2025 ETHERNET ROADMAP

The Past, Present and Future of Ethernet

10 YEAR ANNIVERSARY EDITION

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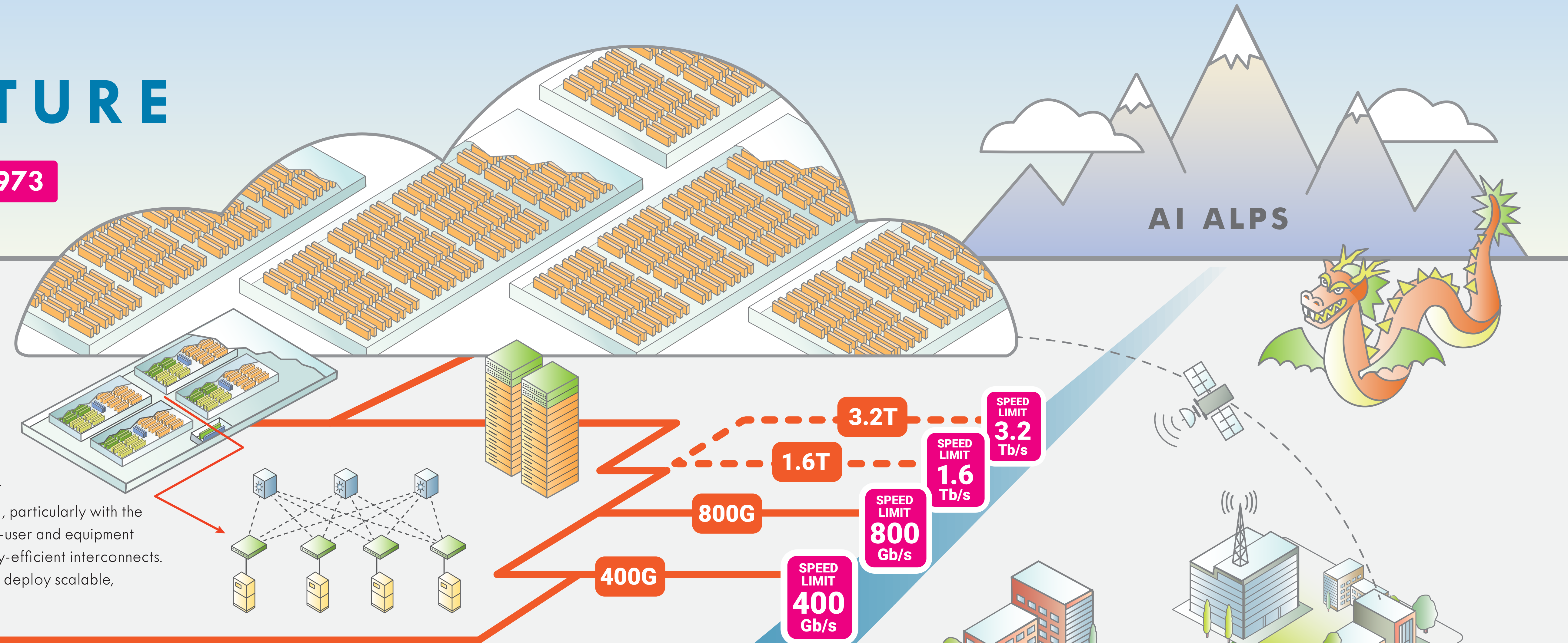
BACK TO THE FUTURE OF ETHERNET

