Consortium For On-Board Optics
Optical Connectivity Options for 400 Gbps and Higher On-Board Optics

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1. Introduction

1.1 - Scope and Purpose

The Consortium for On-Board Optics (COBO) has issued its On-Board Optical Module Specification to support 400G and 800G initially, with the intent to expand to higher rates in future. [1] 400G and 800G refer generically to multiple optical applications with aggregate bitrates of approximately 400 Gbps and 800 Gbps respectively. The specification includes 400G and 800G optical connectivity between the on-board optics (OBOs) and the front panel.

This white paper provides additional context on connectivity options, fiber choices, connector choices, handling and cleaning recommendations. It will describe the issues and options in order to inform the implementer community. The options described are not exhaustive or prescriptive. Other standards are referenced as additional useful sources of information.

The COBO specification was developed with high-density applications in mind. This whitepaper includes discussion of the concerns and proposed methods for applications with high fiber counts. It discusses connectivity learnings based on experience with existing OBOs as well as new concepts and emerging technologies that may be applicable to both COBO defined modules and other OBOs. The general term "OBO" will be understood to refer to all on-board optics whether existing or compliant with the COBO specification.

1.2 - Advantages of On-board Optical Modules

For high-density applications such as data center switches, where the system is fully populated at beginning of life, pluggability imposes undesirable and unnecessary mechanical, electrical and cooling requirements that increase the challenges for scaling to 400 Gbps, 800 Gbps and beyond. One serious constraint is limit on additional pluggable connectors due to faceplate size. By addressing thermal requirements, electrical interfaces, and module design now, the COBO specification enables a roadmap for data center infrastructure to support expected increases in traffic generated by new innovative technologies.

The density advantages of on-board optics have been recognized for decades. Existing OBO's have been used in high-performance computing, core routing and other applications. These have primarily been using high-count multimode fiber. The COBO specification has been crafted with an initial goal of supporting the higher thermal requirements of faster and larger radix switches but is intended to be generally applicable to other applications as well.

2. Connectivity options between module and front panel

2.1 - Pigtailed or Connectorized Connectivity Options

The use of OBOs introduces an additional segment of fiber behind the system front panel that is not part of the optical transmission path when using front-panel pluggable modules. The COBO specification has borrowed the term PMD (Physical Medium Dependent) from IEEE and uses it in an additional sense to refer to the electro-optical package mounted to the system circuit board without the fiber necessary to take the signal to and from the card edge. The IEEE and COBO transceiver definitions encompass the PMD plus the additional cabling to the card edge.

This section discusses the issues that should be considered when choosing between options to implement the cabling between PMD and the card edge. Table 2-1 summarizes each type along with advantages and disadvantages. As shown in Figure 2-1, the two connectivity options for this additional segment are:

- Pigtailed: For existing OBOs, this approach is now commonly used. There is no extra connection point between PMD and MDI although there is a length of fiber which is connectorized at one end.
- Connectorized: This approach uses a patch cord with connectors at both ends. The PMD will require a receptacle and retention device to mate to the patch cord.

In principal, a pigtailed but not connectorized module could be spliced to a single-ended patch cord with a connector. However, splicing at the time of host system assembly has significant disadvantages compared to either the pigtailed or connectorized options. These disadvantages include size and cost, skill set at the contract manufacturer and assembly time.

