: Zonal architecture with APL

Ethernet-APL (Advanced Physical Layer) is an innovative communication technology developed specifically for the process industry to meet the unique challenges of industrial communication networks. It meets the requirements for reliable and robust communication in demanding environments.

Below are the key benefits of Ethernet APL in the process industry:

1. Extended Range
Ethernet-APL enables Ethernet data transmission over long distances, making it suitable for large industrial installations.

2. Harsh Environmental Resilience
Ethernet-APL is built to withstand the extreme conditions typical of the process industry, Ethernet-APL excels in environments with explosive atmospheres.

3. Seamless Integration with Existing Systems
Ethernet-APL is designed for seamless integration into existing Ethernet systems, allowing industries to upgrade their infrastructure without major disruptions or complete overhauls. Additional gateways for protocol mapping are no longer required.

4. Deterministic Communication for Critical Applications
For critical process applications, deterministic communication is essential. Ethernet-APL provides a deterministic communication environment, ensuring precise and timely data exchange, which is crucial for time-sensitive applications such as control systems.

5. Compliance with Industry Standards
The development of Ethernet-APL focused on adhering to industry standards to meet the specific requirements of the process industry. This facilitates regulatory compliance and the adoption of the technology.

6. Improved Network Flexibility:
Ethernet-APL offers improved flexibility in network topology, allowing for a more adaptable and scalable communication infrastructure. This is vital for industries that need to accommodate changes in their processes or expand their operations.

7. Enhanced Diagnostics and Maintenance:
The technology offers enhanced diagnostic capabilities, making it easier to identify and resolve issues within the communication network, reducing downtime and facilitating proactive maintenance measures.

	Ethernet-APL	**Single Pair Ethernet**
Technology	Two-wire technology	Two-wire technology
Ethernet Standards	10BASE-T1L, IEC TS 60079-47 (2-WISE)	10BASE-T1S, 10BASE-T1L, 100BASE-T1, 1000BASE-T1
Data transmission	10 Mbit/s	10 Mbit/s up to 10 Gbit/s
Power transmission	2-WISE power supply (2-Wire Intrinsically Ssafe Ethernet) limits the current in hazardous areas, supports various power levels and minimizes sparking.	PoDL (Power over Data Line) transmits up to 50 W via a single wire pair.
Cable / conductor length	Up to 1,000 m	15 to 1,000 m
Main application	Process industry	Factory automation and building infrastructure
Special features	The extension of the 10BASE-T1L standard in accordance with IEEE 802.3cg includes additional safety precautions that are specially tailored to the needs of the process industry in potentially explosive atmospheres.	Miniaturisation, industrial suitability, simplicity, future-proofing
Connection technology	Classic terminal blocks with screw or tension spring connection, like Omnimate® PCB components, built-in and field-attachable connectors (M12).	Connectors with miniaturised mating faces, patch cables, field attachable plugs, M8 adapters as well as IP20 and IP67 sockets in different outlet directions.

Table 4: Differences between SPE and APL

In summary, Ethernet-APL plays a critical role in addressing the unique communication challenges of the process industry by providing a solution tailored to the specific needs of the industry. Its focus on reliability, robustness and seamless integration makes it a valuable technology for improving communication in industrial environments.

5. Technologies for the SPE System architecture

Power concepts for the SPE ecosystem

Power over Dataline (PoDL) for Single-Pair Ethernet (SPE), as described in this document, is standardized in IEEE 802.3cg and IEEE 802.3bu. The 802.3bu standard defines PoDL for 100BASE-T1 and 1000BASE-T1 Ethernet, while 802.3cg extends support to 10BASE-T1L.

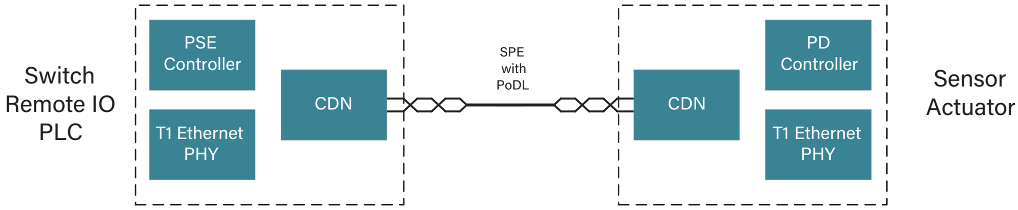


Illustration 15: Simplified PoDL System

Illustration 15 shows a typical PoDL system consisting of power sourcing equipment (PSE) and a powered device (PD). The PSE is typically part of a switch, remote IO, PLC, or media converter. It could also be a mid-span device without an Ethernet PHY. These all commonly consist of a PSE controller handling the power path and coupling/decoupling network circuitry (CDN) combining power and data to one single twisted-pair line implemented by an extra.

