Single Pair Ethernet Association & ASERCOM ASSOCIATION OF EUROPEAN REFRIGERATION COMPONENT MANUFACTURERS



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Single Pair Ethernet (SPE) as a potential successor to Modbus RTU in refrigeration, air conditioning, and heat pump technology (RACHP)

Whitepaper

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1. Management summary

Modbus RTU over RS-485 remains the dominant baseline interface in refrigeration, air conditioning, and heat pump (RACHP) equipment because it is simple, robust, and widely supported. However, the RACHP market is facing increasing requirements for higher data availability, secure connectivity, and lifecycle maintainability—driven by digitalization, energy-efficiency optimization, fleet monitoring, and emerging cybersecurity regulation. These trends expose structural limitations of legacy serial fieldbuses: constrained bandwidth, limited scalability, lack of built-in security, and gateway-heavy architectures that add cost, latency, and operational risk.

Single Pair Ethernet (SPE) enables end-to-end Ethernet/IP connectivity down to sensors and actuators using a single twisted pair, with bandwidth from 10 Mbit/s up to 1 Gbit/s depending on the variant. This supports richer diagnostics, event logging, and data streams required for advanced control and analytics while leveraging mature IP-based security mechanisms (for example, TLS, certificate-based authentication, and network segmentation). In the context of the EU Cyber Resilience Act (CRA) and security-by-design expectations, an Ethernet/IP foundation can reduce the need for proprietary security retrofits on top of legacy protocols. SPE can also carry power via Power over Data Line (PoDL), potentially reducing wiring, installation effort, and cabinet complexity for many RACHP components.

This whitepaper summarizes the technical foundations of SPE, discusses benefits and practical pitfalls for RACHP applications, and provides testing insights from representative setups. Adoption is expected to be evolutionary: the installed base of Modbus RTU will persist, and hybrid concepts (gateways and dual-interface devices) will be required during the transition. To reduce fragmentation and integration effort, ASERCOM and the Single Pair Ethernet Alliance Association (SPEA) advocate coordinated guidance for RACHP-specific profiles, interoperability, and cybersecurity practices. For R&D and system decision makers, recommended next steps include selecting pilot applications with clear diagnostic or security drivers, defining an architecture for coexistence and network segmentation, and aligning device requirements (PHY, IP stack, update mechanism, and PoDL needs) with product cost and lifecycle targets.

2. Introduction and problem description

Anyone who connects a refrigeration system, an air conditioning unit or a heat pump to a supervisory control system today will very likely encounter Modbus RTU over RS-485. Over the past decades, this serial two-wire bus has in effect become the lowest common denominator in the RACHP sector: It is simple, robust, cost-effective and supported by virtually all component manufacturers – from compressors to fans and electronic expansion valves all the way to controllers and monitoring units.

This broad support is a key to its success: System builders and planners generally only need to master a single fieldbus system. From a manufacturer's perspective, a single bus interface is often sufficient to cover the majority of market requirements. Modbus RTU has therefore long been a pragmatic and economically smart solution.

However, this success story has a downside. Modbus RTU was developed in the late 1970s, at a time when neither cybersecurity nor cloud connectivity nor detailed condition monitoring played a major role. Important limitations are becoming increasingly apparent today: The data rate is limited, the number of nodes per bus is restricted, broadcast or multicast mechanisms are lacking, and above all there are no integrated security mechanisms. Authentication, encryption or secure firmware updates must, if implemented at all, be laboriously retrofitted in higher protocol layers.

At the same time, external pressure is increasing. Digitalization, energy efficiency requirements, sustainability reporting and new cybersecurity regulations demand a more modern communication infrastructure. This raises the question: Will Modbus RTU remain the dominant standard for much longer – or is there a need for an IP-capable, more secure and more powerful alternative?

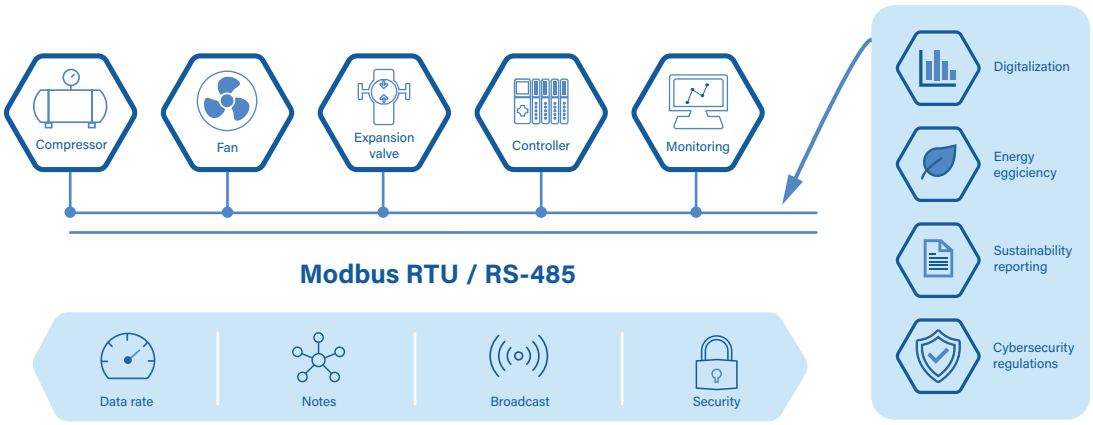


Figure 1: RACHP communication today: Modbus RTU under growing requirements

3. Benefits of SPE in the RACHP Market

The refrigeration, air conditioning, and heat pump industry is undergoing a massive change. The number of networked components in systems is growing: more sensors, intelligent compressors, frequency-controlled compressors and pumps, networked heat pumps, distributed chillers, and integrated building automation systems. Today, these requirements are often met with a mix of Modbus RTU, proprietary fieldbuses, remote I/O modules, and gateways to BACnet, Modbus TCP, or cloud connections. The result is a fragmented communication landscape: Modbus RTU dominates below the IP layer, while above it, a variety of protocols and manufacturer-specific features prevail. Each translation stage (gateway) costs money, generates latency, and is a potential source of errors – and often a security risk. The vision of an SPE-based approach is different: Ethernet communication should no longer end in the control cabinet, but extend all the way to the sensor or actuator. Compressors, fans, expansion valves, heat meters, room controllers, or refrigerant pumps would be directly IP-enabled in the future and could be connected to a common Ethernet network via SPE. Gateways would not disappear, but there would be significantly fewer of them, and they could focus on pure protocol integration (e.g., to a manufacturer's backend) instead of translating serial fieldbuses.