EST. 1973

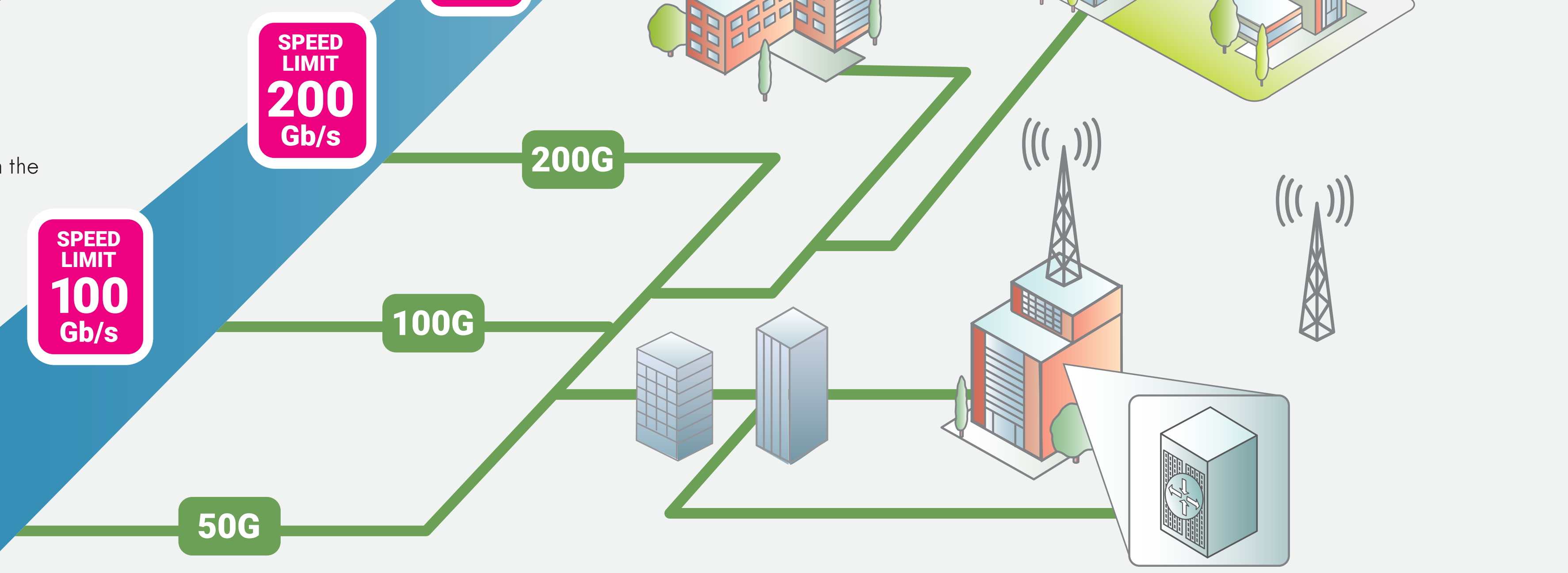


CLOUD PROVIDERS

Cloud providers widely adopted 10G servers in 2010 to support hyperscale data centers. By the 2020s, the growing demand for AI and Machine Learning applications required faster connectivity, leading hyperscalers to transition from 25G/lane speeds to 50G, 100G, and beyond. These warehouse-scale data centers utilize a diverse mix of active and passive copper cables, multi-mode and single-mode fiber, and emerging technologies like Linear Pluggable Optics (LPO) to support 100G, 200G, 400G, and 800G interconnects. The challenge remains balancing bandwidth growth with power efficiency and cooling innovations to sustain rapid scaling.

Over the past decade, the gap between Telco and Cloud provider networking needs has narrowed, particularly with the global expansion of 5G services. Historically, telcos drove technology advancements to match end-user and equipment demands, while cloud and hyperscale providers prioritized higher density, faster speeds, and energy-efficient interconnects. Today, the two sectors are more aligned than ever, fostering greater collaboration to develop and deploy scalable, high-performance networking solutions that meet both enterprise and consumer market needs.

