Fibre Channel Connectivity

Cabling Storage Area Networks

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FIBRE CHANNEL INDUSTRY ASSOCIATION

This paper discusses Fibre Channel links from 1 Gigabit Fibre Channel (1GFC) to 128GFC.
From insertion loss estimates to link lengths, this paper gives a good overview of
fiber optic cabling in storage area networks.

Fibre Channel standards define the links and protocols that form storage area networks (SANs). The Fibre Channel protocol runs on Fibre Channel, Ethernet and long haul (optical transport) links. Each Fibre Channel link has different characteristics and this paper will focus on links within the data center. The fiber optic cabling infrastructure is the same for Ethernet and Fibre Channel, but significant differences do exist. Fibre Channel has been standardized to support a wide variety of cabling connectivity solutions.
Fiber Optic links are defined by four main parameters:

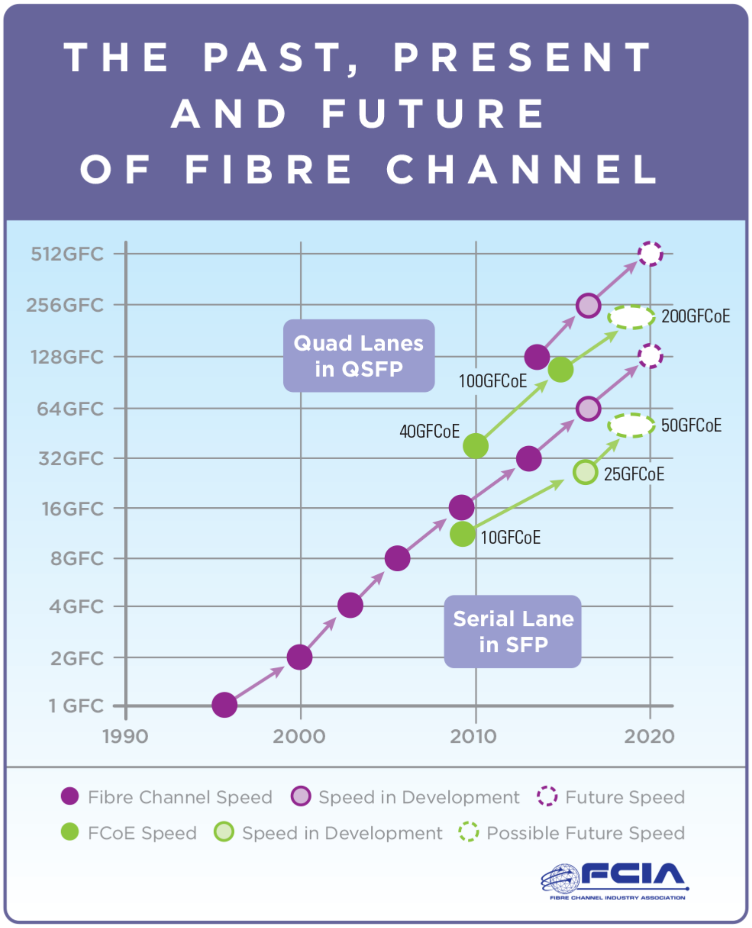
1) Speed
2) Distance
3) Reflectance
4) Insertion Loss

These four parameters define links that connect two ports through cabling infrastructure. Millions of Fibre Channel links are installed each year and most are less than 100 meters long. Fibre Channel links may span over 10 kilometers at billions of bits per second or Gigabits/second (Gb/s). This paper will focus on the most common types of links in SANs. The Fibre Channel Industry Association has developed *The Fibre Channel Roadmap* to explain Fibre Channel in an easy to understand and visually pleasing manner. Download your copy of the roadmap at www.fibrechannel.org/roadmap.html

Speed

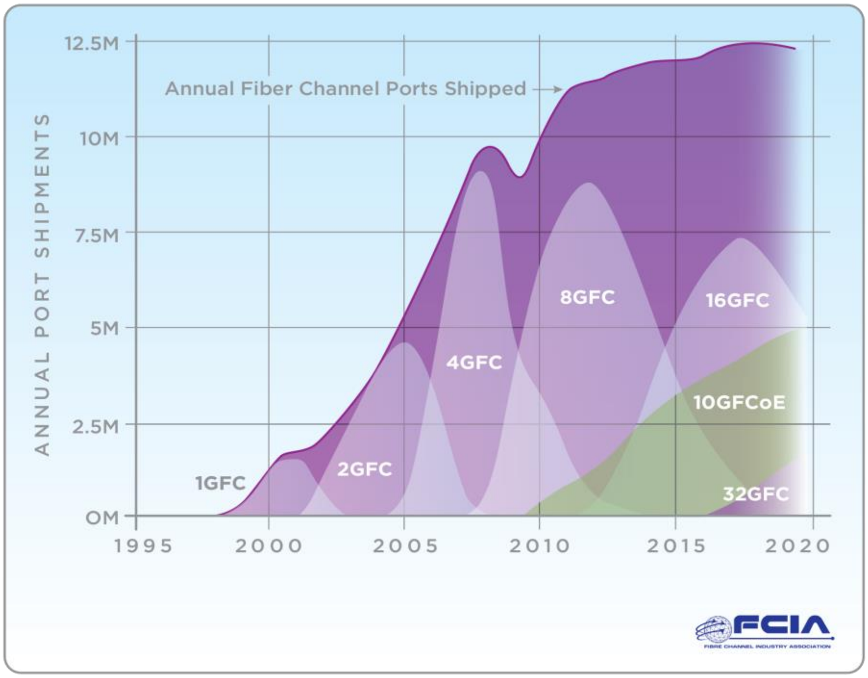
When people think of Fibre Channel, they usually envision high-speed fiber optic links between servers and storage. The speed of the links continues to double every few years and Figure 1 summarizes speeds used within data centers. This figure shows Fibre Channel speeds and the most common Ethernet speeds used for Fibre Channel over Ethernet (FCoE).

