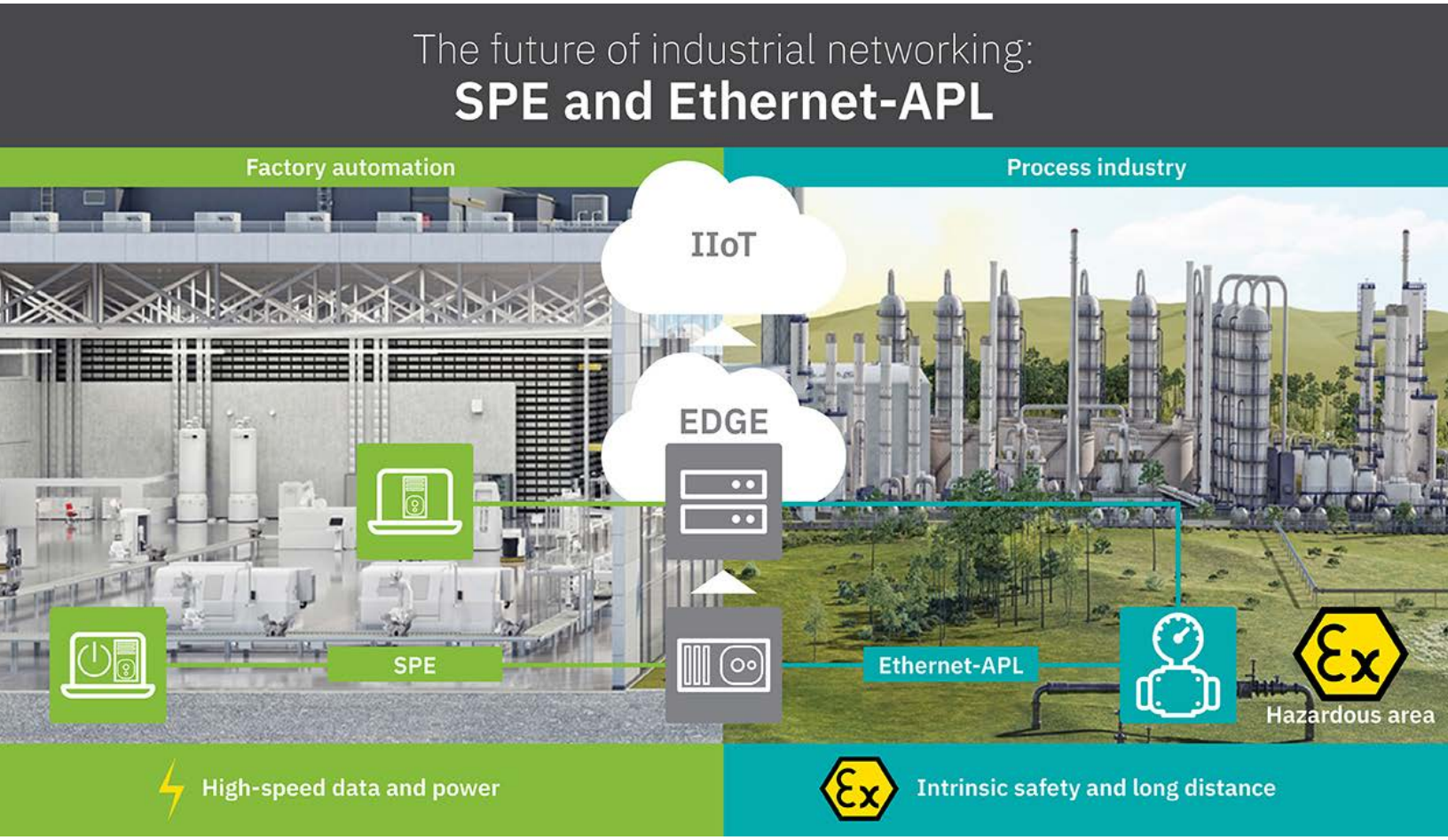

Figure 1: IEEE 802.3 Single Pair Ethernet (SPE) and Ethernet-APL present the natural evolution of Ethernet, engineered for industrial environments.