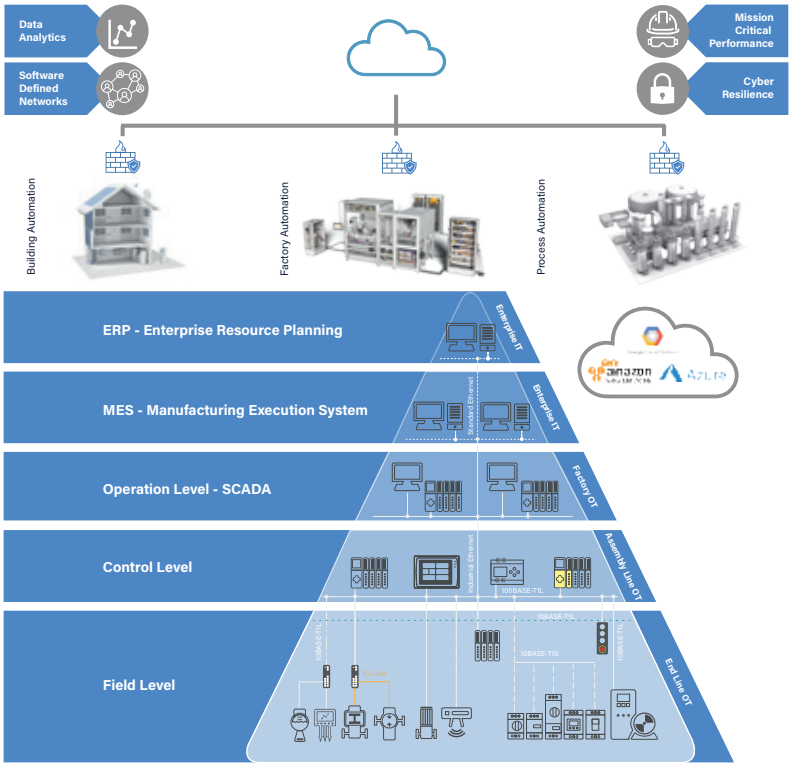


Figure 2: The Automation Pyramid in Current Industrial Applications

Advantages

The most important difference from a user's perspective is the end-to-end IP communication. While Modbus RTU is a fieldbus without IP functionality, SPE is built directly on Ethernet/IP. This enables seamless end-to-end communication from the field device through switches, routers, and firewalls to building management systems or the cloud. Process data, diagnostics, historical trends, and firmware updates use the same communication principle as office PCs or servers. For operators of large plants, this means a unification of the network landscape: IT and OT converge instead of being laboriously coupled via gateways.

A second, very practical advantage lies in the data rate. Even at 10 Mbit/s – the slowest SPE variant – orders of magnitude more bandwidth are available compared to typical Modbus speeds (in the kBaud range). This allows for the exchange of far more than just setpoint and actual values. Detailed diagnostics, comprehensive event logs, and cloud analytics become possible without immediately clogging the network. This is a crucial point, especially with regard to predictive maintenance and condition monitoring, for example, for compressors or large refrigeration systems.

SPE also directly leverages established cybersecurity mechanisms from the IT world. Encrypted connections, certificate-based authentication, role-based access control, segmentation through VLANs and firewalls – all of this is already present in Ethernet and firmly established in standards, best-practice guides, and products on the market. Modbus RTU, on the other hand, offers no inherent protection; any form of authentication or encryption must be laboriously implemented – or omitted entirely for cost reasons. Given new legal requirements for cyber resilience, this is an increasingly unacceptable risk. Even if Modbus RTU is not prohibited by the CRA and cybersecurity in future, SPE offers significant technological benefits.

Added to this is the aspect of supplying power over the same line. With PoDL, a SPE cable can not only transmit data but also simultaneously power compatible field devices. The specified power ratings are perfectly adequate for many components in refrigeration and air conditioning systems—such as sensors, room controllers, and communication modules. Separate low-voltage power supplies and additional power lines are no longer needed. Installation time and material costs are reduced, space requirements in distribution panels decrease, and the fire load from cables is minimized.

Last but not least, SPE also offers ecological advantages. Because only one wire pair is required, copper and plastic consumption is significantly reduced compared to four-pair Ethernet cables. In conjunction with PoDL, additional power lines can often be completely eliminated. For large systems or mass-produced products, this enables considerable resource savings—an argument that is gaining increasing importance in times of CSRD reporting requirements and sustainability goals.

4. Weaknesses and Pitfalls

As convincing as the technical advantages of SPE may seem on paper, it is crucial to consider the practical challenges involved in switching to it. The first and most obvious point is the cost at the device level. A simple RS-485 transceiver for Modbus RTU is very inexpensive and has minimal requirements for processing power and memory. In contrast, an SPE-enabled device requires a significantly more complex Ethernet PHY, often a more powerful microcontroller with an IP stack, security libraries, and update logic. In the short term, this means higher unit costs, especially for simpler devices produced in high volumes. One thing is certain: as SPE becomes more widespread, the prices of its components will decrease. However, during the transition phase, cost pressure remains a significant concern, particularly in highly price-sensitive markets.
Another aspect is installation practice. Refrigeration technicians are accustomed to Modbus buses: two wires plus a shield, termination resistors, addressing, and perhaps one or two repeaters – often, all that is needed. Ethernet, even in the form of SPE, introduces a different set of challenges: IP addressing concepts, subnet planning, switch configuration, and potentially VLANs and firewalls. This is initially unfamiliar to many installers and commissioning engineers and can lead to errors and frustration if the implementation isn't accompanied by appropriate training and support. Furthermore, industry-specific profiles for SPE are only just emerging in the RACHP world.
With Modbus RTU, de facto standard registers and data models have become established over the years, even if they aren't always perfectly documented. For SPE-based communication, such consolidated profiles are only just beginning to appear. The cooperation between ASERCOM and the Single Pair Ethernet Association aims precisely to develop clear recommendations early

on, preventing each company from defining its own incompatible Ethernet variant for refrigeration and air conditioning equipment. However, as long as this work is still ongoing, there is a risk of IP-based fragmentation. The migration issue should also not be underestimated.
The installed base of Modbus devices is enormous and will not disappear overnight. For many years, a coexistence of Modbus RTU and SPE-based solutions is therefore realistic. The transition will require gateways, hybrid devices with both interfaces, and transitional concepts. This will increase system complexity, at least temporarily, before it can decrease in the long term. Anyone planning to use SPE in new projects must therefore carefully plan how existing and new systems will communicate with each other and what strategy should be pursued for service and spare parts management.
Finally, the question arises whether a full-fledged Ethernet stack is simply „overkill" for very simple applications. For local, non-networked temperature sensors or simple on/off signals, a straightforward serial solution may remain the most pragmatic option. It is quite conceivable that, in the long term, there will be a coexistence: SPE/Ethernet where security, remote access, analytics, and interoperability are paramount, and lean serial solutions where simplicity and price are the primary considerations.

5. Transition from Modbus RTU to SPE

From Serial to Digital Connectivity — Why the RACHP Industry Cannot Ignore SPE

The refrigeration, air conditioning, and heat pump (RACHP) industry has relied on Modbus RTU over RS-485 as its de facto communication backbone for decades. The reasons are straightforward: the technology is simple, inexpensive, robust, and almost universally supported across component manufacturers — from variable-speed compressors and electronic expansion valves to heat pump controllers and refrigeration monitoring units. Historically, a single Modbus interface was often sufficient to cover the vast majority of market requirements.