Figure 1: Fibre Channel Speeds



Fibre Channel rapidly develops new speeds and these speeds have replaced previous speeds as shown in Figure 2. Fibre Channel started shipping 1 Gigabit/second Fibre Channel (1GFC) in 1998 and 1GFC ports stopped shipping in about 2004. 2GFC was shipping in high volume in 2005 when 4GFC was being released. This obsolescence of one speed when another speed was about to be released has continued through the years but the speeds began to overlap more as speeds began to live longer as a wider variety of applications were addressed by Fibre Channel.

Figure 2: Fibre Channel Port Shipments

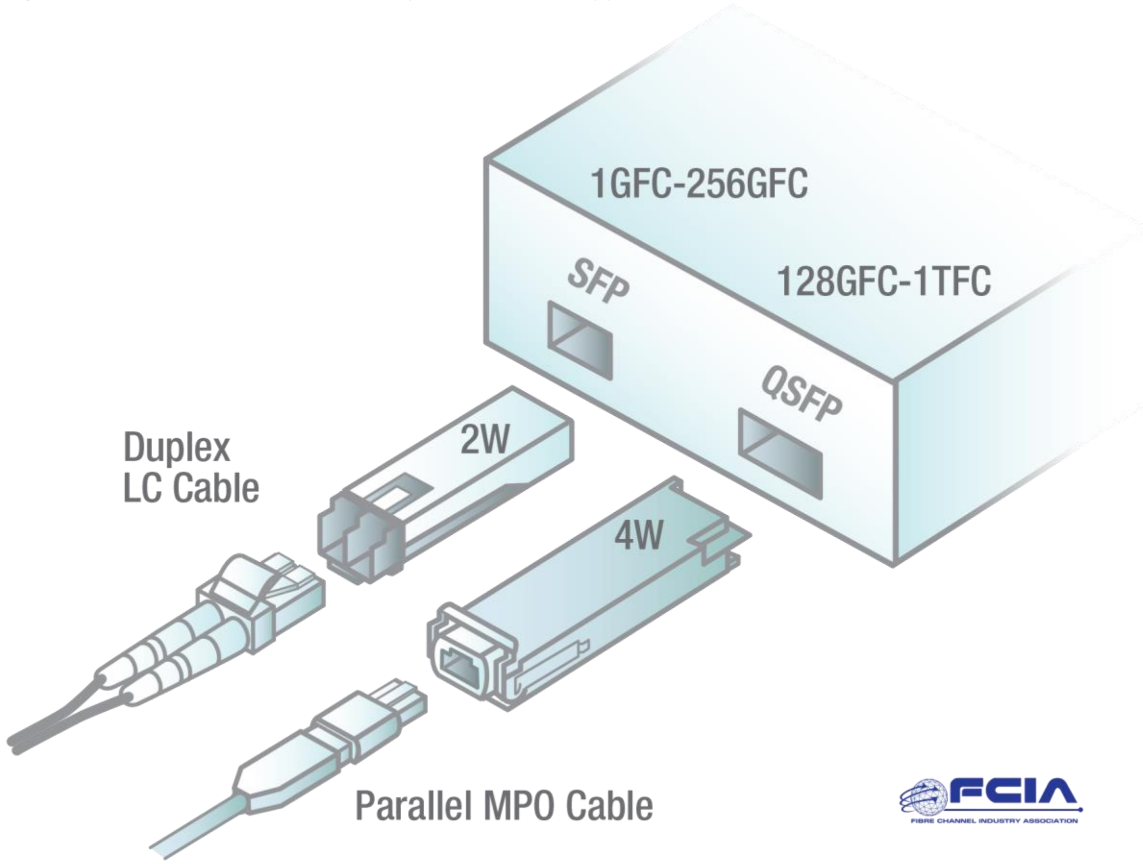


Source: Dell'Oro SAN Forecast Report and The Fibre Channel Roadmap

Another aspect of Fibre Channel, not shown in these charts, is how a Fibre Channel port can support multiple different fiber optic modules or transceivers that run at different speeds and distances. Figure 3 shows the two types of fiber optic modules used in Fibre Channel. Some implementations also use copper-based direct attach cables (DACs). 1GFC to 32GFC use Small Form factor Pluggable (SFP) family of modules that ship in very high volumes. SFP modules were designed to run up to 5 Gb/s, so SFP+ modules were defined for operation on 8GFC, 10GFC, 10 Gigabit Ethernet (10GbE) and 16GFC. To run above 16GFC, the SFP28 was defined to operate at up to 28Gb/s and it is used for 32GFC and 25GbE. 50GbE and 64GFC should also be able to use SFP28 modules. Three generations of SFP (SFP, SFP+, SFP28) have been defined with better signal integrity performance for continually increasing speeds.