The future of industrial networking runs on Single Pair Ethernet (SPE) and Ethernet-APL

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Key takeaways:

- Single Pair Ethernet (SPE) is a true “field-to-cloud” Ethernet network
- SPE unlocks longer reach, simpler installations, and lower costs than traditional approaches, resulting in better data access
- Ethernet-APL is a subset of SPE designed to enable intrinsically safe operation in environments where standard SPE is not suitable

Introduction

Smart manufacturing has reached a tipping point. As digital transformation initiatives expand across factories and process plants, the limitations of traditional industrial networks have become increasingly visible, especially at the field level. Enterprise and control networks have largely standardized on Ethernet and IP technologies. However, the last mile of automation (sensors, actuators, and field instruments) has remained fragmented by legacy fieldbuses, gateways, and protocol conversions. Even at the distribution layer, where longer distances often drive fiber use, field serviceability, installation complexity, and the fragility of fiber in harsh industrial environments have posed additional challenges.

A new technology is transforming that reality: IEEE 802.3 Single Pair Ethernet (SPE), which establishes a unified Ethernet infrastructure from the field to the cloud. By enabling seamless, end-to-end communication across devices, systems, and networks, SPE eliminates traditional data silos and simplifies industrial architectures. This unified approach provides real-time visibility into operations, empowering teams with advanced diagnostics and predictive insights that improve uptime and efficiency. As a result, organizations can make faster, data-driven decisions while bridging the gap between factory and process environments — laying the foundation for a more connected, scalable, and intelligent industrial future.

Ethernet-APL (Advanced Physical Layer) or APL for short, extends Ethernet into hazardous and long-distance process applications, supporting intrinsically safe operation and cable lengths up to 1,000 meters for trunk links using a two-wire Ethernet connection. In parallel, IEEE 802.3 SPE enables high-performance Ethernet connectivity in space-constrained and sensor-dense environments, making it ideal for discrete manufacturing, infrastructure, and intelligent edge applications. Combined, SPE and APL form a complementary, standards based approach to extending Ethernet wherever industrial data is generated.

Built on IEEE 802.3 Ethernet standards and IEC-defined connector and physical layer specifications, SPE and APL are not proprietary technologies or niche solutions. They represent the natural evolution of Ethernet, engineered specifically for industrial environments, and designed to scale across factory automation, building infrastructure, transportation, utilities, and process industry applications.

This convergence is not about replacing existing Ethernet — it is about extending it. And it is rapidly becoming foundational for smart manufacturing use cases, such as asset health monitoring, predictive maintenance, and scalable Industrial Internet of Things (IIoT) deployments, from hazardous process areas to the most compact field devices.

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Why industrial networks must evolve

For decades, industrial automation architectures have been optimized for reliability and determinism rather than data accessibility. This led to layered communication models: fieldbuses at the sensor level, industrial Ethernet at the control level, and IT networks for analytics and enterprise systems. While functional, this approach introduces complexity, limits data availability, and increases total cost of ownership.

As industrial assets become smarter and more connected, these limitations increasingly conflict with the requirements of modern manufacturing and process operations. Condition monitoring, energy optimization, cybersecurity visibility, and AI-driven maintenance all depend on continuous real-time, high-quality data from the field – data that legacy fieldbus architectures struggle to provide.

SPE addresses these challenges by collapsing network layers, reducing infrastructure complexity, and delivering native Ethernet connectivity directly to field devices, regardless of environment or distance.

Common challenges with traditional field-level networking include:

- Limited bandwidth and rigid data models that restrict diagnostics and monitoring
- Complex gateways and protocol conversions that add latency and ongoing maintenance burden
- Separate cabling infrastructures for power and communication
- Difficulty scaling networks to support large numbers of sensors and IIoT devices
- High costs associated with fiber deployment or cabinet-dense architectures

What makes SPE different

SPE is not a single protocol but a family of Ethernet physical layers within IEEE 802.3, optimized for different distances, data rates, and application requirements. This is an expansion of the existing Ethernet-based standard that was originally designed for IT environments, where SPE is specifically tailored for industrial and automotive applications.