However, this pragmatic success story is increasingly confronted with the realities of a changed technological and regulatory environment. Modbus RTU was designed in the late 1970s, long before cybersecurity, cloud connectivity, and detailed condition monitoring became central concerns. Three structural limitations are now reaching critical relevance for the RACHP industry.

Bandwidth: Where Modbus RTU Runs Out of Headroom

The first pressure point is data throughput. Modbus RTU operates in the range of 9.6 to 115.2 kBaud — data rates that were perfectly adequate when systems exchanged little more than setpoints, actual values, and alarm bits. Today's demands are fundamentally different.
Consider a modern commercial refrigeration rack in a supermarket: a single rack may integrate variable-speed compressors with real-time vibration monitoring, electronic expansion valves with detailed positioning logs, suction-pressure and superheat sensors sampled at high frequency for dynamic optimization, and multiple cold case controllers — each generating event logs, diagnostic data, and energy consumption figures. Polling all of this meaningfully over a single Modbus segment at 19.2 kBaud quickly reveals the ceiling of what the technology can deliver.
The same challenge arises in other RACHP segments. Intelligent heat pumps equipped with predictive control algorithms require continuous exchange of multi-zone temperature profiles, compressor operating maps, and grid interaction signals (e.g., demand response or dynamic tariff data). Large chiller plants in process cooling or data center cooling applications are beginning to implement digital twin architectures, where real-time operational data must be streamed continuously to simulation models for optimization — data volumes that no Modbus bus can realistically support.
SPE, even in its most conservative form — 10BASE-T1L at 10 Mbit/s over a single twisted pair — offers roughly two to three orders of magnitude more bandwidth than a typical Modbus bus. This is not over-engineering; it is the minimum prerequisite for the connected, analytically capable RACHP systems that energy efficiency regulations and sustainability obligations are beginning to demand.

Cybersecurity and the EU Cyber Resilience Act

The second, and arguably most urgent, driver for transition is cybersecurity. Modbus RTU has no security mechanisms whatsoever. There is no authentication — any device connected to the bus can read or write data. There is no encryption — all communication is plain text. There is no mechanism for secure firmware updates, no role-based access control, and no audit logging built into the protocol. Any cybersecurity measures must be retrofitted in higher layers, which in practice often means they are either implemented inconsistently or omitted entirely for cost reasons.

This is a weakness under emerging European legislation. The EU Cyber Resilience Act (CRA), which entered into force in December 2024 and fully applicable from December 2027, imposes mandatory cybersecurity requirements on all products with digital elements placed on the EU market. RACHP equipment — heat pumps, chillers, refrigeration controllers, building automation interfaces — falls squarely within this scope. Manufacturers will be required to ensure that their products are designed with security by default, support secure software updates throughout the product lifecycle, have no known exploitable vulnerabilities at the time of market release, and provide documentation and transparency for security-relevant properties.

Meeting these requirements with Modbus RTU is technically possible but architecturally awkward. It requires layering security logic — TLS, token-based authentication, update authentication — on top of a protocol that was not designed for any of it, typically via proprietary gateways. This introduces complexity, single points of failure, and additional certification burden.

Single Pair Ethernet, as a physical layer variant of standard Ethernet, changes the situation fundamentally. Because SPE is native Ethernet, it inherits the complete security ecosystem of the IP world. TLS 1.3 can encrypt communication end-to-end from the field device to the cloud or building management system. Certificate-based authentication (X.509) ensures that only authorized devices and systems can communicate. Secure Boot and secure OTA firmware updates (e.g., via HTTPS or MQTT with TLS) can be implemented using well-tested, standardized mechanisms. Network segmentation via VLANs and firewalls allows RACHP subsystems to be isolated from general IT infrastructure while still being manageable centrally. All of these mechanisms are available in mature, standardized, and widely audited implementations — not as proprietary extensions, but as integral parts of the IP stack.

For RACHP manufacturers subject to the CRA, this means that designing for SPE/Ethernet from the ground up is architecturally the cleaner path. The security building blocks are available, documented, certifiable, and used at scale across the IT industry. Modbus RTU forces manufacturers into a position of constructing security infrastructure that the protocol was never intended to support, with all the associated complexity and audit risk this entails. The ongoing discussions in the joint SPE Association/ASERCOM working group have explicitly identified CRA compliance as an important argument for SPE adoption in RACHP applications.

How Single Pair Ethernet Enables Real-Time Industrial AI

Industrial AI delivers significant benefits across a wide range of applications, including predictive maintenance through vibration and temperature monitoring, AI-based quality inspection, energy optimization, and production process analytics. These applications generate a continuous stream of data that must be collected, transported, and processed in real-time to create meaningful business value. To fully harness this potential, three major obstacles must be overcome: connectivity chaos, insufficient data throughput, and limited real-time capability. Industrial AI requires seamless end-to-end networking, high-bandwidth communication, and deterministic data exchange across all levels of the automation architecture. In addition, AI systems depend not only on raw data but also on contextualized information, such as where and when data was generated, from which device it originated, and under which process conditions it was captured. Single Pair Ethernet addresses these challenges through a unified Ethernet-based communication infrastructure, enabling the reliable transport of large volumes of contextualized sensor and device data directly from the field level to AI applications. By simplifying connectivity, increasing data availability, and supporting real-time communication with data rates up to 1 Gbit/s, SPE provides the foundation for scalable and efficient Industrial AI deployments.

Power over Data Line (PoDL) — New Possibilities in RACHP

The third dimension of SPE's value proposition for the RACHP industry is Power over Data Line (PoDL). PoDL enables field devices to be powered directly over the same single twisted pair that carries the Ethernet data signal, eliminating the need for separate power supply cables.

The potential applications in RACHP are significant. Room temperature and humidity sensors in distributed HVAC zones can be SPE-connected and powered via PoDL, requiring only a single two-wire run from a nearby SPE switch — no separate 24 V supply needed. Electronic expansion valves in refrigeration systems equipped with diagnostic electronics and network interfaces can receive both

control data and power over a single SPE cable. Refrigerant leak detectors and air quality sensors placed at distributed points in a cold store can be powered via PoDL, simplifying installation considerably in retrofit scenarios.
The economic implications are clear: fewer cable runs, reduced material costs, smaller distribution boards, and lower installation labor. For RACHP manufacturers developing the next generation of connected products, designing for SPE with PoDL support creates a compelling value proposition for system integrators and building operators facing both cost pressure and CRA-driven security requirements.

A Coordinated Industry Transition

Realistically, Modbus RTU will not disappear from RACHP systems overnight. The installed base is enormous, and for simple, non-networked applications with no security requirements, serial communication will remain viable for years. The transition will be evolutionary rather than revolutionary — with hybrid devices carrying both interfaces, gateways bridging legacy and IP segments, and SPE-native products emerging first in new installations and higher-end product lines.