The Quad SFP (QSFP) has four electrical parallel lanes that support higher speeds like 40GbE, 100GbE and 128GFC. Gen6 Fibre Channel is the term used for 32GFC, 128GFC and other technologies released as the 6th generation of Fibre Channel. The QSFP form factor was originally defined to support up to 5 Gb/s per lane like the SFP. 40GbE requires the QSFP+ and the QSFP28 supports 128GFC and 100GbE. The QSFP28 is also expected to support 200GbE and 256GFC; two standards that are currently being defined. Similar to SFP, QSFP has three generations of QSFP, QSFP+ and QSFP28 based on the maximum speed that the module supports.

Figure 3: Fiber Channel Fiber Optic Module Types



Distance

Fibre Channel typically uses multimode fiber (MMF) for intra-data center links and single-mode fiber (SMF) for inter-data center links. Mainframe deployments usually require SMF for all links within and between data centers. Figure 4 shows the reach of present and future speeds of Fibre Channel over various generations of Optical Multimode (OM) fiber. The fourth generation of multimode fiber (OM4) is required for operation over 100 meters for 32GFC.

To go longer distances, single-mode fiber (SMF) is required. Figure 5 shows the distances supported by single-mode fiber. Every single lane speed up to 32GFC has supported 10 km of fiber. To reduce the costs of some SFP+ modules, some modules use lower cost components that support shorter distances than 10km. 128GFC supports 500 meter links with parallel single-mode (128GFC-PSM4) fiber and 2km over duplex SMF (128GFC-CWDM4). Many optical module vendors have exceeded the standards and support distances over 10km. Consult individual suppliers for supported distances beyond 10km over SMF with coarse or dense Wavelength Division Multiplexing (WDM).

Figure 4: Multimode Fiber Link Distances

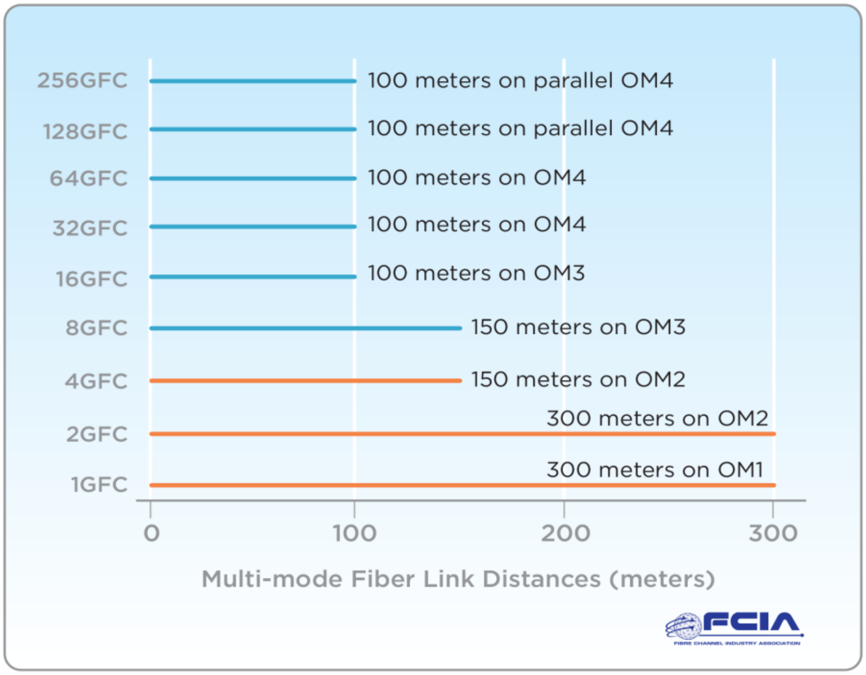
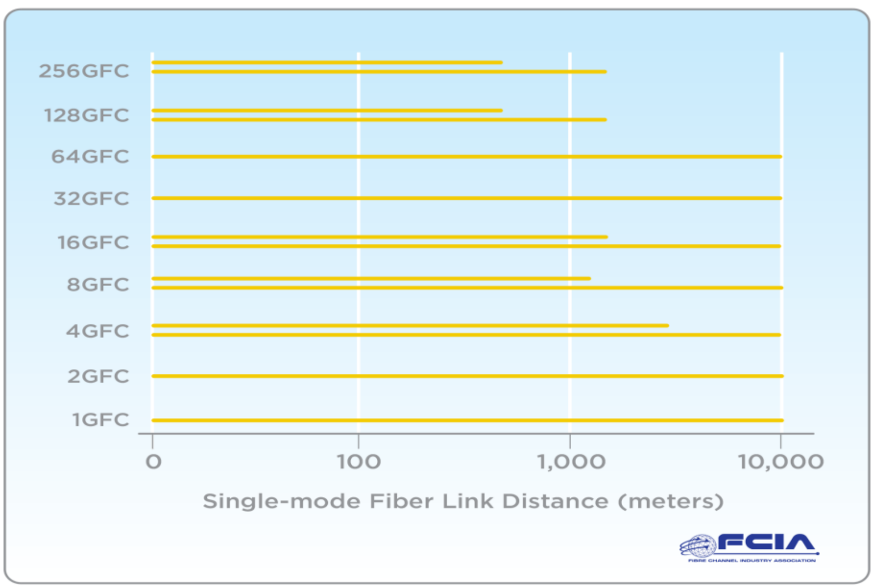