Key technological characteristics include:

- Long cable reaches up to 1,000 meters for SPE (10BASE T1L) and 500 meters for 100BASE-T1L that halves the distances by 10 times the bandwidth
- Easy retrofit of existing infrastructure by keeping the existing cabling in place
- Power over Data Line (PoDL) for SPE

This combination of simplicity, performance, and environmental suitability makes SPE uniquely capable of extending Ethernet deeper into industrial environments than ever before. Applications can range from building automation to the smallest sensors on the factory floor.

Ethernet-APL: Intrinsic safety and digitalization for oil & gas and process industries

While SPE addresses the needs of discrete manufacturing and infrastructure, Ethernet-APL (Advanced Physical Layer) extends the same Ethernet principles into the most demanding industrial environments. This is especially critical in the oil & gas, chemical, and process industries, where intrinsic safety and long-distance connectivity are non-negotiable. Ethernet-APL is based on IEEE 802.3cg 10BASE-T1L Single Pair Ethernet, but it adds a standardized physical-layer profile specifically designed for process automation. This profile incorporates intrinsic safety requirements, engineered power concepts, and topology rules that allow Ethernet to be deployed safely in hazardous areas, down to Zone 0 or Class I, Division 1.

A defining capability of APL is its ability to operate safely in hazardous environments through intrinsic safety built directly into the physical layer. This is enabled by the 2-WISE (Two-Wire Intrinsically Safe Ethernet) concept, which standardizes power and communication parameters to ensure safe operation in explosive areas. As a result, Ethernet-APL extends high-bandwidth, digital communication into zones traditionally limited to low-speed analog technologies, unlocking richer diagnostics, improved asset visibility, and more informed decision-making. By bridging the gap between IT and OT, Ethernet-APL provides a scalable, future-ready foundation for industrial digitalization and Industrial IoT.

Historically, process plants have relied on 4–20 mA and fieldbus technologies to meet explosion-protection requirements. While reliable, these systems severely limit bandwidth and data accessibility. Ethernet-APL removes this trade-off. This capability fundamentally changes what is possible in oil & gas and process environments. Instruments in hazardous areas can now provide continuous access to process variables, secondary parameters, and rich device diagnostics without gateways or protocol conversions. Maintenance and reliability teams gain visibility that was previously impractical, enabling asset health monitoring and predictive maintenance in areas where manual inspection was once the norm.

Equally important, Ethernet-APL aligns process industries with the broader trend toward Ethernet standardization across OT and IT. By using the same underlying communication principles as SPE and Industrial Ethernet, Ethernet-APL allows process data to integrate seamlessly with analytics platforms, MES systems, and cloud-based asset management tools, while supporting initiatives such as NAMUR Open Architecture (NOA) and Open Process Automation (OPAS).

Core benefits for original equipment manufacturers (OEMs)

Native Ethernet connectivity at the device level

SPE allows OEMs to integrate true Ethernet and IP communication directly into field devices, rather than terminating connectivity at a controller or gateway. Sensors, actuators, drives, and intelligent modules can become first-class Ethernet nodes, simplifying system architectures and enabling direct access to data for controllers, edge platforms, and cloud systems. This approach reduces reliance on protocol conversion, lowers integration effort, and aligns OEM products with modern Ethernet-based automation ecosystems. The higher throughput and lower overhead enable faster sampling rates and converging several sensors into a single package.

Unified power and data delivery

With Power over Data Line (PoDL), SPE enables OEMs to deliver power and data over the same single twisted-pair cable. Eliminating separate power connectors reduces wiring complexity, minimizes assembly steps, and lowers the risk of field installation errors. For compact devices and high volume products, this simplification supports cleaner mechanical designs and improved manufacturability.

Figure 2: This chart explains the technical specifications for different PoDL classes.