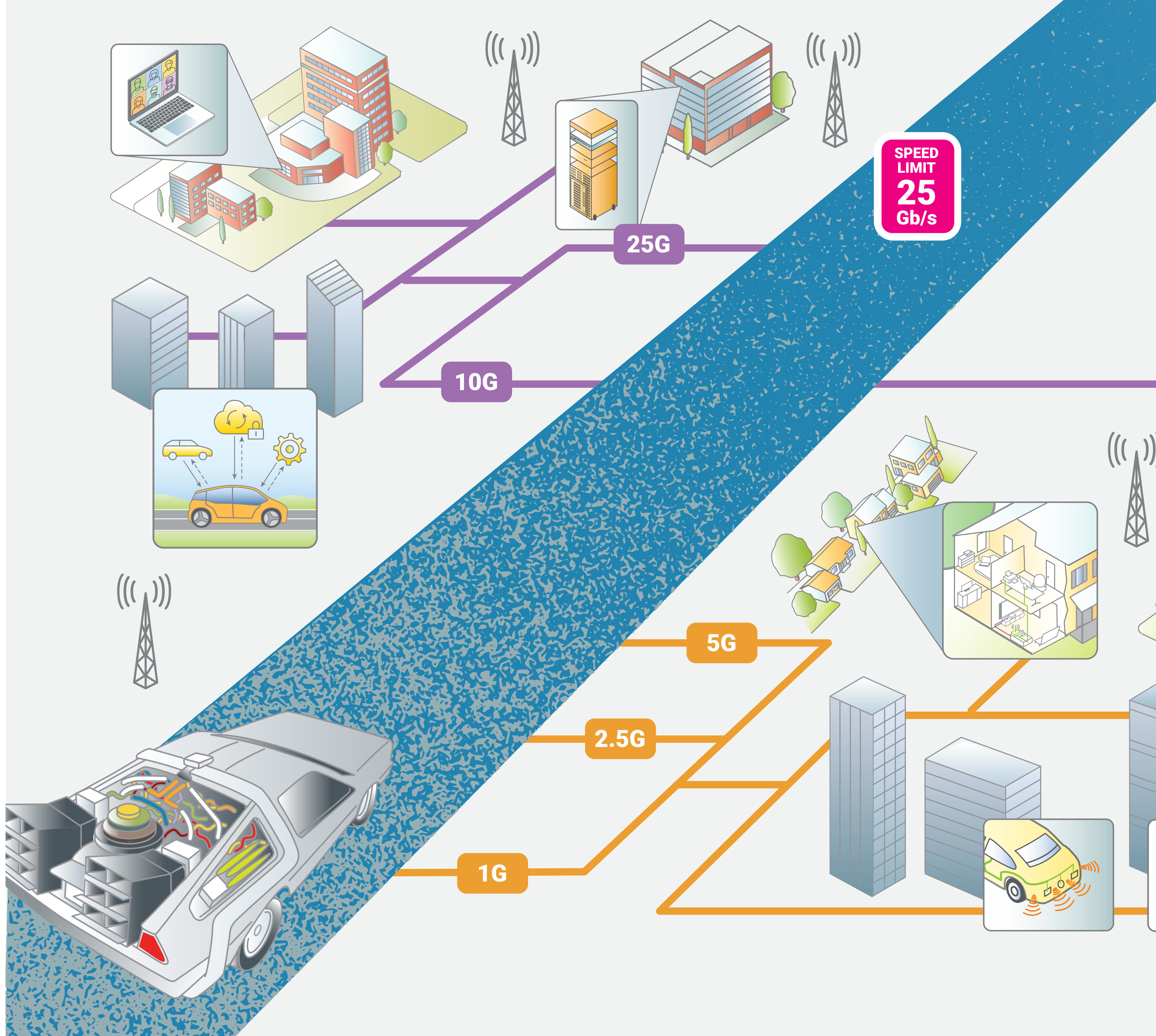
SERVICE PROVIDERS & ENTERPRISE



Service providers have long been at the forefront of high-speed Ethernet innovation, driving advancements in router connections, EPON, optical transport (OTN) client optics, and wired and wireless backhaul. The global rollout of 5G networks has intensified demand for fronthaul and backhaul solutions, accelerating Ethernet's evolution toward higher speeds and longer distances.

With consumer video consumption surging, bandwidth requirements show no signs of slowing. Service provider networks continue to push Ethernet speeds forward, with 1.6 Tb/s on the horizon to meet growing data demands. Synchronous Ethernet (SyncE) has become a cornerstone of 5G network synchronization, and its adoption is expected to expand significantly in the coming years as Telcos deploy next-generation services.

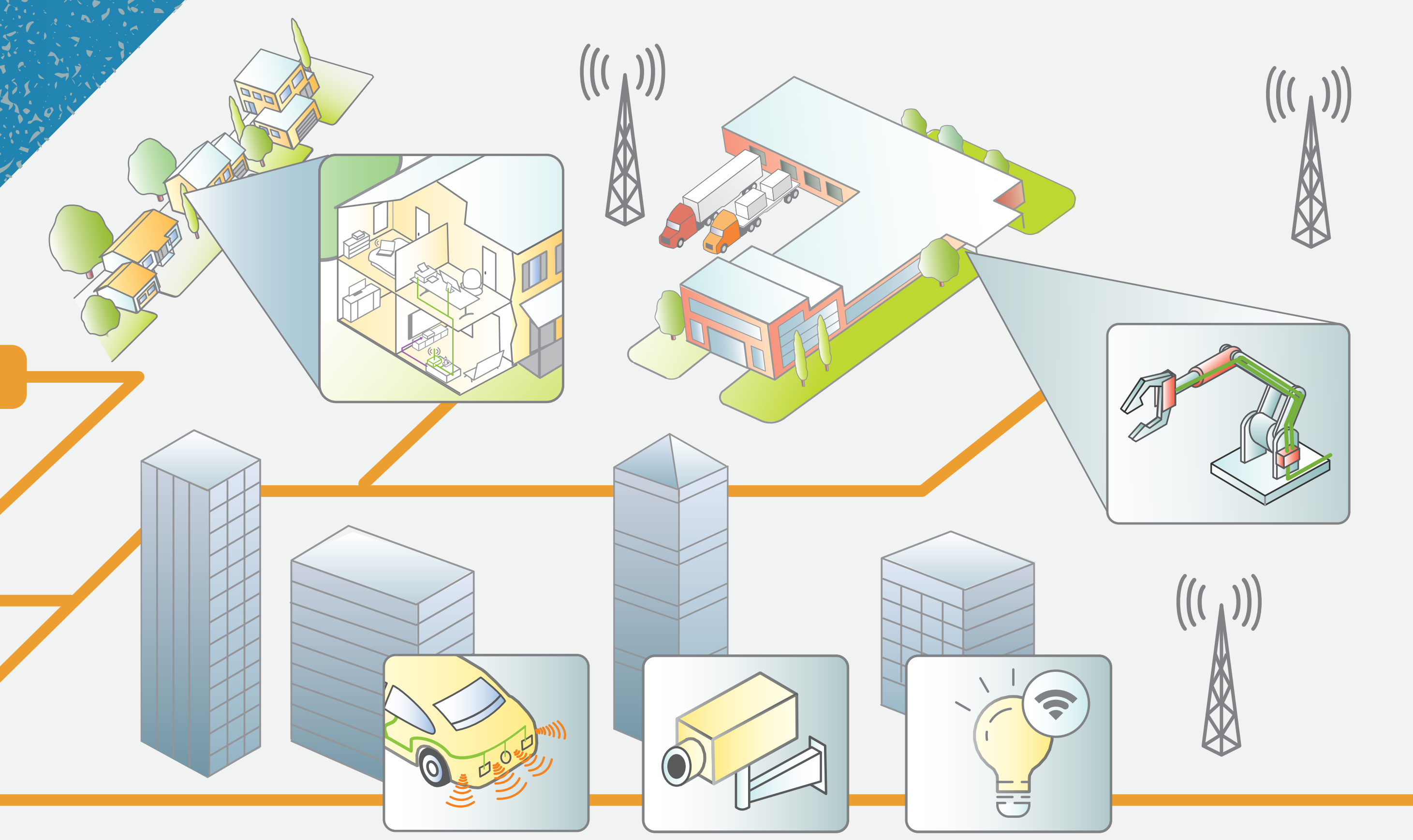
Enterprise and campus networks represent a massive market for Ethernet, with over a billion ports shipping annually. The majority of these ports are BASE-T at the access layer, while multi-mode (MMF) and single-mode fiber (SMF) support higher-speed connections deeper in the network. Evolving Wi-Fi access points and Enterprise-class client devices are accelerating the transition to higher-speed Ethernet. BASE-T ports are shifting from 1000BASE-T to 2.5G, 5G, and 10G BASE-T, while optical ports are rapidly advancing from 10G/40G to 25G, 100G, and 200G, ensuring greater capacity, efficiency, and future scalability.



