Applications & Considerations for 10 Gigabit Ethernet & Beyond

White Paper

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Introduction

There have been a series of trends that have occurred over the past two decades that have resulted in skyrocketing bandwidth requirements for home, enterprise, and industrial networks. These trends include demands for higher speed home internet, enterprise push toward data-driven processes, and the ramp up of Industry 4.0 with a remarkably quick adoption of intelligent/networked systems. The latest trend permeating virtually all industries and markets is the furious exploration of artificial intelligence/machine learning (AI/ML). Each of these trends puts greater demands and pressure on Ethernet technology, which is largely considered the basic plumbing of the internet and digitally networked systems. Some sources have observed that bandwidth demands are growing by a factor of 10 every 5 years, which is 100-fold growth in a decade. This is why there has been the development of 10 gigabit Ethernet (GbE) in the early 2000s to terabit Ethernet (TbE) in the 2020s.

Where datacenters and connections between networking facilities may require extreme speed connections in the hundreds of gigabits and terabits, homes and many edge applications are still running on 1 GbE with 10 GbE just now becoming common.

These trends and trickle down of high-speed Ethernet technology has created an interesting landscape of solutions and considerations when installing new networking technology and systems. This whitepaper aims to educate readers in the basics of high-speed Ethernet and some of the interconnect considerations involved in deploying new networks or retrofitting old networks with high-speed Ethernet.

Cable Jacket Key Properties

Ethernet is a group of networking technologies that are designed to facilitate the communication of various devices over a local area network (LAN). Ethernet operates on the Data Link Layer of the open system interconnection (OSI) model, which is the conceptual model used to standardize data packet framing and enabling error-free communication. Where earlier versions of Ethernet used other physical layer interfaces, the main interface for GbE applications is Serial Gigabit Media Independent Interface (SGMII) or the reduced pin variant Reduced Gigabit Media Independent Interface (RGMII). The Media Access Controller (MAC) of an Ethernet network is responsible for the data framing and logical addressing functions where the Physical Layer (PHY) includes the encoding, decoding, and signaling of the physical data transmissions. The PHY interfaces directly with the physical medium, or interconnect, of the network. For high-speed Ethernet, these physical connections are either copper cables or fiber optic cables.

The overall bandwidth capability of an Ethernet connection is a combination of the interface width, or the number of lanes, and the rate per lane in gigabits per second. This configuration allows for some flexibility between individual link speed and the available number of lanes to achieve certain total data rates. There has largely been an acceptance in the networking industry for an 8-lane standard, though more or less lanes may be used in certain applications. This structure dictates the type of copper (CU) and fiber optic cabling that may be used in high-speed Ethernet applications, namely Cu Ethernet Cable, multi-mode fiber optic (MMF) cable, and single-mode fiber cable (SMF).

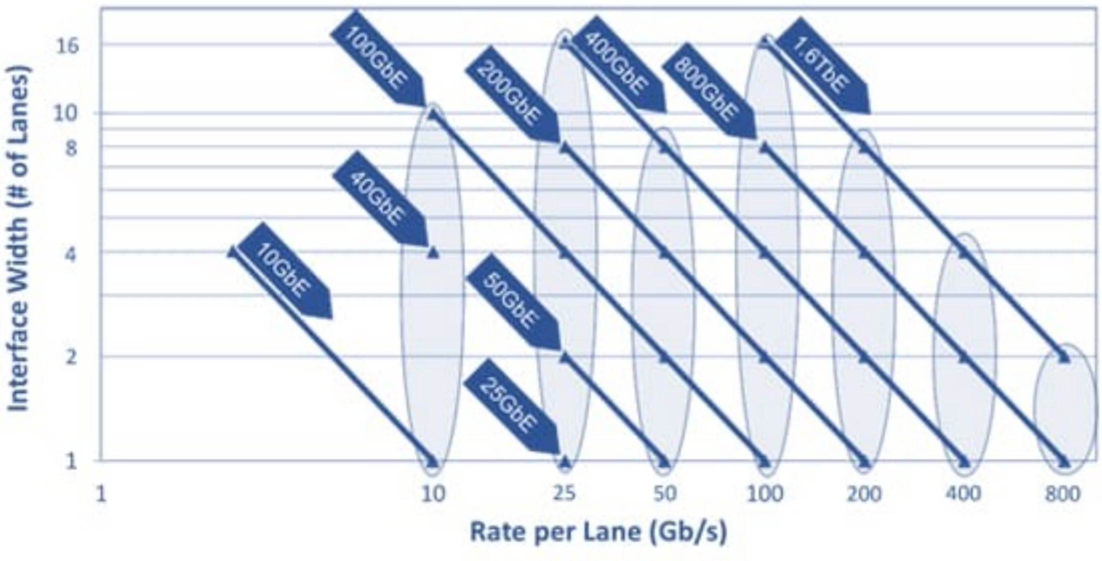


Image 1: The combination of interface width and rate per lane for 10 GbE to 1.6 TbE.
Source [1]