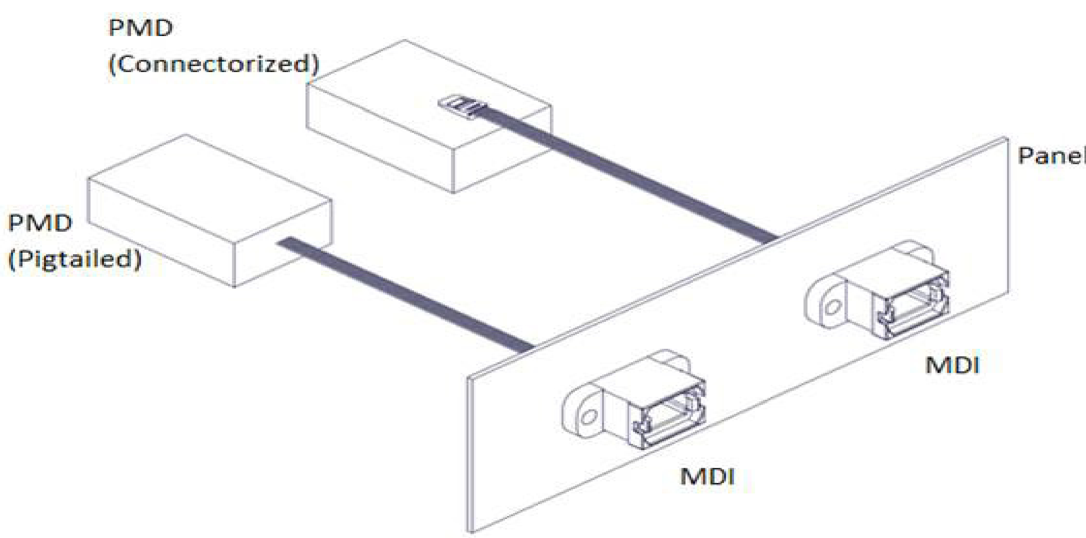


FIGURE 2.1: CONNECTIVITY OPTIONS FOR COBO MODULES

These options and the considerations discussed below apply in all cases independent of whether the fiber is single-mode or multimode. They also apply independent of fiber count. The COBO specification encompasses cases where there are a small number of fibers per OBO (e.g. two fibers for a duplex PMD type) and where there are multiple fibers per OBO (e.g. 32 fibers for an 800G parallel fiber PMD). The MDI (Medium Dependent Interface) is always defined at the faceplate for all connectivity options.

This definition of the MDI from the COBO specification [1, p. 46] is aligned with IEEE Ethernet standards definition for the MDI [2]. The end-user of the system simply sees an MDI interface at the faceplate regardless of COBO connectivity type, and indeed regardless of whether a COBO or pluggable module is used.

Note that the end of the fiber at the COBO PMD is not considered a standard-defined connection point but is considered internal to the COBO implementation. This is true for any of the connectivity options. The output power and receiver sensitivity of the OBO is specified at the MDI even for a connectorized COBO module.

Table 2-1 below shows a comparison of connectivity types for OBO. The comparisons here are relative only and applicable for module and system manufacturers. The issues are discussed in more detail below in Section 2.2 including different impacts on module and system manufacturers.

Variable	Pigtailed	Connectorized
Module and board density	Higher	Lower
Ease of manufacturing and test	Lower	Higher
Control of loss variation and reflectance	Higher	Lower
Ease of system assembly	Lower	Higher
Ease of repair	Lower	Higher

TABLE 2-1 COMPARISON OF OBO CONNECTIVITY OPTIONS

2.2 - Connectivity Considerations

This section expands on the discussion of how connectivity options affect the life cycle of a COBO system from design and performance through manufacturing and supply chain to repair.

2.2.1 Environmental, Power and Size Targets for a Reference Application

In all cases, the design of the host system needs to allow space for management of the fiber between PMD and MDI. See Section 4.0 for a discussion of allowable fiber bend dimensions that govern this design. The connectorized option also requires additional space so the connector can be inserted (and removed as necessary for repair). Retention structures for the connector on the PMD will protrude from the front of the PMD module.

2.2.2 Environmental, Power and Size Targets for a Reference Application

The COBO specification was developed with high-density systems in mind. It is highly likely that there will be multiple rows of COBO modules on a host system board, with different lengths of fiber required to reach the front panel. With pigtailed OBOs, module vendors likely will need to prepare multiple product variants with different lengths of fiber pigtails or terminate to order. Connectorized OBO manufacturing is streamlined to a single product variant independent of the fiber assembly and length.

2.2.3 System Assembly and Risk of Damage

A major advantage of the connectorized option is simplification of system assembly. The modules can be placed and electrically connected to the host board without fiber. The fiber jumpers can be added in a separate step. The more complex process for pigtailed OBOs also increases the risk of damage to the fragile fibers. Handling both at the same time as in the case of pigtailed modules is complicated. Fiber management design is also impacted by the presence of fiber pigtails when placing additional modules.

A connectorized OBO type adds another fiber interface that needs to be cleaned. See section 6.0 for a description of cleaning practices. The procedure and equipment are the same as needed for the front-panel connection, so the main impact is to increase the time needed for this manufacturing step. This additional interface has a risk of damage if contaminated.