AUTOMOTIVE, WI-FI, ENTERPRISE & 5G

Automotive industry is embracing Ethernet as the backbone of next-gen vehicle connectivity. Single-Pair Ethernet (SPE) enables cost-effective, scalable in-vehicle networking, supporting ADAS, autonomous vehicles, and infotainment while accelerating the convergence of legacy IVN technologies. A major shift to zonal architectures is reducing vehicle weight and complexity, while Time-Sensitive Networking (TSN) ensures deterministic, real-time communication for safety-critical applications. With software-defined vehicles (SDVs) on the rise and the rapid growth of the automotive Ethernet market, demand is surging for high-speed, low-latency networking. These advancements position Ethernet as the foundation for intelligent, connected transportation, delivering the performance, reliability, and scalability needed for the future of mobility.

As **Wi-Fi** 7 (802.11be) rolls out, Ethernet remains the backbone ensuring high-speed, low-latency connectivity for next-gen wireless networks. With multi-link operation (MLO), 320 MHz channels, and 4096-QAM, Wi-Fi 7 delivers faster speeds and improved efficiency, but reliable wired backhaul is essential to unlock its full potential. Ethernet's role in powering dense enterprise, industrial, and home networks continues to expand, supporting higher-speed access points (APs), lower latency, and seamless integration with 5G and fiber networks. The synergy between Wi-Fi and Ethernet is critical for enabling scalable, high-performance hybrid networks for the future.



AUTOMATION, 5G, AUTOMOTIVE & ENTERPRISE

The convergence of Ethernet, 5G, and automation is transforming industrial and building networks. 5G's wireless flexibility combined with Ethernet's reliability enables real-time, deterministic communication, crucial for Industrial IoT (IIoT) and smart automation. This synergy enhances network efficiency, scalability, and automation, paving the way for Industry 4.0 innovations.

Industrial and building automation applications are rapidly shifting from legacy fieldbus networks to Ethernet, accelerating the adoption of Interconnection, Information Transparency, Technical Assistance, and Decentralized Decisions—the core themes of Industry 4.0. Ethernet unlocks decades of IT networking advancements while delivering ruggedized physical layers like 10BASE-T1L, designed for harsh operational environments. Additionally, Time-Sensitive Networking (TSN) is revolutionizing real-time automation, bringing Ethernet back to its roots with 10/100 Mb/s speeds and shared media, now enhanced for modern industrial applications.

INTEROPERABILITY AND CERTIFICATION

The Ethernet Alliance is committed to building industry and end user confidence in Ethernet standards through its multi-vendor interoperability demonstrations and plugfests. Our PoE Certification Program takes this mission to the next level!

Our industry-defined PoE Certification Test Plan is based on the IEEE 802.3 (Ethernet) PoE standards, and products passing this test will be granted the Ethernet Alliance PoE Certification Logo. The trademarked logo provides instant recognition for products based on these standards, and increases multi-vendor interoperability between products bearing it. The logos indicate the power class and product type providing clear guidance on which devices will work with each other.

The first generation of the program (Gen 1) certifies Type 1 and Type 2 products that use 2-Pair wiring (PoE 1). The second generation of the program (Gen 2) certifies Type 3 and Type 4 products using 2-Pair and 4-Pair wiring (PoE 2). See table below for details:

PoE Types and Classes	PoE 1 2-Pair PoE – Type 1				PoE 1 2-Pair PoE – Type 2	PoE 2 4-Pair PoE			
Class	0	1	2	3	4	5	6	7	8
PSE Power (W)	15.4	4	7	15.4	30	45	60	75	90
PD Power (W)	13	3.84	6.49	13	25.5	40	51	62	71.3
		PoE 2 4-Pair PoE – Type 3						PoE 2 4-Pair PoE Type 4	