The designation for a type of Ethernet is the aggregate of the total port bandwidth, and high bandwidth ports can be created from lower rate lanes. For instance, a 50 GbE can be made of two 25 GbE lanes. As of the adoption of IEEE 802.3df™-2024, there is now a standardized x8 structure for 800 GbE, where dual 400 GbE links are already supported for single x8 copper or optical interconnect. This flexibility allows for an 800 Gb/s port to be based on combinations of 400 GbE, 200 GbE, or 100 GbE links configurations, which will likely continue forward as the 1.6 Tb/s Ethernet Task Force continues to develop the standard for the first generation of terabit Ethernet.

This flexibility is crucial as there is a shortening window between standardization and adoption for Ethernet standards in extreme throughput applications. For instance, it is predicted that AI/ML datacenter applications will be adopting the 800 GbE and 1.6 TbE standards just a year or two after official standardization (possibly sooner). This is why for rack-scale connectivity, 400 GbE is the de facto standard, where 800 GbE will soon gain prominence. For automotive applications, of which 100 Mbps and 1 GbE isn't uncommon, the future will likely see the replacement of legacy networking technology with 10 Mbps Ethernet for low bandwidth applications and up to 10 GbE for high bandwidth applications.

In the case of building automation and some industrial automation, 100 Mbps Ethernet is replacing a lot of legacy networking protocols with modern IP stacks. However, there are also trends in building/industrial automation where autonomous robotics and security systems are being deployed that are much more bandwidth heavy than the host of sensors and actuators common to these applications. The more advanced autonomous robotic and security systems are extremely bandwidth heavy, which is why 10 GbE and higher links may be needed to facilitate the data exchange between autonomous intranet and cloud infrastructure or remote operations when remote operation is required. This is a similar circumstance to medical applications that are becoming increasingly remote operated over high speed and low latency Ethernet connections, such as robotically assisted surgery (Robosurgery) and AI/ML assisted diagnoses systems.

Smart home early adopters are also moving to 10 GbE from 1 GbE, as smart home security/surveillance and automation systems with higher bandwidths are also becoming more popular. Like with enterprise automation, many of the common sensors and actuators used in smart home automation are relatively low bandwidth, but new security systems with multiple 4k camera streams and either cloud or edge AI/ML algorithms interpreting the data are often over burdening 1 GbE networking systems.

High-Speed Ethernet Interconnect Considerations

Ethernet interfaces and cables are available in a variety of configurations. The main two types are often designated as copper or fiber optic. Though there are also wireless links that can operate as Ethernet interconnects, that is outside of the scope of this paper. Copper-type Ethernet is what most laymen are familiar with, namely the RJ45 connector and 8 strand/4 twisted pair cable. This type of cable, sometimes called patch cable in certain computing applications, is mainly used for shorter interconnect runs (100 m or less) and where cost considerations are primary. Ethernet can also be carried on coaxial or twinaxial coaxial cable, but data rates or maximum interconnect distances in this application are limited as only a single channel is used.

Fiber optic cables can be either single-mode or multi-mode fiber. Multi-mode fiber uses a larger fiber core that can allow for more frequency channels and a wider range of fiber optic transceivers, but at the cost of range. Single-mode fiber can be bandwidth limited compared to multi-mode fiber but is a much more efficient optical waveguide allowing for far greater runs than multimode fiber. Typically, fiber optics are more expensive and complex than copper Ethernet solutions and specialized tools, equipment, and skills are needed to troubleshoot fiber optics.

The following table is an example of the types of Ethernet interconnect commonly available for 10 GbE:

10 Gigabit Ethernet Types

Ethernet Type	Standard	Transmission Media	Transmission Rate	Maximum Distance	Wavelength
10GBase-SR	IEEE 802.3ae	Fiber optic cables (MM)	10 Gbps	Up to 300m	0.85μm
10GBase-LR	IEEE 802.3ae	Fiber optic cable (SM)	10 Gbps	Up to 10km	1.3μm
10GBase-ER	IEEE 802.3ae	Fiber optic cable (SM)	10 Gbps	Up to 40km	1.5μm
10GBase-CX4	IEEE 802.3ak	Twin axial cables	10 Gbps	Up to 15m	-
10GBase-T	IEEE 802.3an	Unshielded twisted pair	10 Gbps	Up to 100m	-

The single mode fiber options have the greatest range of 10 km to 40 km, where the multi-mode fiber is limited to 300 m. The twisted pair ethernet cable is limited to 100 m and twinaxial cable solutions are only rated to 15 m.