6. Overview of SPE technology

Single Pair Ethernet extends the Ethernet family down to the field level—the part of the automation pyramid that has traditionally been dominated by legacy fieldbuses and serial links. In classic architectures, this creates “data islands” and requires gateways to bridge between OT devices and enterprise IT systems, increasing wiring complexity and lifecycle cost. SPE addresses this by enabling end-to-end Ethernet connectivity—from sensors and actuators up to controllers, SCADA/MES, and cloud—using a single balanced pair of conductors.

What is SPE and why it matters

SPE is “Ethernet over one pair”—but the reason it matters is not only the cable count. Ethernet is already the most ubiquitous IP-capable wired ecosystem, with mature software stacks, tooling, and a broad component supply chain (switches, cables, connectors, PHYs). SPE leverages that ecosystem while targeting the cost, size, and wiring constraints found at the device edge.
At the OT edge, future IIoT applications require more sensors, more data, and better integration across levels. Traditional fieldbus structures “work,” but are constrained in bandwidth and integration capability, especially when you want secure remote access, predictive maintenance, and continuous diagnostics across sites. SPE is intended to remove those bottlenecks by providing a uniform Ethernet/IP foundation all the way to sensors and actuators.
From a system perspective, SPE is also about simplifying architectures: instead of many specialized networks and gateways, a single Ethernet backbone can connect heterogeneous segments (long-reach, multidrop, higher-speed) using standard bridging/switching at the Ethernet frame level. That preserves application-layer protocol continuity (e.g., OPC UA, Modbus TCP, EtherNet/IP, BACnet/IP, KNX/IP) and supports modern security patterns (e.g., TLS/DTLS at higher layers) without requiring “media breaks.”
Finally, SPE enables power + data on the same pair. This directly reduces installation effort (one cable, one connector) and supports smaller device form factors—particularly relevant where space, weight, or installation time are critical

Technical Foundations of SPE technology

SPE is not a single standard but a family of Ethernet PHY variants designed for different reach and bandwidth targets. SPE into three major sub-branches focused on cost-optimized device connectivity:

- high-speed (100/1000BASE-T1)
- long-range (10/100BASE-T1L)
- multidrop (10BASE-T1S/T1M)

These variants remain compatible at the Ethernet frame level and can be interconnected with adapters or switches, maintaining IP continuity.

An “All-Ethernet” design allows different physical layers at different points of the system, while Layers 3–7 remain unchanged. Practically, that means slower streams at the sensor edge (often sufficient at 10 Mbit/s) can be aggregated and carried over faster uplinks higher in the hierarchy.

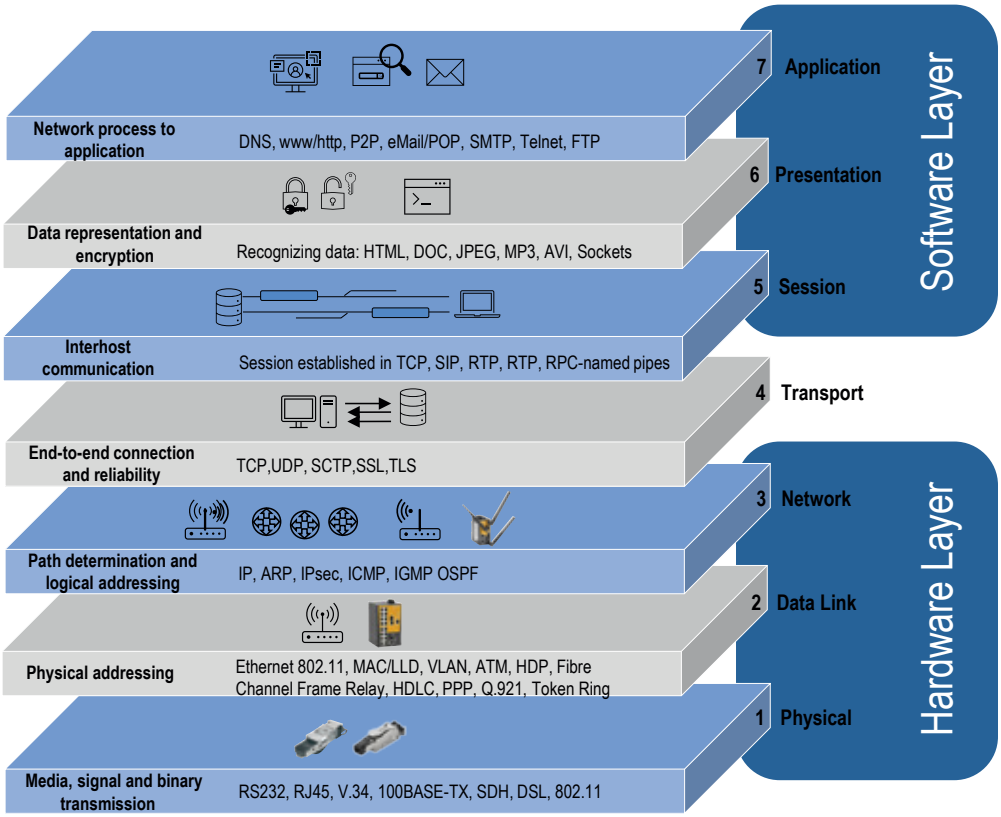


Figure 3: OSI Model Picture

A recurring engineering theme is the trade-off between distance, throughput, EMC robustness, and cost. SPE extends Ethernet reach beyond the classic 100 m limitation at common industrial data rates (10 Mbit/s to 1 Gbit/s), while keeping Ethernet’s management and software advantages.

PoDL stands for Power over Data Line. It enables transmission of both power and data over one single twisted pair in SPE connectivity. PoDL supplies DC power while Ethernet data are transmitted as high-frequency differential signals over the same cable. Power and data are separated by Coupling & Decoupling Networks (CDNs) that allow the DC supply and high-frequency Ethernet signals

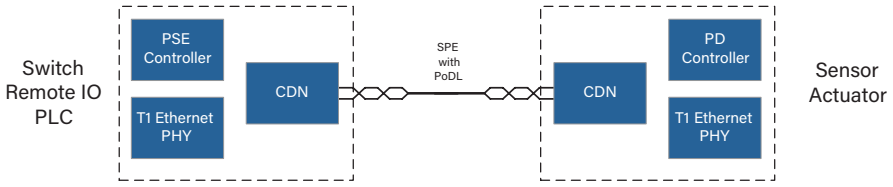


Figure 4: Simplified PoDL System

to coexist on the same cable. (Simplified view: coupling networks behave similarly to high-pass paths for data and low-pass paths for power.) Depending on the selected PoDL class, up to approximately 58 V DC can be supplied by a Power Sourcing Equipment (PSE) to a Powered Device (PD) over the same SPE link (according to the IEEE 802.3bu PoDL without a multidrop extension).