On the other side of this line, a PD, such as a sensor or actuator, is connected. Here a coupling network separates power and data. The power path is fed to a PD controller, responsible for handshaking and providing power to the next level of power tree. The data path is connected to an Ethernet PHY.

Power over Dataline (PoDL)

The IEEE 802.3bu and 802.3cg standards describe this process and define power classes and device types for data compatibility. These power classes are listed in the tables below.

	12-V-Unregulated PSE		12-V Regulated PSE		24-V-Unregulated PSE		24-V-Regulated PSE		48-V-Regulated PSE	
Class	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
$V_{PSE\ (max)}$ (V)	18	18	18	18	36	36	36	36	60	60
$V_{PSE\_OC\ (min)}$ (V)	6	6	14.4	14.4	12	12	26	26	48	48
$V_{PSE\ (min)}$ (V)	5.6	5.77	14.4	14.4	11.7	11.7	26	26	48	48
$I_{P\ (max)}$ (mA)	101	227	249	471	97	339	215	461	735	1360
$P_{Class\ (min)}$ (W)	0.566	1.31	3.59	6.79	1.14	3.97	5.59	12	35.3	65.3
$V_{PD\ (min)}$ (V)	4.94	4.41	12	10.6	10.3	8.86	23.3	21.7	40.8	36.7
$P_{PD\ (max)}$ (W)	0.5	1	3	5	1	3	5	10	30	50

Table 5: Power classes as defined by IEEE 802.3bu

Class	**10**	**11**	**12**	**13**	**14**	**15**
$V_{PSE\ (max)}$ (V)	30	30	30	58	58	58
$V_{PSE\_OC\ (min)}$ (V)	20	20	20	50	50	50
$V_{PSE\ (min)}$ (V)	20	20	20	50	50	50
$I_{P\ (max)}$ (mA)	92	240	632	231	600	1579
$P_{Class\ (min)}$ (W)	1.85	4.8	12.63	11.54	30	79
$V_{PD\ (min)}$ (V)	14	14	14	35	35	35
$P_{PD\ (max)}$ (W)	1.23	3.2	8.4	7.7	20	52

Table 6: Power classes as extended by IEEE 802.3cg

An understanding of the complete procedure for implementing a PoDL system is important. The standard specifies that a detection and classification phase is required (similar to standard Ethernet PoE). As the name implies, during detection the power sourcing equipment (PSE) senses if a compliant powered device (PD) is connected. If this is the case, it switches to the next stage, the classification. Now the PSE reads out from the PD what power classes are supported. If PSE and PD support the same classes, the PSE turns the power on.

Although the steps are similar to standard Ethernet PoE, they are implemented in a different way. For detection, a PoE PSE must detect a resistor on the PD side. A PoDL PSE must detect a Zener diode on the PD. To do this, the PSE supplies a constant current on the line and measures the voltage. The Zener diode limits this voltage. If the voltage is within a certain range, the PSE evaluates this as a valid condition for detection.

The classification process also differs. Where PoE uses a constant voltage from the PSE and a current sink on the PD to signal the power class, PoDL implements a simple digital one-wire communication, the serial classification protocol (SCCP).

Detection and classification in a PoDL system are not always required. A system can implement a fast start-up and skip the classification, so only the detection mechanism needs to be implemented and the system can save time at start-up. Also, it is possible to skip the detection, which makes the classification necessary. A system that omits both detection and classification is not permitted under the PoDL standard.

Engineered PoDL

A system without detection and classification is called Engineered PoDL. It simplifies system design and reduces costs and size. Only the CDN and PHY remain unchanged, while the PSE and PD controllers can be significantly simplified.

Recommended Safety Measures:

- PSE: Current limiting to prevent damage in case of short circuits.
- PD: Protection against reverse polarity and over-voltage.

Applications:

- Advanced Physical Layer (APL) is a well-known implementation.
- Suitable for systems where the manufacturer controls both sides, such as in the automotive industry with closed networks.