EA Certified™ | EA Certified 2.0™

https://ethernetalliance.org/poecert/

LATEST INTERFACES AND NOMENCLATURE

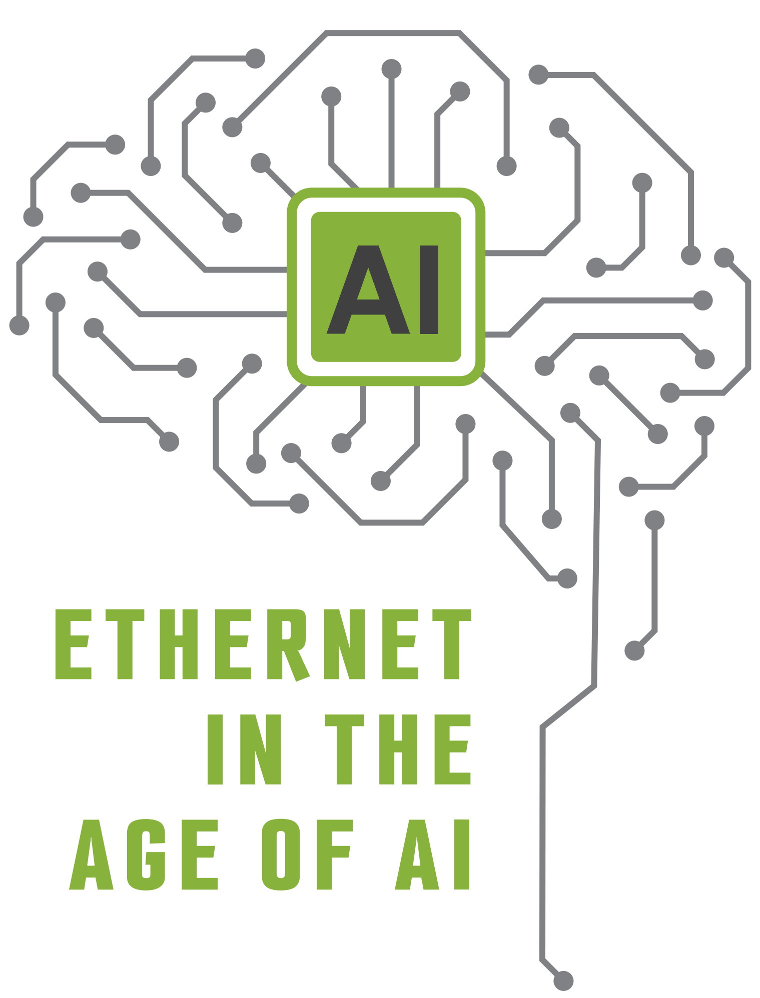
	Backplane	Twinax Cable	15-40m(OT) Single Twisted Pair	>100m (OT) Single Twisted Pair	100m (IT) Twisted Pair (2/4 Pair)	MMF	500m SMF	2km SMF	10km SMF	20km SMF	30 km SMF	40km SMF	80km SMF	Electrical Interface	Pluggable Module
10BASE–	T1S		T1S	T1L	T										
100BASE–			T1	T1L	T										
1000BASE–			T1		T										SFP
2.5GBASE–	KX		T1		T										SFP
5GBASE–	KR		T1		T										SFP
10GBASE–			T1		T	SR			LR BR10-D/U	BR20-D/U		ER BR40-D/U			SFP
25GBASE–	KR1 KR	CR1 CR/CR-S	T1		T (30m)	SR			LR EPON BR10-D/U	EPON BR20-D/U		ER BR40-D/U		25GAUI	SFP
40GBASE–	KR4	CR4			T (30m)	SR4/eSR4	PSM4	FR	LR4			ER4		XLAUI XLPPI	QSFP
50GBASE–	KR2 KR	CR2 CR				SR		FR	LR EPON BR10-D/U	EPON BR20-D/U		ER BR40-D/U		LAUI-2/50GAUI-2 50GAUI-1	SFP/QSFP
100GBASE–	KR4 KR2 KR1	CR10 CR4 CR2 CR1				SR10 SR4 SR2 VR1/SR1	PSM4 DR	CWDM4 FR1	LR4/ 4WDM-10 LR1	4WDM-20 LR1-20	ER1-30	ER4/4WDM-40 ER1-40	ZR	CAUI-10/CPPI CAUI-4/100GAUI-4 100GAUI-2 100GAUI-1	SFP/SFP-DD QSFP/QSFP-DD OSFP
100G–							DR1-LPO							LEI-100G-PAM4-1	
200GBASE–	KR4 KR2 KR1	CR4 CR2 CR1				SR4 VR2/SR2	DR4 DR1	FR4 DR1-2	LR4			ER4		200GAUI-4 200GAUI-2 200GAUI-1	QSFP/QSFP-DD SFP-DD
200G–							DR2-LPO							LEI-200G-PAM4-2	
400GBASE–	KR4 KR2	CR4 CR2				SR16 SR8/SR4.2 VR4/SR4	DR4 DR2	FR8 FR4 DR4-2 DR2-2	LR8 LR4-6/LR4-10		ER4-30	ER8	400ZR	400GAUI-16 400GAUI-8 400GAUI-4 400GAUI-2	QSFP/QSFP-DD OSFP
400G–							DR4-LPO							LEI-400G-PAM4-4	
800GBASE–	ETC-KR8/KR8 KR4	ETC-CR8/CR8 CR4				VR8/SR8 VR4.2/SR4.2	FR4-500 DR8 DR4	FR4 DR8-2 DR4-2	LR4 LR1	ER1-20		ER1	800ZR-A 800ZR-B 800ZR-C	800GAUI-8 800GAUI-4	QSFP-DD OSFP/OSFP-XD
800G–							DR8-LPO							LEI-800G-PAM4-8	
1.6TBASE–	KR8	CR8				VR8.2/ SR8.2	DR8	DR8-2						1.6TAUI-16 1.6TAUI-8	QSFP-DD OSFP/OSFP-XD

Gray Text = IEEE Standard Red Text = In Task Force Green Text = In Study Group Blue Text = Non-IEEE standard but complies to IEEE electrical interfaces

Orange Text = LPO MSA specification in early stages of standardization, not compliant with IEEE electrical interfaces.