This principle is well established in Power over Ethernet (PoE), where power and data are transmitted over conventional multi-pair Ethernet cabling in point-to-point topologies. Traditional IEEE PoDL was originally developed for point-to-point SPE links. IEEE P802.3da extends 10BASE-T1S multidrop networks with optional standardized power distribution mechanisms, enabling multiple powered devices to share the same communication and power infrastructure.
In many RACHP applications, the available power over PoDL is sufficient for sensors, leak detectors, room controllers, environmental monitoring nodes and other low-power field devices, eliminating the need for a separate local power supply.
Several modern 10BASE-T1S PHYs support Ethernet sleep and wake-up mechanisms, comparable to Wake-on-LAN and timer-based wake-up functions used in conventional Ethernet networks. Sleep and wake-up mechanisms allow SPE devices to minimize energy consumption whenever communication is not required. Lower device power consumption reduces current flow through the cable and therefore minimizes voltage drop and transmission losses. This contributes both to improved energy efficiency and to more sustainable operation of large-scale building automation and refrigeration networks.
For building automation and refrigeration systems, PoDL can significantly reduce installation effort by combining communication and power supply into a single two-wire infrastructure for sensors, actuators and edge devices.

PoDL Power Classes and Engineered PoDL

IEEE 802.3bu PoDL defines a standardized method to deliver power and data over the same SPE link. Unlike normal Ethernet communication, IEEE PoDL requires an initial detection and classification phase before power is applied. Before normal Ethernet communication begins, the PSE and PD perform a dedicated detection and classification procedure. This process uses SCCP signaling rather than standard Ethernet communication and exists solely to establish safe power delivery and determine the required power class. This dedicated signaling mechanism establishes compatibility and power requirements between the PSE and PD. It also enables interoperable operation between equipment from different vendors. Depending on the selected class, PoDL can supply up to approximately 58 V DC and power levels ranging from a few watts for simple sensors up to around 50 W for more demanding field devices.

In controlled environments such as building automation or refrigeration systems, where compatibility between PSE and PD is known in advance, the detection and classification process can be simplified. This approach is often referred to as Engineered PoDL. By reducing or simplifying dynamic power negotiation, system complexity and implementation cost can be lowered while retaining the benefits of a shared data and power infrastructure. However, proper system design is required as compatibility is ensured by the installer or equipment manufacturer rather than by standardized negotiation.
In contrast to IEEE-compliant PoDL, Engineered PoDL relies on predefined system compatibility rather than standardized power negotiation.

Class	Typical Voltage Range	Approx. Power Level at PD	Typical Use Case
10	24 V	up to ~7 W	Simple sensors
11	24 V	up to ~13 W	Advanced sensors / small actuators
12	24 V	up to ~25 W	Compact field devices
13	48–58 V	up to ~15 W	Sensors over longer distances
14	48–58 V	up to ~30 W	Actuators / IO devices
15	48–58 V	up to ~50 W	High-power field devices

For many RACHP and building automation applications, these power levels are sufficient to operate sensors, leak detectors, room controllers, environmental monitoring nodes and other low-power field devices using only a single SPE cable for both communication and power supply.

Network Topologies (Multidrop / P2P)

Point-to-Point Single Pair Ethernet:

The Point-to-Point topology in connects exactly two devices directly. It is ideal for stable and dedicated bandwidth between endpoints. The simple structure allows for straightforward configuration and troubleshooting. The standard for this topology is covered in IEEE 802.3 clause 100.Single Pair Ethernet



Figure 5: 10BASE-T1L Long reach, ideal for factory-, process- and field applications outside the cabinet

Multidrop with PLCA:
The Multidrop topology connects multiple devices over a single pair of wires. The PLCA mechanism (Physical Layer Collision Avoidance) manages communication coordination, preventing data collisions. This approach is cost-effective, reducing cabling needs and supporting multiple nodes on a single segment. The standard for this topology is defined in IEEE 802.3cg.

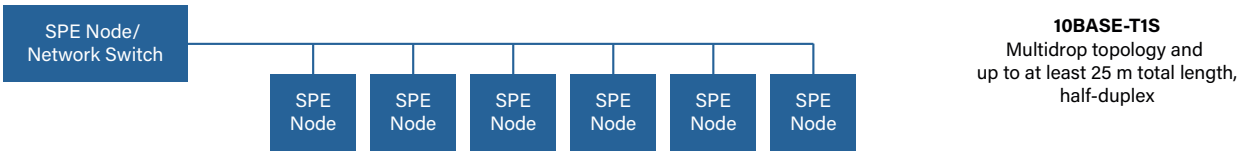


Figure 6: 10BASE-T1S Short reach, daisy-chained, ideal for in-cabinet applications.

Standardization Landscape

Single Pair Ethernet standards refer to a set of guidelines and specifications established for the use of Ethernet technology over a single pair of twisted copper wires. The specifications include every aspect of SPE, like Ethernet interfaces, wiring, and data transfer. The standard for SPE is defined as IEEE 802.3. This specification sets the technical parameters for Ethernet-based data communication over a single pair of wires. These standards differ in their transmission speeds and distances and ensure interoperability and provide guidelines for designing compliant products . The currently most relevant standards for the industry are 10BASE-T1L up to 1,000 m and 10BASE-T1S for Multidrop applications. 100BASE-T1 enables 100 Mbit/s up to 100 m and 1000BASE-T1 even 1 Gbit/s up to 40 m. When being available, it is estimated that also 100BASE-T1L (IEEE802.3dg) will be very important for the industry.