Drawback:

- The installer must ensure component compatibility to avoid damage.

2-WISE Power Concept for Ethernet-APL

A trunk connection allows cable lengths of up to 1000 meters for hazardous areas in Zone 1, while a spur connection supports cable lengths of up to 200 meters in Zone 0.
The 2-WISE power supply limits power delivery to devices in hazardous areas, supporting different power levels for trunk and spur connections. This reduces the risk of sparks during power failures and ensures protection in Ex zones.

Maximum power output:

- Ex-Zone 2 & 1 (Trunk), non-intrinsically safe rated:
  Power class 3: 57.5 W
  Power class 4: 92 W
- Ex-Zone 0 (Spur), intrinsically safe rated:
  Power class A: 0.54 W
  Power class C: 1.1 W

Maximum Load power:

- Ex-Zone 2 & 1 (Trunk):
  Power class 3: 36 W
  Power class 4: 57.6 W
- Ex-Zone 0 (Spur):
  Power class A: 0.5 W
  Power class C: 1.0 W

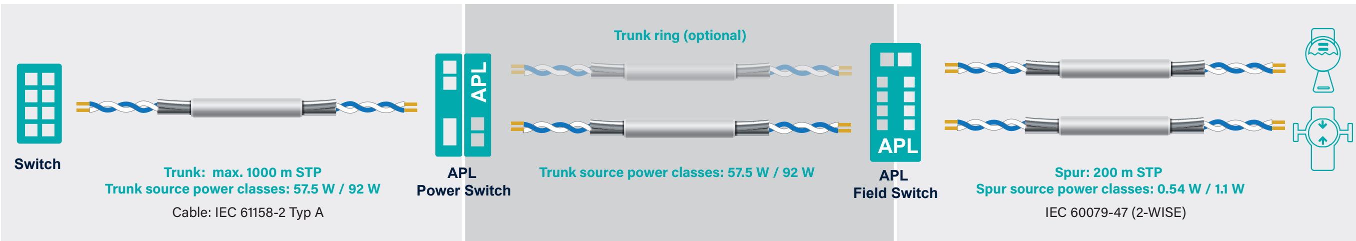


Illustration 16: 2-WISE APL Structure

SPE Specific Hardware

When designing an industrial SPE Ethernet device, several hardware aspects must be addressed to ensure a functional system. This includes using a MAC and PHY device, which are part of the lower two layers of the OSI communication model (see Illustration 17).

7	Application
6	Presentation
5	Session
4	Transport
3	Network
2	Data link
1	Physical

Illustration 17: OSI communication model showing all layers

This requires connecting the processor, including the data link and physical layers, into the system. Key components like connectors, cables, and coupling networks must be selected, alongside factors like real-time capabilities and system determinism. These choices affect system performance, particularly in harsh industrial environments, ensuring the system meets its intended use.