Figure 5: Single-mode Fiber Link Distances



Ethernet links used for FCoE are summarized in Table 1. Ethernet uses both copper twinax cables and the same fiber optic cabling.

Table 1: Ethernet Links and Distances

	Twinax	MMF	SMF
10GbE	15m	300m on OM3	10km
25GbE	3 and 5m	100m on OM4	10km
40GbE	7m	150m on OM4	10km
100GbE	5m	150m on OM4	500m, 2km, 10km

Reflectance

The reflectance, or return loss, of the link defines how much light is reflected back into the transceiver. Light reflected back into the receiver can cause feedback in the laser and may cause bit errors. The reflectance of the cable plant is usually specified to -23dB for MMF. For single-mode fiber links, the reflectance requirement is -26dB. 128GFC-PSM4 requires angle polished connectors at the module interface.

Insertion Loss

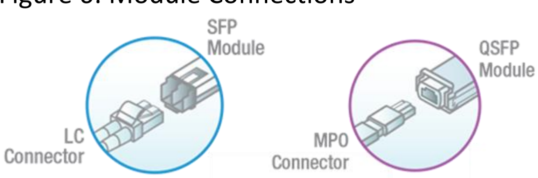
Insertion loss in a link depends on the number of fiber optic connections and the length of the link. Fibre Channel links are defined so that the initial connection to the SFP or QSFP module, as shown in Figure 6, are not considered part of the insertion loss of the link. The insertion loss of the link is the sum of connector loss and fiber loss or attenuation as shown in equations 1-3.

Equation 1: Insertion Loss (dB) = Fiber Loss + Connector Loss

Equation 2: Fiber Loss (dB) = link length (km) * Fiber Loss per distance (dB/km)

Equation 3: Connector Loss (dB) = Sum of Loss of Intermediate Connections + Splice Losses

Figure 6: Module Connections



The best way to determine the insertion loss of a link is to measure the link with an optical power meter. If measurements are unavailable, then estimates for the connector loss and the fiber loss can be made based on vendor specifications. The fiber loss can be estimated by measuring or estimating the link distance in feet or meters and converting to kilometers.

The fiber loss plays a small role in the insertion loss, so a fairly accurate fiber loss will be fine if the estimate is within 20 meters of the actual length. To calculate the fiber loss, multiply the kilometer distance by the fiber attenuation according to Table 2.

Table 2: Fiber Attenuation

Fiber Type	Fiber Attenuation (dB/km)
Multimode Fiber	3.5 dB/km
Single-mode Fiber	0.5 dB/km

For MMF links, the connector loss usually dominates the insertion loss of links. Connector loss is the sum of losses from intermediate connections and splices in a fiber optic link. Splices are typically only used in long-distance single-mode connections that leave the data center. Splices are often used to connect SMF trunk cables to pigtailed LC or MPO connections. Most MMF connections are factory terminated and professionally polished to connector grades summarized in Table 2.

Table 2: Grades of Multimode Fiber Connections

	Grade A	Grade B	Grade C
Maximum Loss (dB)	0.25	0.5	0.75
Max Loss for >97% (dB)	<= 0.2	<= 0.40	<= 0.60
Mean Loss (dB)	<= 0.1	<= 0.20	<=0.30
Description	Premium Factory Polish	Standard Factory Polish	Standard Field Polish

To estimate the connector loss of a link, identify the number of splices and connections in the link and the loss of each in dB. Then add the loss of the connection up to get a rough estimate of the connector loss. While a worst case, back of the envelope calculation shows four Grade B connections would have 2.0dB of loss (four connections at 0.5dB/connector), the statistical analysis presented in Technical Committee T11 as 15-265v0 shows that 99.53% of links with four Grade B connectors would have less than 1.5dB of connector loss. This statistical analysis works because connector grades have a maximum loss measurement, but the mean or average connector loss is 40% of the maximum loss. Many optical modules also exceed the standard and most links do not go the full distance of the specification, so the links can operate with higher loss than the standard specifies.