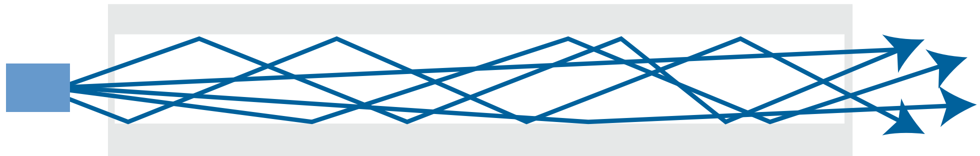
As Ethernet speeds have been increased, new categories of twisted-pair Ethernet cable have been created to accommodate these higher bandwidths. The latest category of copper Ethernet cable is Category 8.2 (Cat8.2), which is capable of 40 Gbps (40 GbE) up to 30 m.

The various generations of copper Ethernet cable are listed below:

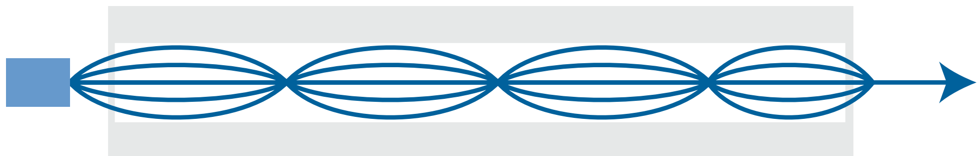
Category	Max. Data Rate	Bandwidth	Max. Distance	Application
Category 1	1 Mbps	0.4 MHz		Telephone/modem
Category 2	4 Mbps	4 MHz		LocalTalk & Telephone
Category 3	10 Mbps	16 MHz	100 m (328 ft.)	10BaseT Ethernet
Category 4	16 Mbps	20 MHz	100 m (328 ft.)	Token Ring
Category 5	100 Mbps	100 MHz	100 m (328 ft.)	100BaseT Ethernet
Category 5e	1 Gbps	100 MHz	100 m (328 ft.)	100BaseT Ethernet, residential homes
Category 6	1 Gbps / 10 Gbps	250 MHz	100 m (328 ft.) / @ 10 Gbps 37 m (121 ft)	Gigabit Ethernet, commercial buildings
Category 6a	10 Gbps	500 MHz	100 m (328 ft.)	Gigabit Ethernet in data centers and commercial buildings
Category 7	10 Gbps	600 MHz	100 m (328 ft.)	10 Gbps Core Infrastructure
Category 7a	10 Gbps / 40 Gbps	1000 MHz	100 m (328 ft.) / @ 40 Gbps at 50 m (164 ft.)	10 Gbps Core Infrastructure
Category 8	25 Gbps (Cat8.1) / 40 Gbps (Cat8.2)	2000 MHz	30 m (98 ft.) / 25 Gbps/40 Gbps	Core Infrastructure

It can be seen from these standardized specifications that copper Ethernet cable isn't designed for extended interconnect lengths, and future copper Ethernet cables will likely continue this trend of sacrificing maximum distance for greater bandwidth. This has to do with the intrinsically higher losses that twisted pair transmission lines have at higher frequencies. Moreover, even with shielded twisted pair transmission lines there is still some signal leakage and ingress of interference. These factors are significant limiters, along with copper transmission losses, which prevent higher bandwidth usage of these cables at greater lengths.

Fiber optic cable, switches, and fiber transceivers operate using optical lasers or diodes over optical waveguides. The optical fiber is the waveguide that contains the transmitted lightwaves. Matching the fiber optic core to a specific frequency range of light can allow for incredibly efficient transmission, which is why single-mode fiber optics have the greatest range of common networking interconnect technologies.