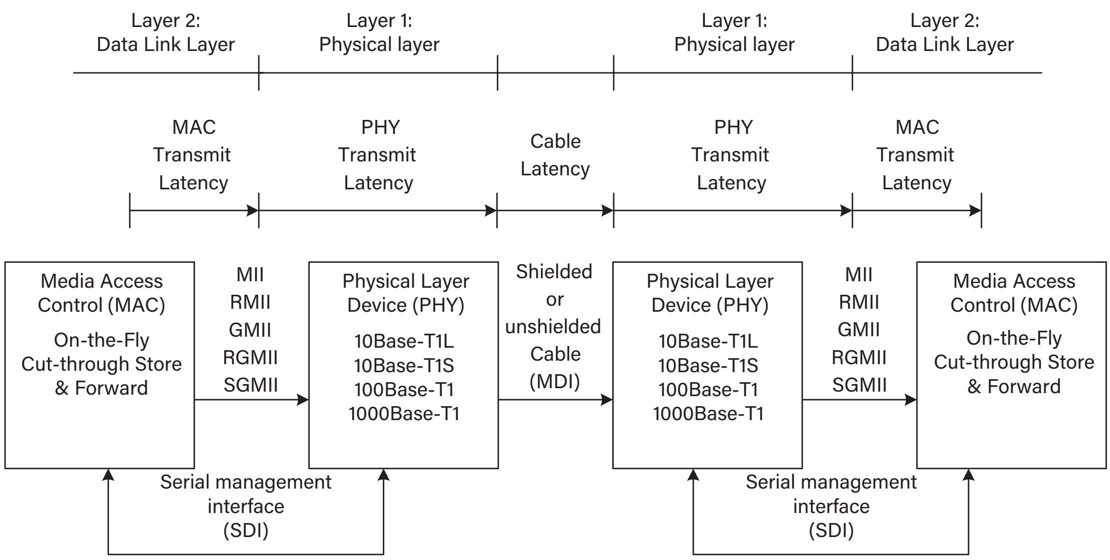


Illustration 18: Showing the Ethernet connections and interfaces which needs to be considered and some key latency parameter of each layer

1. MAC to PHY connection:
   The MII (Media Independent Interface) is a 50 Ohm single-ended trace on the PCB, providing both TX and RX paths, impro ving performance when length and impedance matching are considered.

2. MDI connection:
   This defines the cable type, connector, and coupling network. The system needs to be differential, with length and impedance matching for optimal performance. The PHY impedance is 100 Ohms, while the common mode termination (shown in Illustration 19 and 20) must be adapted to the cable type.

3. Serial Management Interface:
   This interface enables access to the PHY's internal registers, allowing for additional features such as real-time diagnostics (e.g., Single Quality Indication, SQI) for cable and connector signal quality.

Understanding key communication interface parameters, as shown in Illustration 18, is crucial to developing the best system solution for your application. Three key considerations include:

- Cable length capability
- Data rate and/or cycle time for real-time communication
- EMC/EMI performance

Based on cable length, a specific cable type must be chosen to ensure correct common mode termination. While Ethernet specifications typically assume 100 Ohm cables, RS485 cables with 120 Ohms can also be used with proper adaptation of the common mode termination to maintain functionality over the maximum cable length.

As data requirements increase, the bandwidth/data rate for the system must be analyzed to meet the communication needs. Developers should assess if the chosen data rate is compatible with the cable length or if Ethernet repeaters or other extenders are needed.

EMC/EMI Requirements: Compliance with IEC61000-4-x and CISPR-xx standards must be considered. The choice between capacitive and galvanic coupling networks plays a crucial role in noise immunity. Typically, galvanic coupling (Illustration 20) is preferred in industrial environments due to its superior noise immunity.

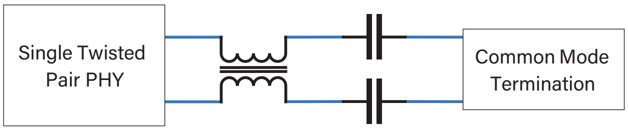


Illustration 19: Vereinfachtes kapazitives Kopplungsnetzwerk

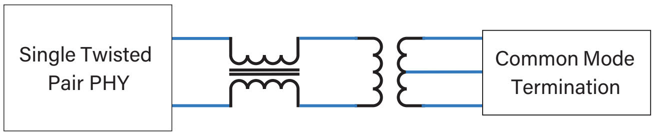


Illustration 20: Vereinfachtes galvanisches Kopplungsnetzwerk

Illustration 19 (capacitive) and Illustration 20 (galvanic) show simplified implementations. Galvanic coupling provides better noise immunity, and proper placement of common mode chokes is essential for optimal system performance.

Software security and safety

Ethernet offers robust, well-defined security mechanisms trusted in critical applications such as banking and file sharing. These mechanisms are mature, widely understood, and benefit from rapid updates when vulnerabilities are found. An all-Ethernet architecture leverages this established security framework, extending proven IT protocols seamlessly to the edge of digital and physical systems.

Unlike legacy technologies lacking built-in security, Ethernet eliminates the need to develop protocols from scratch. Standardized hardware solutions support secure provisioning with shared secrets like keys and certificates. Additionally, tamper-resistant Ethernet-compatible semiconductors simplify and accelerate protocol execution.

By utilizing Ethernet's inherent security capabilities, manufacturers can efficiently meet new cyber-resiliency standards, even without in-house security expertise.