This statistical analysis shows that virtually all Fibre Channel links with four Grade B connections will work over the supported distance. Statistics also show that up to eight Grade A connections will have less than 1.5dB of connector loss. While worst case analysis of the max connector loss is quick and dirty, many links are deployed today that use four Grade B connections to support trunk cables.

Fibre Channel MMF links are standardized with 1.5dB of total connector loss except for 128GFC-SW4 which has a connector loss of1.0dB. Higher connector loss is supported, but the supported link length and insertion loss depends on the connector loss. Table 3 shows the insertion loss for multiple speeds and OM3 and OM4 MMF. The column with 1.5dB of connector loss is highlighted because the link length for this connector loss is most commonly discussed and standardized. The 1.5dB of connector loss can support 10 connections with 0.15dB/connection or 2 connectors with 0.75dB/connection. If the connector loss is higher or lower than 1.5dB, the link works for a different length that is shown table 3. OM1 and OM2 fiber are not recommended for Fibre Channel.

Table 3: Insertion Loss of Multimode Fibre Channel Links

Distance (m) / Insertion Loss Budget (dB)*					
	Connector Loss				
	3.0dB	2.4dB	2.0dB	**1.5dB**	1.0dB
4GFC with OM4	200 / 3.72	300 / 3.49	370 / 3.34	**400 / 2.95**	450 / 2.63
4GFC with OM3	150 / 3.54	290 / 3.45	320 / 3.16	**380 / 2.88**	400 / 2.45
8GFC with OM4	50 / 3.18	120 / 2.83	160 / 2.58	**190 / 2.19**	220 / 1.80
8GFC with OM3	35 / 3.13	110 / 2.80	125 / 2.45	**150 / 2.04**	180 / 1.65
16GFC with OM4	N/A	50 / 2.58	100 / 2.36	**125 / 1.95**	150 / 1.54
16GFC with OM3	N/A	40 / 2.54	75 / 2.27	**100 / 1.86**	120 / 1.43
32GFC with OM4	20 / 3.04	65 / 2.64	80 / 2.36	**100 / 1.86**	110 / 1.48
32GFC with OM3	15 / 3.03	45 / 2.64	60 / 2.24	**70 / 1.87**	80 / 1.41
128GFC with OM4	N/A	25 / 2.51	60 / 2.25	**85 / 1.94**	100 / 1.35
128GFC with OM3	N/A	20 / 2.48	45 / 2.17	**60 / 1.82**	70 / 1.46

*The Insertion Loss is the sum of the connector loss and the fiber loss. The insertion loss changes with the distance because of signal impairments and the fiber length, but the connector loss corresponds to the connector loss on the top column.

The insertion loss for single-mode links is considerably higher because SMF links are designed for much higher insertion loss because of the long distance of the link and more connections in multiple patch panels. SMF links have significant fiber loss when the links exceed 2km. Traditionally based on 2.0dB of connector loss, SMF links support a variety of link distance shown in Table 4. If a 10km fiber optic module is used in a 2km link, then additional connector loss can be supported in the link.

Table 4: Insertion Loss for Single-mode Fibre Channel Links

Link Type	Insertion Loss (dB)	Connector Loss (dB)
4GFC to 4km	4.8	2.0
4GFC to 10km	7.8	2.0
8GFC to 1.4km	2.6	2.0
8GFC to 10km	6.4	2.0
16GFC to 2km	2.6	2.0
16GFC to 10km	6.4	2.0
32GFC to 10km	6.34	2.0
128GFC to 500m (PSM4)	3.01	2.75
128GFC to 2km (CWDM4)	4.10	3.0

Structured Connectivity

Structured connectivity in Fibre Channel environments allows for rapid connection and cabling management of switches to servers and storage and enables data centers to plan for evolution and growth of IT infrastructure. Form meets function in structured connectivity to enable a higher level of infrastructure density without sacrificing manageability. With link loss budgets and connecter loss becoming more critical with each new generation of Fibre Channel, planning, preparation, and implementation of agile “any to any” connectivity is key.