2.2.4 Inventory

Per section 2.2.2, pigtailed OBOs may vary by length of pigtail. A contract manufacturer responsible for system assembly would then have to stock these multiple part numbers. For connectorized or spliced OBOs, the inventory impact is limited to stocking multiple lengths of the passive jumpers. A contract manufacturer may wish to use a preferred connector and jumper supplier independent of their choice of OBO supplier.

2.2.5 Performance: Loss, Reflectance and Loss Variation

Any connection point where one fiber mates to another fiber incurs insertion loss (IL) and return loss/reflectance (RL). IL is the amount of optical signal lost at the connection point; RL is the ratio of the optical power reflected back toward its source. Performance in a fiber-optic network depends on assuring that losses for the entire link are kept within tolerable levels. Typical IL and RL values for different grades of connectors are discussed in Section 5.2.4.

Connectorized OBOs have an extra connection point compared to pigtailed OBOs so it may seem that they would have more loss and therefore lower performance. In reality, direct comparisons are more complex and also vary by implementation even within the same type of connectivity.

While it is likely that the connector at the PMD will incur a few tenths dB of loss, this loss does not impact link performance. Consider that there is a finite and unknown coupling loss within either an OBO PMD to either a pigtail or the mating connector receptacle. There are similarly possible losses within a front-panel pluggable transceiver between internal optics and the connector receptacle. The connection loss at the PMD has the same impact. The external link performance is assured as long as the transmitter power and receiver sensitivity meet specifications at the MDI.

Note that the main difference between connectivity options is on the variability of the loss, which is greater for the connectorized version. The module manufacturing test will use a temporary connection with a different jumper than the one that will be installed during system assembly. The splice pigtail may also have slightly different loss than in module test. Therefore, it is likely that module manufacturers will need slightly more manufacturing margin to assure compliance at the MDI in case the assembled loss is greater. System vendors and their contract manufacturers can specify higher grades of connectors both on the PMD and the jumper to minimize loss variation.

The additional connector at the PMD is an additional reflectance point. Splice reflection is typically insignificant. Reflections back into a transmitter may affect laser performance. Particularly at high speeds, multi-path interference may create link penalties. The amount of this reflectance and reflectance tolerance depends on implementation detail. It also depends on optical link type.

2.2.6 Failure Points and Repair Process

Fault location may be simpler with a pigtailed OBO since there are fewer possible points of failure are limited to the PMD, the fiber and the front-panel connector. A connectorized OBO adds the risk of risk to damage to the PMD connector interface particularly due to contamination or mishandling during assembly. A spliced pigtail adds the splice point as a potential failure point as well has more fiber handling during the splicing process.

However, repair may be simpler for a connectorized OBO if the failure is confined to the fiber. If a replacement of the jumper suffices, the repair may be done at the contract manufacturer or even in the field. Repair of a pigtailed module requires demounting the entire module and sending it back to the module manufacturer. Repair of a connectorized module would also require demounting and repair by the manufacturer if the failure is in the PMD including the mating receptacle.

The pigtail may be more difficult to remove than a connectorized jumper. Depending on fiber routing, this removal may have greater risk of damage to other fibers.

2.2.7 Impact on Choice of Fiber Cabling Type

As already stated above, the fiber may be single-mode or multimode, and may range in fiber count per OBO. Multifiber cable and ribbon fiber can be used as well; loose tube multifiber cables are more difficult to splice. Connectorized or pigtailed OBO's could be used with a planar multi-fiber flex circuit for easier fiber routing for many OBO modules. Such multi-fiber flex planes may reduce the hindrance of the airflow compared to multiple cables or ribbons within the housing.

3. Optical media

3.1 Fiber Types

The optical media used for the pigtail of a COBO module are composed of either single-mode or multimode fiber. Manufactures can choose the types of fiber according to their optical engine operational function. In general, multimode fiber is to support a VCSEL based optical engine, whereas single-mode fiber supports longer wavelength single-mode light sources.