	IEEE 802.3bu										IEEE 802.3cg						Units
Class	**12 V unregulated**		**12 V regulated**		**24 V unregulated**		**24 V regulated**		**48 V regulated**		**24 V**			**55 V**			
Class #	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
$V_{PSE(max)}$	18				36				60		30			58			V
$V_{PSE(min)}$	6		14,4		12		26		48		20			50			V
$I_{PI(max)}$	101	227	249	471	97	339	215	461	735	1360	92	240	632	231	600	1579	mA
$P_{PD(max)}$	0,5	1	3	5	1	3	5	10	30	50	1,23	3,2	8,3	7,7	20	52	W

Longer reach without added network complexity

SPE supports Ethernet communication over distances of up to 1,000 meters, depending on the standard, without requiring repeaters or intermediate switches. For OEMs designing machines or systems with large physical footprints, such as conveyors, material handling systems, or distributed infrastructure, this capability simplifies product architectures. It reduces the number of external components required to support Ethernet connectivity.

Smaller, lighter, and more flexible device designs

Compact SPE interfaces, including IP20, M8, and M12 variants, allow OEMs to significantly reduce connector size and cable bulk compared to traditional Ethernet. This enables smaller enclosures, denser PCB layouts, and lighter devices. Such advantages are especially valuable in robotics, mobile machinery, embedded automation, and space-constrained sensor designs.

Lower system and BOM costs compared to fiber

By leveraging copper-based single pair cabling rather than fiber, OEMs can reduce the cost and complexity associated with optical transceivers, specialized connectors, and assembly processes. Over large production volumes, these savings scale quickly. This supports more competitive pricing while maintaining Ethernet performance and interoperability.

Enablement of smart, data driven products

Because SPE is standards based Ethernet, OEM devices can support advanced capabilities such as network based firmware updates, detailed diagnostics, continuous condition data, and secure communication. This allows OEMs to move beyond hardware only differentiation and support value added services, such as predictive maintenance, remote monitoring, and lifecycle optimization, to align with modern IIoT business models.

Core benefits for end users and system integrators

Power and data over long distances

SPE enables both power and data to be delivered over a single twisted-pair cable across distances far exceeding traditional Ethernet's 100-meter limit. In practice, this allows installation of sensors, actuators, and monitoring devices along long conveyor systems, pipelines, process units, utility corridors, or distributed production areas without additional power wiring, gateways, or intermediate cabinets. The result is faster deployment, reduced infrastructure cost, and greater flexibility in device placement.

Easier field installation than fiber

Compared to fiber Ethernet, SPE cabling is significantly easier to install and terminate in the field. No fiber splicing, polishing, or optical testing is required, allowing standard industrial electricians to complete installations without specialized tools or training. Being a copper-based technology, the cable is more robust than fiber that has glass or plastic core that can break. For system integrators, this reduces labor costs, minimizes scheduling risks, and shortens commissioning timelines, particularly in remote or harsh industrial environments.

Reduced maintenance complexity and downtime

Simplified cabling architecture means fewer connectors, fewer active components, and fewer potential points of failure. SPE connected devices are directly addressable over Ethernet, enabling remote diagnostics and faster fault isolation. For example, failing field instrumentation in a hazardous area or a motor sensor on a production line can be identified through Ethernet diagnostics before it causes unplanned downtime.

Lower cabling costs across large facilities

Single pair cabling significantly reduces material usage, cable tray congestion, and installation effort. In large factories, process plants, warehouses, or infrastructure projects with hundreds or thousands of field devices, these reductions translate into substantial cost savings over the entire system lifecycle. In retrofit scenarios, SPE can often leverage existing cables.

Scalable architecture for IIoT growth

Because SPE is based on open Ethernet standards, new sensors and devices can be added incrementally as operational needs evolve. Facilities can expand condition monitoring, energy management, or quality tracking initiatives without redesigning or replacing their existing communication infrastructure

Market adoption: The primary challenge — and why SPE is poised to follow (and exceed) the IO-Link trajectory

As with any new industrial networking technology, the primary challenge facing SPE is market adoption, not technical capability. SPE and, by extension, Ethernet APL are built on mature IEEE Ethernet standards, supported by a growing ecosystem of device, semiconductor, and infrastructure vendors. The technology itself is well understood, standardized, and proven in early deployments.

What remains is the familiar industrial journey from early adoption to mainstream acceptance.