Multimode - Step Index



Multimode - Graded Index

Multimode - Step Index

Image 2: A comparison of multi-mode and single mode light transmission through optical fiber. The single mode step index smoothness is exaggerated as there is still bouncing occurring, just more optically for single mode fiber.
Source (https://rfindustries.com/fiber-optic-cable-types-multimode-and-single-mode/)

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Optical Mode (OM) Multi-mode fiber optic cable types

Type	Jacket Color	Core Size (um)	Data Rate	Optical Source	Min. Modal Bandwidth (850 / 953 / 1300 nm)	Applications
OM1	Orange	62.5	1 Gbps / 10 Gbps	LED	200 / – / 500 MHz·km	Short-haul networks, Local Area Networks(LANs) & private networks
OM2	Orange	50	1 Gbps / 10 Gbps	LED	500 / – / 500 MHz·km	Short-haul networks, Local Area Networks(LANs) & private networks
OM3	Aqua	50	1 Gbps / 10 Gbps / 40 Gbps / 100 Gbps	VCSEL	1500 / – / 500 MHz·km	Larger Private Networks
OM4	Aqua	50	1 Gbps / 10 Gbps / 40 Gbps / 100 Gbps	VCSEL	3500 / – / 500 MHz·km	High-Speed Networks, Data Centers, Financial Centers and Corporate Campuses
OM5	Lime Green	50	10 Gbps / 40 Gbps / 100 Gbps	VCSEL	3500 / 1850 / 500 MHz·km	High-Speed Networks, Data Centers, Financial Centers and Corporate Campuses

Like with twisted pair Ethernet cable, multi-mode fiber optic cable of earlier generations is capable of operating at higher data rates, but with limited range. The latest multi-mode fiber generation, OM5, is capable of operating to 100 GbE at 150 m range. OM5 cable is back compatible with earlier OM generations, but also features several advancements. Mainly, OM5 cable is wideband, allowing for wavelengths ranging from 850 nm to 950 nm. This covers several optical multi-mode fiber channels. Moreover, OM5 specifications reduce the overall attenuation within the waveguide pair compared to OM3/4. This allows for longer runs at even higher throughput. Though most common specifications for OM5 are only designated to 100 GbE, there are more capable variants available to 400 GbE, and 800 GbE variants will become more widely available in the near future.

Optical Mode (OM) Multi-mode fiber optic cable Ethernet range				
Type	1 GbE	10 GbE	40 GbE	100 GbE
OM1	275 m	33 m	--	--
OM2	550 m	82 m	--	--
OM3	550 m	300 m	100 m	100 m
OM4	550 m	550 m	150 m	150 m
OM5	--	550 m	440 m	150 m

Single mode fiber (SMF) is either optical single mode one or two (OS1/OS2). OS1 is primarily designed for shorter range indoor environments, such as within a data center, where OS2 is designed for robust outdoor applications for extended runs. To transmit higher data rates with SMF, multi-core cables are used, allowing for several separate lanes.

Though cabling is a critical consideration for fiber optic Ethernet, fiber optics also require transceiver modules. The fiber optic cable connects to the transceiver modules which are then connected to the Ethernet switches and other networking hardware. This differs from twisted pair Ethernet cable, which is often RJ45 connectors that directly plug into the networking equipment. The optical transceiver modules convert the electrical signals to and from the networking equipment to optical/light signals carried by the fiber optic cabling. There are several optical transceiver form factors that are generally compatible from various vendors based on a Multisource Agreement (MSA). These common form factors are Gbic, SFP, SFP+, CFP, CFP2, CFP4, and QSFP28. Moreover, there are range related types of transceivers, either short range at 850 nm (SR), long range at 1310 nm (LR), extended range at 1550 nm (ER), or further extended range at 1550 nm (ZR).

Fiber optic cables can have two fiber optic waveguides with two connections to each transceiver, a receiving and transmitting side, or a bi-directional transceiver capable of transmitting and receiving on the same optical waveguide (fiber). Wavelength division multiplexing (WDM) systems, either coarse or dense, are used to carry several wavelengths of light over the same fiber. Hence, when selecting fiber optic equipment, it is essential to match the networking hardware with transceivers and cabling to ensure compatibility and that each element of the interconnect is capable of meeting the link specifications.

Conclusion

The networking equipment and hardware landscape is a mix of several generations of various Ethernet technologies. Where advanced applications in AI/ML, high-performing computing, and massive enterprise networks may make use of the latest Ethernet generations and capabilities, there are many networking applications that are just now seeing 10 GbE, while 1.6 TbE is soon to be on the shelves. 100 GbE is still only common in high performance networking applications with 400 GbE emerging and 800 GbE on the horizon. It is critical for networking professionals to have an understanding of these new Ethernet standards and the diverse range of interconnect hardware that make these technologies possible.

References

1. https://standards.ieee.org/beyond-standards/ethernets-next-bar/