3.1.1 Single-mode Fiber Types

There are several types of single-mode fiber defined by IEC 60793-2-50 [3] Cabled single-mode fiber types are defined in ITU-T recommendations [4] [5]. For pigtail connectivity users should consider two general types of fiber: standard single-mode fiber (IEC: B-652 / ITU-T: G.652 types) and bend insensitive fiber (IEC: B-657 / ITU-T: G.657 types). Although standard single-mode fiber is used for pigtail applications, users may require bend insensitive fiber to achieve tighter bends in more difficult fiber routing architectures. It should be noted these standards are regularly reviewed and renewed. It is the user's responsibility to find the latest versions. See the end of References section for some useful links.

The macro bending loss is an important factor when considering the section of fiber for the pigtail fiber of a COBO module. Table 3 1 summarizes the comparison of the specified maximum macro bending loss for each fiber type. From top to bottom, the bending loss decreases significantly.

			Macrobending Loss (dB/Turn)				
Fiber Category	Sub Category	Wavelength (nm)	R 5 mm	R 7.5 mm	R 10 mm	R 15 mm	R 30 mm
G.652	A/B/C/D/E	1625					0.001
G.657	A1	1550 1625			0.075 1.500	0.025 0.100	
	A2/B2	1550 1625		0.500 1.000	0.100 0.200	0.003 0.010	
	B3	1550 1625	0.150 0.450	0.080 0.250	0.030 0.100		

TABLE 3-1: MAXIMUM BENDING LOSS OF CABLED FIBER TYPES ([4], [5])

3.1.2 Multimode Fiber Types

Multimode fiber is characterized by core diameters larger than those of single-mode fiber. As a result, it has larger alignment tolerances and easier optical alignment assembly. Multimode fiber is much less sensitive to macrobending loss than single-mode fiber due to a higher index difference between core and cladding. The reach of multimode fiber is limited compared to the reach of single-mode fiber due to modal delay difference that deteriorates the optical signal quality. The reach and bandwidth can be traded off in application. There are multiple types of multimode fiber with different reach-bandwidth specifications and target applications.

Data center applications typically use multimode graded-index 50 µm fibers sub-category A1-OM3 to A1-OM5 specified in IEC 60793-2-10 [6]. The standard specifies the minimum modal bandwidth for several wavelengths and supports the minimum reach of Ethernet variants as defined in ISO/IEC 11801-1 [7] . Below is a table showing the multimode categories versus modal bandwidth and reach.

			Minimum Reach (m)			
Category	Core/Cladding Diameter (µm)	Min Modal Bandwidth @ 850 / 953 / 1300nm (MHz-km)	10GbE 10GBASE-SR	40GbE 40GBASE-SWDM4	40GbE 40GBASE-SR4	100GbE 100GBASE-SR10
OM1	62.5/125	200 / - / 500	33	Not Supported		
OM2	50/125	500 / - / 500	82			
OM3	50/125	1500 / - / 500	300	240	100	100
OM4	50/125	3500 / - / 500	400	350	150	150
OM5	50/125	3500 / 1850 / 500	400	350	150	150

TABLE 3-2: MULTI-MODE FIBER CATEGORIES AND RELATION FOR MODAL BANDWIDTH AND MINIMUM REACH [7]

3.1.3 Emerging Technology: High Density Fiber Interface with Thinner Fibers

The COBO specification is driven by a need for greater density. It takes advantage of increasing densities of the optical chips inside. In response to pressure to improve the fiber density to better match the chip density, there is a new project in IEC TC86 JWG9 (Joint Working Group 9) working to standardize to a finer fiber pitch. The new "half-pitch" interface proposal describes an array pitch of 125 µm, down from today's typical 250 µm. The new proposal applies to both multimode and single-mode, using fibers with 80 µm cladding outer diameter in a single row of 32 channels.

The proposed standard is expected to find use in high density board-to-board and optical backplane interconnects, optical print circuit boards, optical backplanes, PIC (Photonic Integrated Circuit) packages and package level integration of LSI and optical engines. Technical challenges that increase with reduced pitch include handling and ribbonizing of the smaller fibers, controlling manufacturing of precision holes and greater accuracy in assembly.

Another challenge is that a half-pitch interface of 125 µm is not compatible to the existing installed and widely manufactured cable assemblies where a pitch of 250 µm is used. Jumper assemblies with a pitch of 125 µm on one side and of 250 µm on second side are required to connect to installed cabling.