This challenge is not unique. A clear and instructive parallel can be found in IO-Link. When IO-Link was first introduced, it was often viewed as "nice to have" — an incremental improvement over discrete I/O rather than a foundational technology. Adoption was initially slowed by questions around ROI, ecosystem maturity, and coexistence with existing architectures. Yet over time, the value proposition became undeniable. As sensors became smarter and data transparency more critical, IO-Link moved rapidly from optional to expected, particularly in automotive, packaging, and assembly automation.

SPE is following a similar adoption curve, but from a fundamentally stronger position.

Where IO-Link digitized the sensor interface, SPE digitizes the physical network itself, extending native Ethernet all the way to the device. It eliminates entire classes of gateways, protocol conversions, and parallel infrastructures.

Several factors suggest SPE adoption may ultimately be even more aggressive than IO-Link:

- Stronger pull from system level architectures: Digital twins, AI-driven analytics, and asset health monitoring require continuous, high-quality data streams that legacy fieldbus and discrete I/O architectures cannot easily support.
- Ecosystem alignment from the start: SPE is backed by IEEE, IEC, and major automation organizations, avoiding the fragmentation that slows many emerging technologies.
- Clear coexistence strategies: SPE does not force a rip-and-replace approach. It complements IO-Link, traditional Ethernet, and existing field infrastructure, enabling incremental adoption.
- OEM and silicon-level momentum: As SPE PHYs (physical layers), connectors, and devices become standard options in new designs, adoption accelerates naturally through product refresh cycles.

In doing so, SPE aligns directly with broader industry trends toward Ethernet convergence, IT/OT integration, and software-defined automation.

Perhaps most importantly, SPE adoption is being driven not by novelty, but by necessity. The growing gap between what modern industrial applications demand from networks — and what legacy architectures can deliver — is widening. As factories and process plants pursue higher sampling rates, richer diagnostics, and fully converged Ethernet infrastructures, the question shifts from if SPE will be adopted to where it will be deployed first.

Just as IO-Link became the default choice for intelligent sensors, SPE is positioned to become the default physical layer for Ethernet at the edge.

Why future factories will leverage SPE

Faster data, converged networks, and the age of AI and digital twins

The factories of the future will not be defined solely by automation. They will be defined by data fidelity, speed, and continuity from sensor to software. As artificial intelligence, machine learning, and digital twin technologies move from pilots into production, the requirements placed on industrial networks are changing fundamentally.

Digital twins depend on high-resolution, high-frequency data from the physical world. To accurately model assets, processes, or entire factories, data must be captured at faster sampling rates, transmitted with low latency, and contextualized across multiple systems. Legacy fieldbuses were designed primarily for cyclic control data. They were never intended to support this level of data throughput or transparency.

SPE addresses this gap by enabling direct, continuous Ethernet communication at the field level, eliminating the need for protocol conversions and data bottlenecks. SPE supports higher data rates in compact and sensor-dense factory environments.

As factories evolve, there is also a clear trend toward converged IT/OT networks. Maintaining parallel networks for control, monitoring, asset management, and analytics adds cost, complexity, and cybersecurity risk. SPE supports a single, standards-based Ethernet infrastructure capable of carrying control traffic, diagnostics, and analytics data simultaneously. This creates a consistent data fabric from field device to digital twin.

In practical terms, this convergence enables:

- Faster sampling and richer datasets for AI models
- Real-time synchronization between physical assets and virtual twins
- Closed-loop optimization where analytics insights can influence operations immediately
- Scalable architecture that supports incremental digitalization rather than disruptive upgrades

In the age of AI-driven manufacturing, data quality matters as much as data availability. SPE provides the physical layer foundation that allows factory networks to keep pace with the computational and analytical capabilities now being deployed above them.

About Phoenix Contact

Since 1923, Phoenix Contact has created products to connect, distribute, and control power and data flows. Our products are found in nearly all industrial markets. Sustainability and responsibility guide every action we take, and we are proud to collaborate with our customers to empower a smarter and better world for future generations. Together, we are creating a sustainable world based on our passion for technology and innovation.

For more information about Phoenix Contact or its products, visit **www.phoenixcontact.com**, call technical service at **800-322-3225**, or email **us-info@phoenixcontact.com**.