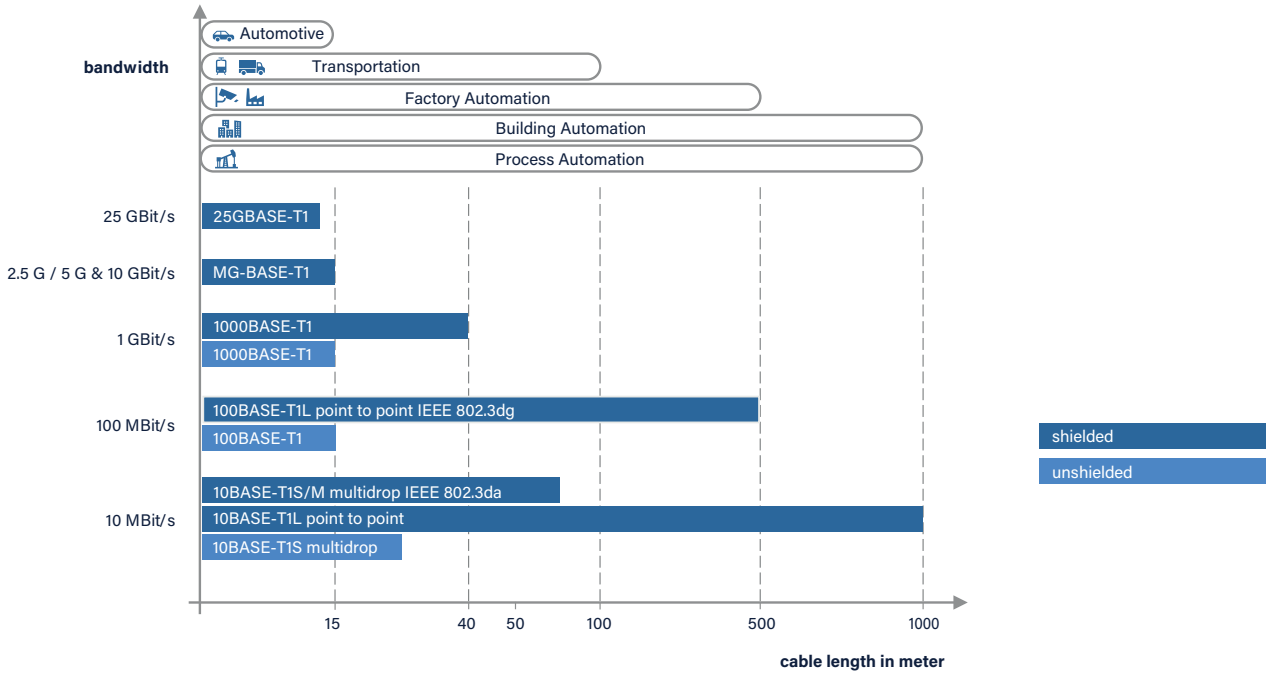


Figure 7: Different SPE topologies

Connector standardization

The IEC standard IEC 63171 considers the standardization of the connection technology of Single Pair Ethernet. This defines basic information, testing techniques and requirements for SPE connectors and includes electrical and transmission properties as well as different mating faces. In addition, the MICE concept (Mechanical, Ingress, Climatic and Electromagnetic) is integrated into the standard, which deals with environmental conditions and areas of application. Recently, international automation communities have highlighted the need for a standardized connector for Single Pair Ethernet, which has been submitted for international standardization is now internationally standardized based on essential application requirements. With the agreement on a uniform connector face for Single Pair Ethernet, the industry is now making a significant step towards the future. The new SPE connector system provides a consistent mating face for applications in control cabinets, in the field, and for hybrid installations. Numerous manufacturers have already announced realized their plans to implement it soon.

The New IEC 63171 7 ED.2 Standard: globally harmonized SPE Interfaces

To support device manufacturers in adopting SPE, the connector industry has aligned with the new IEC 63171 7 Edition 2 standard. This interface provides a unified mating face across IP20, IP67 and Hybrid connectors, enabling seamless interoperability across different vendors and network devices.

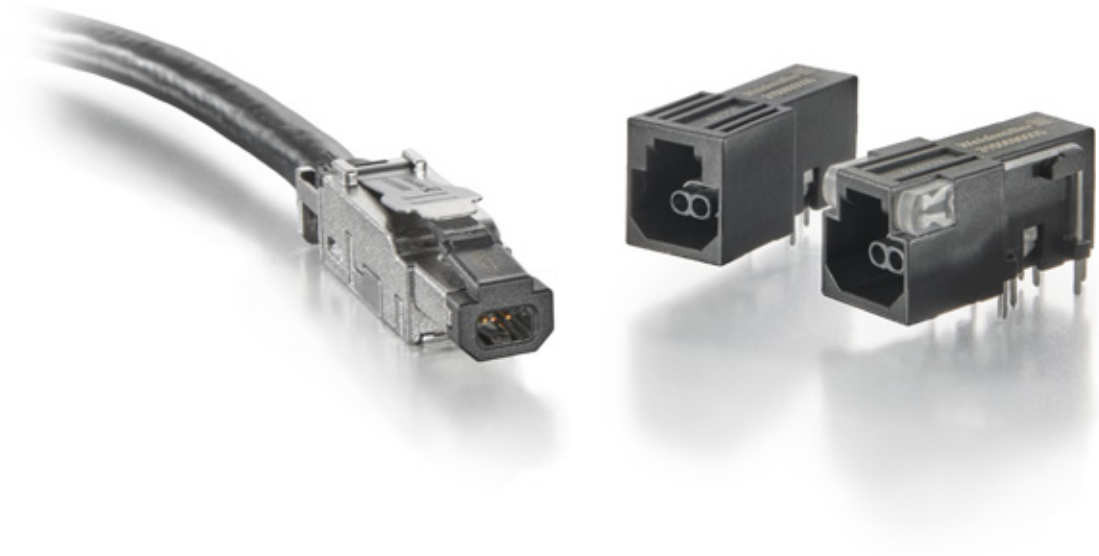


Figure 8: Connector interface (Source: Weidmüller)

Compliance with IEC 63171 7 (ED. 2) not only ensures devices meet all necessary certification requirements but also reduces engineering risks, simplifies planning, and accelerates time-to-market. For PROFINET over SPE, IEC 63171 7 is already recognized as a standard, providing clear guidance for device and system manufacturers. Backed by the world's leading industrial networking organizations, IEC 61158-2-100 provides a globally harmonized foundation for SPE and Ethernet-APL deployments. The coordinated support from FieldComm Group, ODVA, OPC Foundation, and PROFIBUS & PROFINET International (PI) enables seamless interoperability, consistent certification, and rapid market adoption, giving end users confidence in a future-proof and vendor-neutral Ethernet infrastructure. Simultaneously, these organizations are driving consistent SPE standardization, including Power over Data Line (PoDL) power classes, installation guidelines, and standardized connector systems, to guarantee interoperable solutions from the field level to IT systems. A key element of this strategy is the harmonized IEC 63171-7 connector interface, which is being positioned as the common connector standard for future SPE and Ethernet-APL applications across factory, process, and building automation. Together, IEC 61158-2-100 and IEC 63171-7 create the foundation for a unified, globally accepted Ethernet ecosystem that simplifies deployment, ensures multi-vendor compatibility, and accelerates industrial digitalization.

IEC Standardization of SPE Cables

The international standardization of Single Pair Ethernet 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. Four main SPE cable standards are relevant for the different IEEE applications:

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: 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

Comparison of key performance indicators Modbus/ SPE / CAN

Various field busses are used in RACHP applications today. Based on their technical features, the use cases and applications differ.