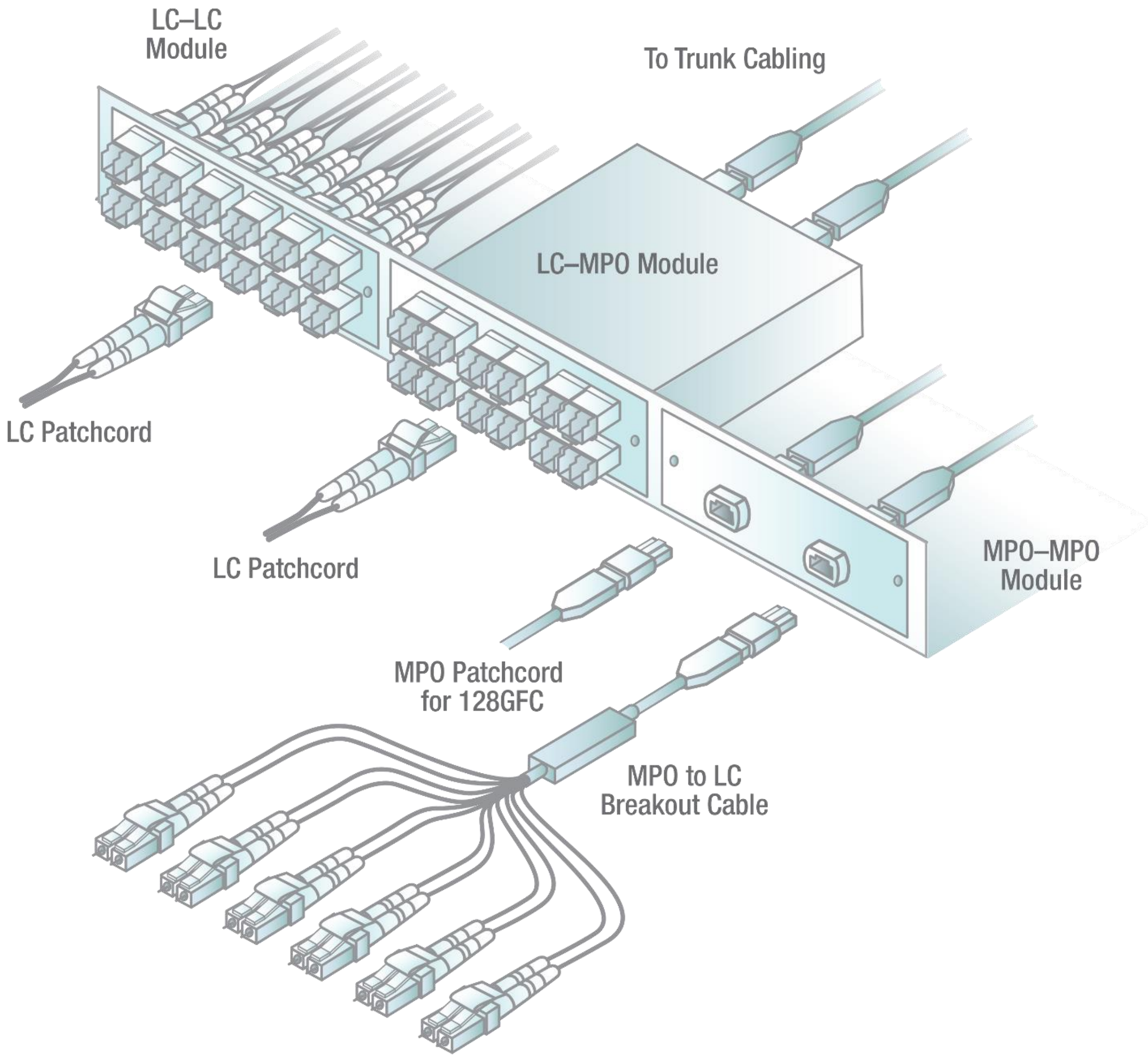
The result of structured connectivity is that all switches, servers and storage throughout the data center are represented by individual ports on the front of the patch panels in a centralized patching location often called the main distribution area (MDA). Connecting two ports is accomplished by a simple patchcord or jumper cable on the front side of the patch panels at the MDA, allowing for instant device to device connectivity. With this approach IT personnel never have to manipulate active equipment, such as director class switches, unless a hardware change is necessary.

Structured Connectivity or Cabling is the key to cable plant that is easy to document, manage, and grow with the current and future demands of Fibre Channel connections.

To facilitate structured cabling, intermediate link connections are made at patch panels to accommodate reconfigurations. The number and quality of these connections determine the connector loss of the link. Figure 7 illustrates how trunk cables are terminated at patch panels with MPO and LC connections. Trunk cables usually have between 12 and 300 fibers and extend over long distances within the data center. The trunk cables are terminated with LC or MPO connections that connect to the back of the patch panel.
In the 1 rack unit (1RU) patch panel drawn in Figure 7, three types of patch panel modules are supported. Each patch panel module shown supports 24 fibers in 12 duplex LC connectors or two 12-fiber MPO connectors. Here is a brief explanation of each patch panel module shown.

1. LC-LC Module – This type of patch panel module is also known as an LC Adapter Panel and requires trunk cables with LC termination. The LC-LC Module offers the lowest connector loss of any of the patch panel modules.
2. LC-MPO Module – This patch panel module is also called an MPO to LC Cassette and converts MPO trunk cables to LC connections. This module type has two connectors (an MPO in back and an LC in front) and is not currently available in Grade A. The MPO trunk cables can be installed quickly and up to four of these Grade B modules may be supported with less than 1.5dB of connector loss.
3. MPO-MPO Module – This patch panel module is also known as an MPO adapter panel and supports MPO trunk cables and each MPO connection supports 8-12 fibers. While MPO connectors can support up to 72 fibers (6 rows of 12 fibers), the most common MPO connector supports 12 fibers (Base-12) while 8-fiber (Base-8) versions are becoming popular to support 8-fiber QSFP implementations. A 12-fiber MPO-LC breakout cable can be used to connect up to 6 SFP+ optical modules. An MPO patchcord connects two 128GFC QSFP28 ports. The MPO-MPO Module can easily support 12 MPO connections and 144 fibers or more.