Warning! The Ethernet landscape is evolving rapidly – technologies listed here are subject to change.

ARTIFICIAL INTELLIGENCE/MACHINE LEARNING (AI/ML)



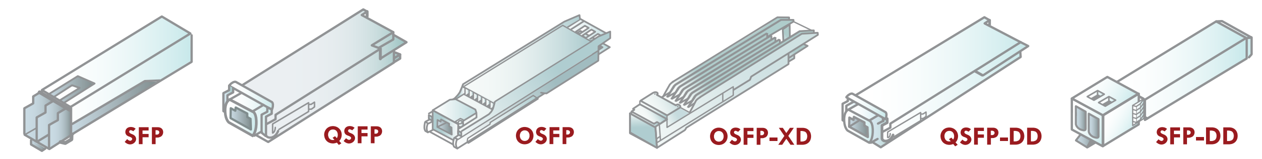
Artificial Intelligence is rapidly moving beyond 400G Ethernet speeds to support the training and inference of large language models (LLMs). AI and Machine Learning (ML) are driving the roadmap extending Ethernet speeds to 1.6T and beyond. The architecture within AI-driven data centers is evolving, leveraging a blend of copper and fiber solutions to meet AI's soaring bandwidth demands. Ethernet's progression towards higher speed interfaces, the widening variety of interconnect options, and advancements in power efficiency are ensuring that Ethernet can meet the needs of AI/ML workloads.

To address these demands, the **Ultra Ethernet Consortium** (UEC) is introducing the Ultra Ethernet standard, an open, interoperable, high-performance architecture tailored for AI. Supported by industry leaders across switch, networking, semiconductor, and system providers, as well as hyperscalers, Ultra Ethernet is designed to scale out AI infrastructures efficiently.

Complementing this, the **Ultra Accelerator Link** (UALink) standard focuses on "scale-up" within AI processing clusters to enable efficient communication between 10s to 100s of GPUs. UALink provides the communication primitives and the high-bandwidth, low-latency interconnects essential for the needs of these massive AI accelerator clusters. Together, Ultra Ethernet and UALink address the communications needs for the ever-growing scale of AI networks.

The Ethernet Alliance's latest **Technology Exploration Forum** (TEF 2024) highlighted the critical need for collaboration across the Ethernet ecosystem. Industry experts emphasized the importance of uniting different sectors to tackle the engineering challenges posed by the rapid advancement of AI. This collective effort is ensuring that Ethernet will continue to evolve to provide the network functionality required for next-generation AI networks.

INTERCONNECT TECHNOLOGIES



PLUGGABLE MODULES

Linear Pluggable Optics (LPO) and Linear Receive Optics (LRO)

The current high speed optical market is dominated by retimed optics, but there is rapidly growing interest in linear-based solutions for optical modules which can dramatically reduce the module power consumption. Linear Pluggable Optics (LPO) and Linear Receive Optics (LRO), also known as Transmit Retimed Optics (TRO) and Retimed Transmit Linear Receive (RTLR), are emerging module implementations which remove all/some of the retiming circuitry found in traditional optics.

These implementations utilize common pluggable form factors of QSFP, QSFP-DD, and OSFP and are primarily targeted at 400GbE and higher markets. A fully linear optic can operate at around half of the power of a similar retimed optic. LRO is a half-retimed solution which achieves some of the power reduction while providing a higher quality transmitted optical signal, which may make it an option in configurations where the hardware design cannot support a fully linear solution.

CABLE TECHNOLOGIES

Active Electrical Cable (AEC) – Integrated retimer electronics for signal enhancement
Active Copper Cable (ACC) – Integrated redriver electronics for signal boosting
Active Optical Cable (AOC) – Integrated optical transceivers for low-power, high-speed connectivity

Both AECs and ACCs are active cables providing data transmission over copper cables in applications where standard direct attach cable lengths are insufficient. ACCs provide basic signal boosting for increased cable reach in cost-sensitive applications, whereas AECs offer enhanced signal regeneration capabilities suitable for even longer distances.

AOCs integrate fiber optics and embedded transceivers, providing high-bandwidth, low-latency, and low-power connectivity for short- to medium-range interconnects in high-speed Ethernet applications.

ENERGY EFFICIENCY IN THE AI WORLD

- Blackstone estimates a **40% increase in electricity demand** in the United States over the next decade.[1]
- Gartner estimates the power required for data centers to run incremental AI-optimized servers will reach 500 terawatt-hours (TWh) per year in 2027, which is **2.6 times the level in 2023.**[2]
- The largest data center market globally is in northern Virginia, and the local utility, Dominion Energy, expects **power demand to grow by about 85% over the next 15 years,** with data center demand quadrupling.[3]
- SemiAnalysis forecasts Global Data Center Critical IT power demand will surge from 49 Gigawatts (GW) in 2023 to 96 GW by 2026, of which **AI will consume ~40 GW.**[4]
- By 2026, the AI industry is expected to have grown exponentially to consume at least **ten times its demand in 2023.**[5]