The following table compares some technical key features of exiting field busses with SPE:

Parameter	SPE 10BASE-T1S	Modbus RTU (RS-485)	Modbus TCP	CAN Classic	CAN FD	CAN XL
Primary Standard	IEEE 802.3cg Clause 147	Modbus Serial Line + TIA/EIA-485-A	Modbus TCP/IP + IEEE 802.3	ISO 11898-1 / -2	ISO 11898-1 / -2	ISO 11898-1:2024 / -2:2024
Physical Layer	Single Pair Ethernet	RS-485	Ethernet	CAN HS	CAN FD	CAN XL
Topology	Multidrop Bus or Point-to-Point	Linear Bus	Switched Star	Linear Bus	Linear Bus	Linear Bus
Arbitration Method	PLCA (Physical Layer Collision Avoidance)	Master-Slave Polling	TCP/IP Switching	CSMA/CA Priority-based Bit Arbitration, lossless	CSMA/CA Priority-based Bit Arbitration, lossless	CSMA/CA Priority-based Bit Arbitration, lossless
Typical Node Count	≥ 8 nodes (normatively specified)	32 Unit Loads per segment	Practically unlimited	Transceiver-dependent	Transceiver-dependent	Transceiver-dependent
Maximum Payload per Telegram	Ethernet MTU (1500 bytes)	252 bytes	252 bytes	8 bytes	64 bytes	2048 bytes
Maximum Standardized Data Rate	10 Mbit/s	Baud-rate dependent	Ethernet dependent	1 Mbit/s	≥ 8 Mbit/s (implementation dependent)	20 Mbit/s
Real-Time Capability	Good (with PLCA)	Limited by polling cycle	Depends on network architecture	Excellent	Excellent	Excellent
Ethernet Native	Yes	No	Yes	No	No	Partially (Ethernet tunneling possible)

Typical Bus Length @ Bit rate

SPE 10BASE-T1S	130m@10MBit/s
Modbus RTU(RS-485)	100-200m@115.2kBits, 1200m@9.6kBit/s
Modbus TCP	100m@100MBit/s
CAN Classic	40m@1MBit/s, 250m@250kBit/s, 1000m@50kBit/s
CAN FD	20-40m@8Mbit/s, 100-250m@2MBit/s
CAN XL	not yet defined

Industrial Acceptance of SPE

SPE is attracting growing interest across a wide range of industries as companies look for a future-oriented, standardized communication technology. More and more organizations are evaluating SPE as a key element of their product roadmaps because it enables seamless data and power transmission over a single cable while supporting Ethernet communication from the sensor level to the cloud.

A key advantage of SPE is its ability to meet the requirements of different industrial sectors. In building automation, it supports smart buildings, HVAC systems, lighting, and energy management applications. In factory automation, SPE enables simplified machine connectivity and seamless integration into industrial Ethernet networks. In process automation, it helps connect field devices directly to higher-level systems while reducing installation complexity.

As industries continue to accelerate their digital transformation, SPE is increasingly recognized as an important communication technology for the future, providing a scalable and interoperable foundation for next-generation automation and intelligent infrastructure.

Industrial Automation

As automation advances, an increasing number of sensors and actuators are deployed across all areas of manufacturing. This growth requires a consistent, scalable, and time-critical network from IIoT devices to the cloud, with reliable components that can deliver Ethernet connectivity down to the individual sensor or actuator and device level. Single Pair Ethernet (SPE) is ideally suited for these applications, enabling direct, high-speed connections for devices such as barcode readers, cameras, user terminals, and detection sensors.

SPE eliminates the need for additional gateways, allowing uniform and interoperable networks that simplify system architecture and streamline data acquisition. Long distances of up to 1,000 m can be bridged while maintaining high transmission speeds, and with Power over Data Line (PoDL), both power and data can be delivered over the same two wires, removing the need for separate power lines. The result is faster and more reliable process control, higher plant availability, and a simplified, cost-efficient network infrastructure.



Figure 9: Example factory automation (Source: Weidmüller)

Building Automation

The integration of the Internet of Things (IoT) into building automation has become a critical aspect of the ongoing digital transformation, with its importance expected to rise further. By adopting the IP protocol, building automation becomes more streamlined and effective, as sensors, controllers, and other building technologies can be seamlessly connected to the building's system technology, even over long distances. This method replaces traditional proprietary fieldbus systems with standardized Ethernet cabling, thereby removing the need for expensive and intricate programming and parameterization. With the use of Single Pair Ethernet, additional gateways are no longer necessary.

In designing and developing smart buildings, there is a clear trend towards minimizing the energy consumption of all connected devices. Single Pair Ethernet is crucial in this context. It allows for the simultaneous transmission of high-performance data and power over a single pair of wires using Power over Data Line (PoDL).

Additionally, SPE components including connectors and cables, are engineered to be smart, durable, and efficient. SPE enables the integration of building systems like lighting, HVAC, and security into a unified network that is easy to install and maintain. The ability to support various transmission distances and rates, coupled with high packing density, makes this connection technology highly adaptable for nearly any system. SPE is transformative for IoT devices, allowing for compact, power-efficient designs with reliable Ethernet connectivity. This is vital for applications such as smart grids, smart cities, and home automation.



Figure 10: Example building automation (Source: Weidmüller)

Process Automation

In the process industry, Ethernet-compatible interfaces are increasingly needed to access data from the field via IIoT. There's the challenge that information is required from sensors and devices in the field, with large distances to be bridged. In addition, various IIoT devices must be integrated into the network infrastructure. The Single Pair Ethernet for the process industry is called Ethernet-APL, which is a dedicated definition of 10Base-T1L enriched with functional safety, which requires qualified components for a reliable data transmission at 10 Mbit/s and simultaneous power supply via twisted pair cable up to 1,000 m.

The Ethernet-APL (Advanced Physical Layer) technology enables direct access down to the field and device level via an internationally standardised two-wire solution. This requires powerful IIoT devices with qualified components. By this you will get an increased plant availability and production data: The collection, use, and analysis of data from devices in the field is possible easily to ensure and increase plant availability and to implement new solutions.



Figure 11: Example process automation (Source: Weidmüller)

Handling issues in current applications

RS-485 with Modbus RTU is a proven industrial multidrop communication system based on a differential balanced pair. Reliable operation depends on correct implementation of termination and biasing, which serve different electrical purposes.

Termination suppresses reflections caused by cable impedance discontinuities. RS-485 networks therefore require line termination at the two physical ends of the trunk cable, typically using 120-Ω resistors matched to the characteristic impedance of the cable. Termination must not be placed on stubs or intermediate nodes. Some Modbus implementations additionally use RC termination networks such as 120 Ω in series with 1 nF for improved EMC behavior.

Biasing, also called polarization, ensures a defined idle-state voltage when no transmitter is active. Without biasing, the RS-485 pair becomes electrically floating and susceptible to noise. Modbus therefore recommends a single bias network consisting of a pull-up resistor from D+ to +5 V and a pull-down resistor from D- to common, typically in the range of approximately 450–650 Ω. This bias network must exist only once within the entire segment, usually at the master node. Multiple bias networks increase bus loading and reduce signal margins. Modern failsafe RS-485 transceivers may integrate this function internally.

Compared with RS-485/Modbus RTU, 10BASE-T1S Single Pair Ethernet (SPE) is a significantly more modern multidrop physical layer standardized under IEEE 802.3cg. It operates at 10 Mbit/s over a single balanced pair and supports Ethernet-native multidrop communication with integrated IP capability, diagnostics, and protocol transparency.

A major advantage of 10BASE-T1S is PLCA (Physical Layer Collision Avoidance), which coordinates PHY-level transmit opportunities and greatly improves determinism, fairness, latency behavior, and bus efficiency on shared multidrop segments. Unlike RS-485, which depends on application-layer polling schemes such as Modbus RTU, 10BASE-T1S integrates collision management directly into the physical layer.