Figure 7: Patch Panel Modules and Connections



These three types of patch panel modules support trunk cables terminated with MPO or LC connections. The trunk cables plug in the back of the patch panel modules and LC or MPO patchcords connect to the front of the patch panel. This modular patch panel architecture enables easy installation and scales well. With standard LC interfaces, this modular patch panel architecture supports 36 LC connections in a 1U patch panel, but a 1U patch panel with 56 or more LCs. A 42RU rack full of these patch panel modules can support over one thousand fiber optic ports (42X36 = 1,512 LC ports). The number of LC ports in a patch panel rack is usually limited to a few hundred ports to allow easy cable management and troubleshooting.

Link Types

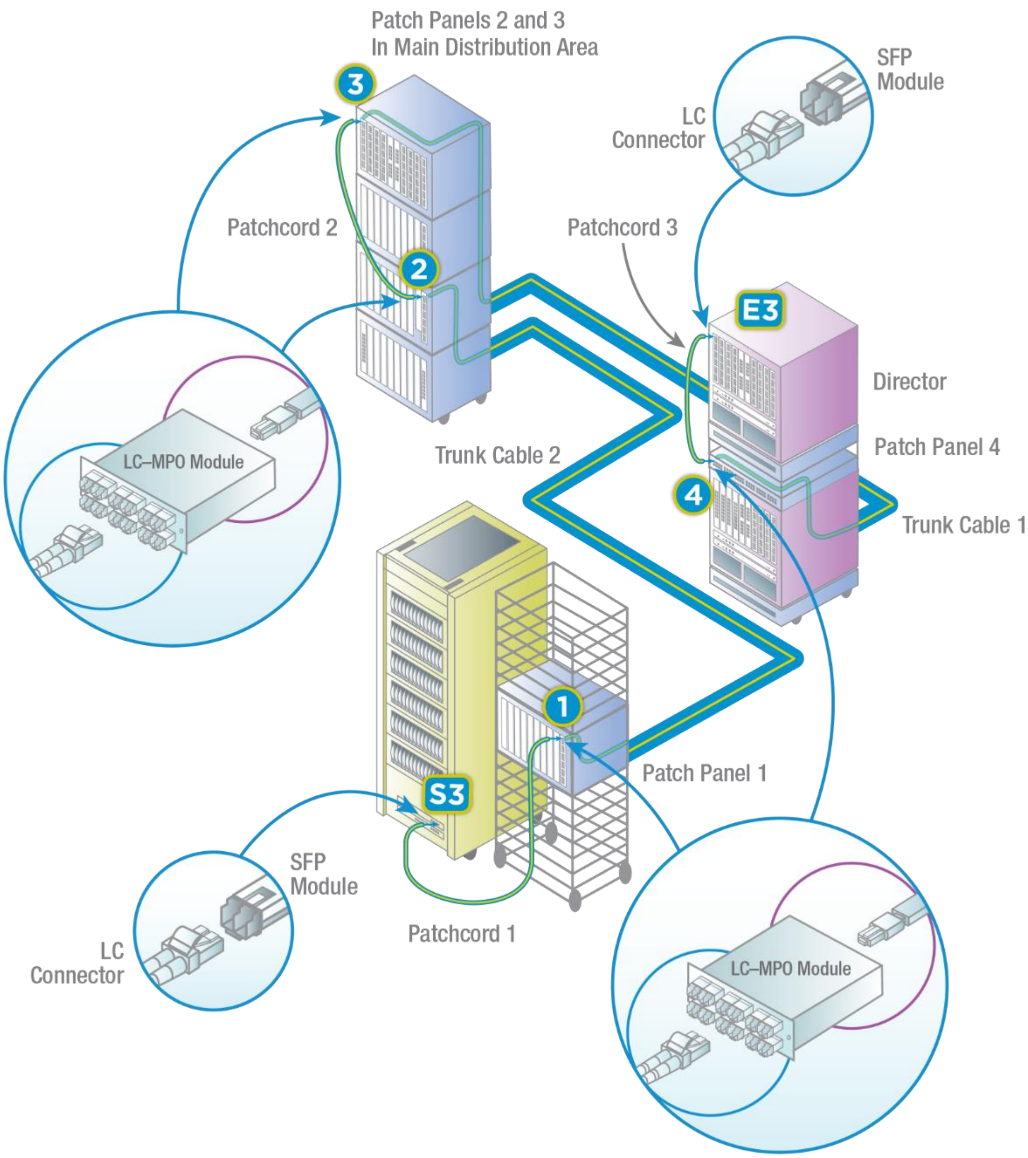
Links can be categorized in many ways. The most common link types can be categorized by the number of intermediate connections supported. Each connection is typically made at a patch panel, so the number of connections in the link depends on the number of patch panels that are used in the link. Fibre Channel links can be categorized by the following system:

1. Point-to-Point Links – 0 connections with a short patchcord between equipment
2. One Patch Panel Links – 1 connection between two patchcords
3. Two Patch Panel Links – 2 connections between three link segments
4. Three Patch Panel Links – 3 connections for centralized patch panels with 1 trunk cable
5. **Four Patch Panel Links – 4 connections for centralized patch panels with 2 trunk cables**
6. Five or more Patch Panel Links – 5 or more connections for multiple trunk cables

These link types are all be supported by Fibre Channel, but the insertion loss must be managed when many connections are in a link. Large data centers often use four patch panel links that have two trunk cables that radiate out from the patch panels in the Main Distribution Area (MDA). Figure 8 shows an example of a link where two trunk cables are connected to an MDA.

Figure 8 shows examples of a Four Patch Panel Link that uses two trunk cables. Each end of a trunk cable usually terminates in a patch panel, so four patch panels are associated with a link that has two trunk cables in it. Two of the patch panels are located in the MDA to connect any port to any port. One patchcord is needed in the MDA to connect the two trunk cables and another patchcord is needed on each end of the link to connect to the optical modules. The four Patch Panel Link has two trunk cables, three patchcords and four patch panels.

Figure 8: Four Patch Panel Link Example



Let's work our way through the connection in the link in Figure 8. The 4 Patch Panel Link starts at an SFP+ port labeled "S3" on the storage device at the bottom of the figure. Patchcord 1 connects the storage device to patch panel 1 that connects to trunk cable 2. Trunk cable 2 connects to patch panel 2 in the MDA and patchcord 2 connects to patch panel 3 and trunk cable 1. Trunk cable 1 connect patch panel 3 in the MDA to patch panel 4 in the switching area. Patchcord 3 connects patch panel 4 to the SFP labeled E3 on the switch. This is a straightforward, yet complex, example of one link in a scalable cabling infrastructure that uses two trunk cables to connect to the MDA.

Figure 8 shows LC-MPO Modules used in the link, but any of the patch panel modules shown in Figure 7 could be used in a link and depend on implementation choices. The patch panel module is the interface between the trunk cable and the patchcord. This data center uses MPO trunk cables to connect LC patchcords. Another possible way to terminate the MPO trunk cables would be to use MPO-MPO Modules and MPO-LC Breakout Cables to SFP+. If the trunk cables were terminated with LC connectors, then LC-LC Modules could be used and enable links with very low connector loss. Fibre Channel was designed to support a wide variety of cable types to meet the industry needs.

There are limits to how many connections a link may support. The 4 Patch Panel Link in Figure 8 has 4 patch panel modules and the insertion loss of the link needs to be limited to meet a particular link distance. If the link is limited to an insertion loss of 1.5dB, each patch panel module must be Grade B according to the statistical models discussed in the Insertion Loss section of this paper. The same link could support up to 8 Grade A patch panel modules and keep under the insertion loss limit of 1.5dB.

While the example of this one link seems complicated, further complications arise when thousands of ports need to be managed in data centers that span multiple rooms and even multiple buildings. The art of managing cabling infrastructure is known as structured cabling. Structured cabling is beyond the scope of this paper, but good references on the art of structured cabling are provided in Appendix A.

Conclusion

Fibre Channel uses fiber optic links to connect thousands of ports in massive data centers and small data centers. Most Fibre Channel links use MMF and support links with 2 trunk cables and four patch panels. In large deployments, more connections in more patch panels are also needed in a link and the insertion loss and link length must be managed. If even longer links are needed within or between buildings, SMF links can go the distance. SMF links have been designed with much higher loss to support inter-room and inter-building links with many patch panels and splices.

Fibre Channel continues to evolve and progress to meet the growing needs of customers. Fibre Channel continues to double the speeds of links and even quadruple the speed in some cases. Gen 6 Fibre Channel has quadrupled the speed of 32GFC with parallel links to support 128GFC. 128GFC requires parallel cabling based on the MPO infrastructure for 128GFC-SW4 and 128GFC-PSM4. 128GFC is an example of how Fibre Channel is expanding to meet the high bandwidth needs for inter-switch links.

Appendix A: Related Standards and References

Fibre Channel links are defined by the T11 Technical Committee of the InterNational Committee for Information Technology Standards (INCITS). Ethernet links are defined by the Institute of Electrical and Electronic Engineers (IEEE) 802.3 Ethernet Working Group. Long haul links are defined by the International Telecommunications Union (ITU) of the United Nations. The Telecommunication Industry Association (TIA) defines standards for cabling infrastructure and structured cabling.