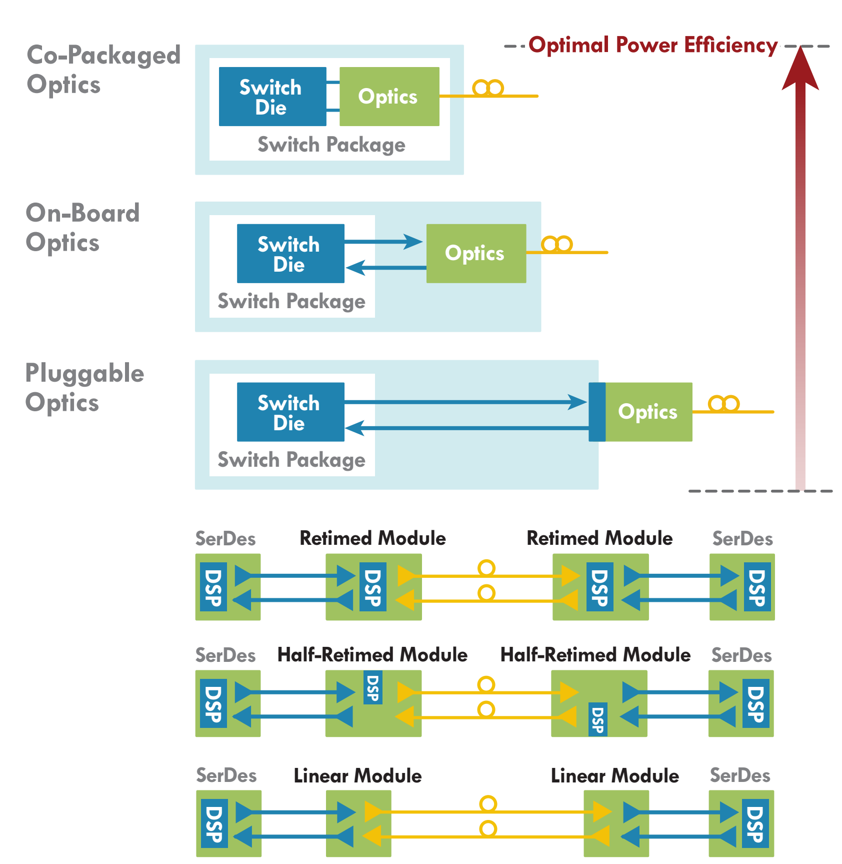
Provision of energy consumption to AI data centers is becoming a controlling limit. A GenAI-based prompt request consumes 10 to 100 times more electricity that a normal search.[5] Data centers will account for about ~2% global electricity use in 2025 and their power usage is expected to double to more than 1,000 TWh by 2030 driven by GenAI.[3]

Ethernet is not the biggest power consumer in the DC, but it is material. Any watt used on the network is a watt not used on the DC workload. It's expected that the Ethernet Industry will keep driving down the picojoules per bit with new technologies.

New PHY technologies, copper and optical interconnect advancements, and intelligent workload-aware traffic management are helping optimize energy use. Additionally, collaboration with AI-driven power management is emerging to further reduce energy waste. As Ethernet scales to 1.6T and beyond, balancing performance and energy footprint will be critical in supporting this global technology evolution.

1 "Blackstone (BX) Q2 2024 Earnings Call Transcript." The Motley Fool. July 18, 2024.
2 "Gartner Predicts Power Shortages Will Restrict 40% of AI Data Centers By 2027." Gartner. Nov 12, 2024.
3 "As GenAI Asks for More Power, Data Centers Seek More Reliable, Cleaner Energy Solutions." Deloitte. Nov 19, 2024.
4 "AI Data Center Energy Dilemma - Race for AI Data Center Space." SemiAnalysis. Mar 13, 2024.
5 "Electricity 2024 - Analysis and Forecast to 2026 Report." IEA. May 2024.