From an architectural perspective, RS-485 remains attractive for long-distance, low-cost, and highly robust industrial serial links, especially in existing Modbus infrastructures. However, SPE/10BASE-T1S is better suited for modern Ethernet-centric sensor and actuator networks where seamless IP integration, higher bandwidth, diagnostics, and convergence with industrial Ethernet systems are required. As industrial automation increasingly moves toward unified Ethernet architectures, 10BASE-T1S is becoming an important replacement candidate for classical RS-485 multidrop fieldbus segments.

7. Application Testing

The working group “PHY Interoperability and beyond” from SPEA took the opportunity to test the requirements set from the ASERCOM for their interoperability testing.

This resulted in a topology, which resembles the utilisation of 10BASE-T1S in a cabinet aisle commonly found in a supermarket where one device is further away from the aisle, (e.g. a control unit) and the other are set with the fronts towards each other connected via 4m long cables with a 20m connection representing the connection of both sides of the aisle.

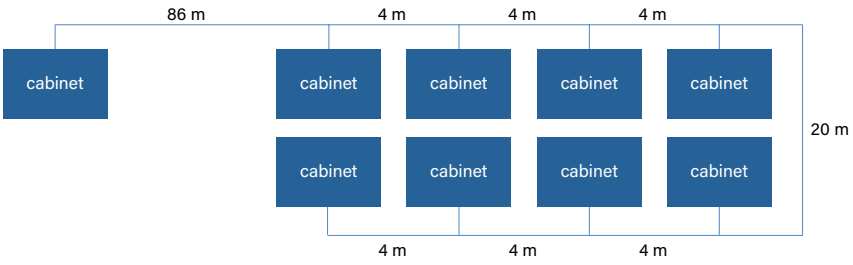


Figure 12: Super Market Topology

For this test three different PHY Vendors evaluation boards are used. This includes Analog Devices, Microchip and onsemi. Furthermore, the devices are connected via PROFINET SPE Cables (PROFINET Type B 1 Pair T1), based on a AWG-22 pair (compliant to IEC 61156-13 & -11) and connected with the new IEC 63171-7ED2 standard connector provided by Weidmüller. The devices use iperf2 for traffic generation as well as a test automation script to configure the nodes via UART (Universal Asynchronous Receiver/Transmitter) commands.

Test Scope, Methodology and results

The test focuses on the interoperability of devices from different vendors with the addition of going beyond the standard. Hereby the 100m of standard Ethernet is used as a benchmark for the devices to work with. Furthermore, additional devices are used, to enable going beyond the standard of “up to at least” 8 nodes and “up to at least” 25 meter.

To test the devices, a test automation is used, where each device is used in idle mode with a differential-mode-probe attaching the devices SPE interface to an oscilloscope, allows the creation of eye diagrams of the devices signal.

Eye diagrams are used to indicate the signal quality on a given device. The height indicates attenuation, the width a jitter which may occur due to reflections on the node. Therefore, the height and width of the eye indicate the signal quality and whether the device can receive the data on the wire due to timing shift caused by jitter or reflections or an insufficient threshold of the amplitude.

Fig. 13 shows the results of this test with the eye diagram matrix. Red marked eye diagrams show the eye diagram direct at the transmitter and the blue ones on the devices next to it from left to right and top-down ascending in device number from the topology.

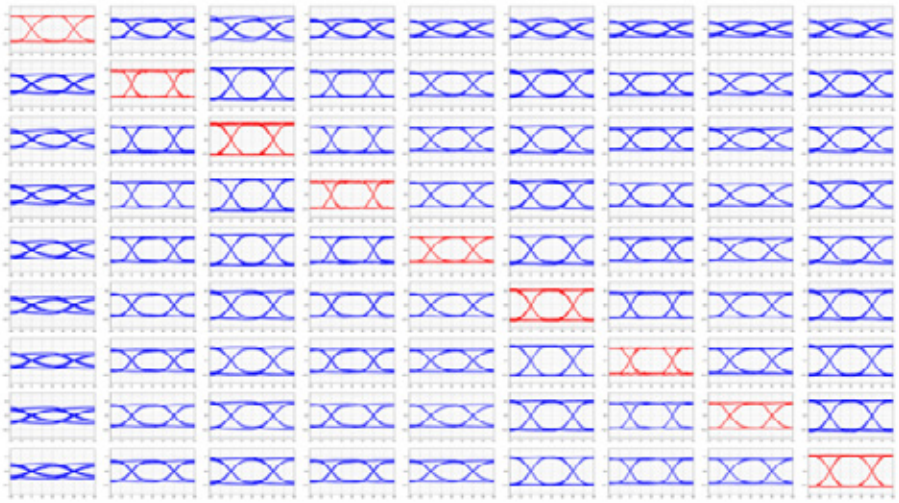


Figure 13: Eyediagramm

It is visible, that the long cable between device one and two led to a high attenuation. Furthermore, the widening of the “eyelids” indicates reflections/jittering. Whilst testing the link with a ping command, the devices were replying and the link was stable enough. Further tests with iperf2 showed that there was no packet loss seen in the worst connection. In this topology we used the connection between device from each party and have not had any bit errors whilst transmitting devices.

Variants of Test Setups

In addition to the prior mentioned test setup, another setup was tested, which comprises of 30 devices connected within 100m. This topology differs by using a longer connection of 86m between device three and four as well as short stubs of 50cm between the other devices, resulting in a topology with high reflections from the short stubs as well as a high attenuation due to the long distance between node three and four (see Figure 14).

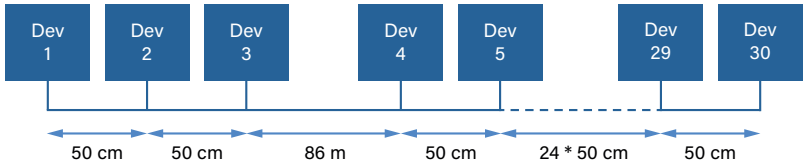


Figure 14: Alternative test setup

The iPerf2 measurement between devices from each party and have not had any bit errors whilst transmitting devices.

Key Technical Insights

The key result of the tests is that 10BASE-T1S is capable to be used in the given topology. Furthermore, it may be suitable to add additional Single Pair Ethernet technologies such as 10BASE-T1L for long distances or the upcoming 100BASE-T1L for distances of 500m and higher speeds as a backbone of cooling solutions in bigger markets. Additional tests with different topologies and wires (shielded/unshielded) will be done in the future. This also includes the usage of more application related software. This is needed to ensure, that devices can work as intended in a brownfield with existing wiring and given applications.

Single Pair Ethernet Association

The perfect pair.

The Single Pair Ethernet Association is a global, open network of leading technology companies and partners from research and academia across various industries and application areas. Together, they pool their know-how and expertise to drive the further development and adoption of Single Pair Ethernet (SPE). Through cross-industry collaboration, the promotion of international standards, and practical solutions, the Association supports the widespread adoption of SPE as a forward-looking technology for a connected world.

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