Functional Safety

Functional safety is critical for industrial systems, ensuring predictable failure modes and preventing catastrophic outcomes in case of errors. SPE originates from the automotive industry, where functional safety is integrated from the start of the design process. SPE semiconductors often include safety documentation essential for developing functionally safe systems.
Each industry has its own functional safety standards, but they are based on similar principles:

IEC 61508	General standard for various industries	IEC 61513	Power plants
ISO 26262	Automotive industry	IEC 62061	Machinery
IEC 62279	Railway systems	IEC 62304	Medical devices
IEC 61511	Process industry	IEC 60880	Nuclear technology

Using Ethernet across all areas simplifies the certification process by relying on the same documentation and mechanisms throughout OT systems, eliminating the need for different communication links for different functions. Software in functionally safe systems also benefits from a unified communication process, supporting compliance with these requirements.

SPE data-centric architectures

Data-centric architectures are crucial for optimized data exchange, where applications share data directly and according to clearly defined rules. The focus is on fast, precise, and reliable data transmission, which enhances scalability and security. System components, both hardware and software, ensure that data is efficiently delivered to the right place—supported by seamless communication through established protocols such as TCP/IP or UDP. Single-Pair Ethernet (SPE) enables these optimized data flows and, through data centering, creates a clear separation between physical infrastructure and functional architecture elements.

6. Challenges

Digital Transition

Digital technologies have developed faster than any other innovation in history, now reaching approximately 50% of the population in developing countries. They are transforming societies and driving both economic and social progress by enabling easier connectivity and access to services.

The anticipated shift from fieldbus systems to IP-based technologies will further accelerate this progress. However, as with any major technological transition, individuals, companies, and organizations often feel overwhelmed due to uncertainty about its implications.

In practice, digitalization creates new opportunities for businesses and entrepreneurs to access previously unreachable customers and markets. To fully leverage enhanced connectivity and its associated business benefits, a focused effort to upskill the workforce is essential.

Demographic Change

Ethernet-based systems require less training effort than fieldbus-specific technologies, reducing costs in areas such as data handling, protocol conversion, and basic maintenance tasks. Key priorities include reliability, availability, diagnostics, and interoperability.

The industry is currently struggling to find enough skilled workers capable of reading ladder or electrical line diagrams, which are critical for troubleshooting existing infrastructure. SPE makes it easier to find suitable professionals, as Ethernet technologies are already widely known and understood. These benefits also apply to system maintenance, replacements, and expansions.
SPE offers a broader range of services than traditional fieldbus networks. Skills in assigning, configuring, and troubleshooting IP addresses are more widely available or easier to acquire compared to legacy communication technologies.

Governmental Requirements and Reporting

The Corporate Sustainability Reporting Directive (CSRD) is a new EU regulation that changes how companies report on sustainability. It expands the scope of the previous Non-Financial Reporting Directive and fills gaps in reporting requirements.

The CSRD holds companies accountable for their major economic, environmental, and social impacts. Sustainability reports help businesses make better decisions to produce more environmentally friendly products. This requires the continuous availability of data across all operational processes.

Digital information on how products are made can help companies comply with the CSRD. SPE facilitates the collection of this data and supports sustainability reporting.

7. Conclusion and recommendations

Conclusion

SPE offers compact, cost-efficient and lightweight cabling with data rates of up to 1 Gbit/s over 1000 meters. It reduces the need for gateways, simplifies installations and enables seamless communication using standard Ethernet protocols - from the cloud to field-level sensors and actuators. This optimizes complex data provision and simultaneously transmits energy via Power over Data Line (PoDL). SPE offers sophisticated security functions, is standardized, scalable, interoperable and ideal for IIoT and Industry 4.0 applications. Products that are already available make SPE ready for use, even for time-critical applications.

SPE is becoming increasingly standardized and is expected to replace traditional bus systems such as CAN. It plays a key role in industries, IIoT, and smart buildings by providing simple connectivity for sensors and actuators. By 2030, an increase to an estimated 50 million installed nodes in factory automation and 12 million in buildings is expected. Performance and range improvements will further drive adoption.

Recommendation

The right time to adopt SPE is now. Companies should start testing, building expertise, and investing in standard-compliant devices. Pilot projects and strategic planning for SPE-based networks will secure long-term competitive advantages and future-proof their operations.

Single Pair Ethernet
System Alliance

The Technology of the Future
Advancing together

The Single Pair Ethernet System Alliance is an open consortium of leading technology companies and scientific organisations from various industries and fields of application. Manufacturers of sensors, cables, connectors, measuring devices, semiconductors, switches and end devices work together to establish SPE solutions for a wide range of applications.

Become a member now

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