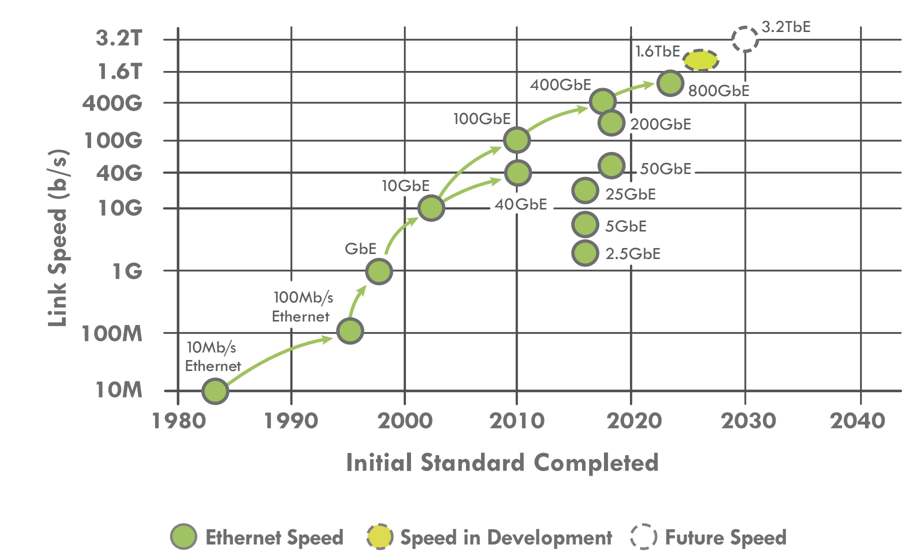
OPTICAL EVOLUTION



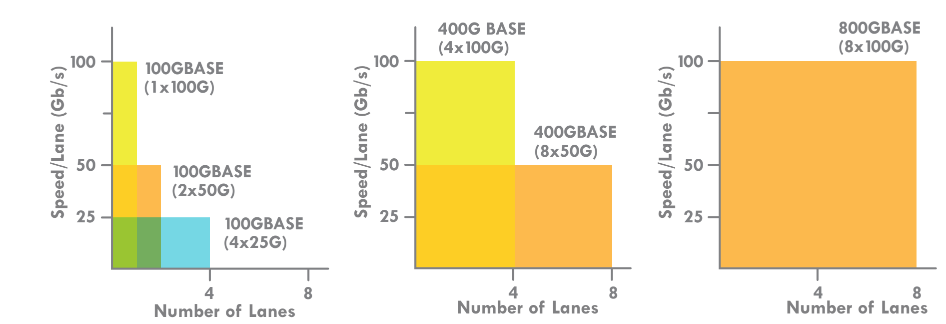
The ever-increasing demand for power efficiency in data centers is driving the transition to new interconnect solutions, such as **Co-Packaged Optics (CPO), On-Board Optics (OBO, and Linear Pluggable Optics (LPO).** As data centers deploy higher and higher link speeds, the power consumption of the optical module increases significantly. The need for reduced-power optical solutions is fueling innovation and creativity in this market.

To meet diverse deployment needs, **retimed, half-retimed, and linear optical modules** each offer varying levels of signal processing and power efficiency to optimize performance across different network architectures.

ETHERNET SPEEDS



FATTER PIPES

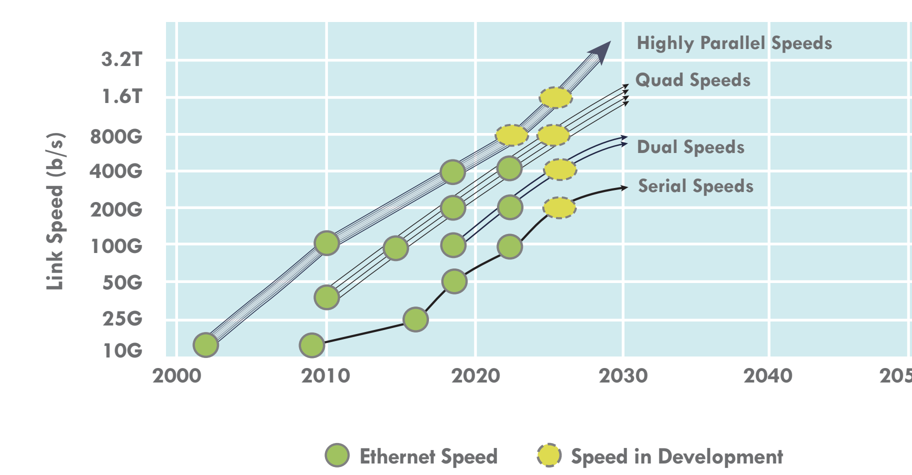


Total throughput (data rate) may be achieved in three general ways, and combinations of them:

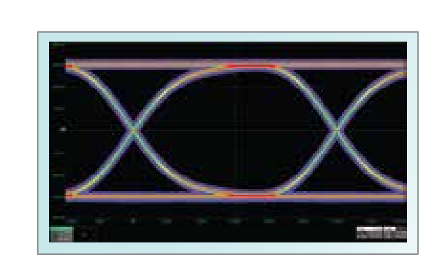
1 **Aggregating multiple lanes** 2 **Increasing the per lane bit rate**
3 **Increasing the bits transferred per sample (Baud)**

After data rate/lane is chosen, the number of lanes in a link determines the speed. See chart on how multiple lanes can be used to generate similar speeds.

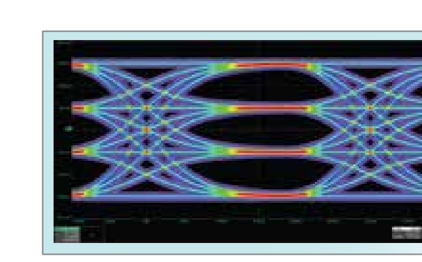
PATH TO SINGLE LANE



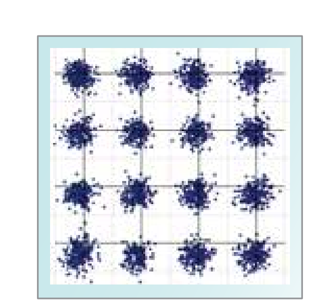
SIGNALING METHODS



NRZ



PAM4



Coherent

Signaling Method Transitions:

- Non-Return-to-Zero (NRZ) used for 25Gb/s per lane and below
- Four level Pulse-Amplitude Modulation (PAM4) for 50Gb/s per lane
- Coherent signaling (both in-phase and quadrature modulation) for 100Gb/s per lane and above.