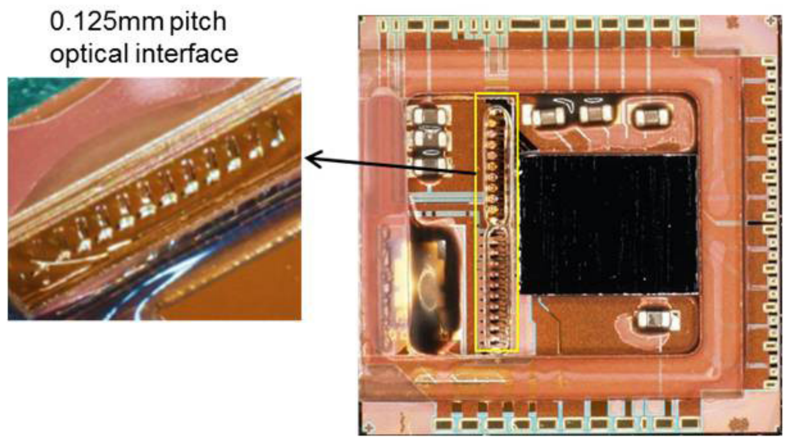


FIGURE 3-1 EXAMPLE OF PIC PACKAGE W/125 µM PITCH OPTICAL INTERFACE [35]

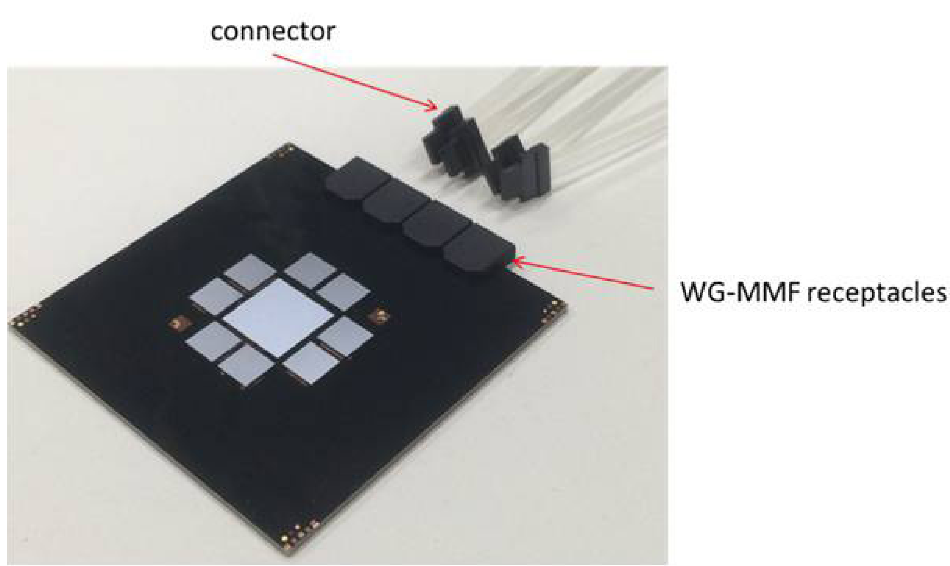


FIGURE 3-2 EXAMPLE OF INTEGRATED PACKAGE OF LSI AND OPTICAL I/OS HAVING CARD-EDGE CONNECTOR WITH 125 µM PITCH FIBER RIBBON

3.2 Fiber Handling

Optical fiber is made of glass and therefore should be handled carefully for integrity (no fiber damage or breakage) and user safety. The fiber coating, usually made of acrylate, mechanically protects the glass fiber and should not be damaged or removed unnecessarily. As long as the fiber coating (typically Ø250 μm) is protecting the glass fiber, the fiber is resistant to breaking under bending. If the fiber coating is removed for some assembly step, the fiber becomes significantly more brittle and extra care needs to be taken. Users need to understand the risks of fiber handling and follow the guidance below:

- Do not crush fibers as it may cause fiber damage or breakage.
- Do not apply bend and/or load more than the value of the fiber specification.
- Treat fiber carefully to prevent unnecessary breakage. Although fiber is screened for tension proof test, it can still break easily.
- Proper protection should be used (e.g. safety glasses) when handling bare fiber. Broken fiber pieces can be dangerous. They are extremely small and once inside the human body they are very hard to identify. It may cause human body injury.
- Avoid eye or skin exposure to direct radiation from the fiber or connector end(s) as this may result in injury. Laser light used in data communications and telecommunication is not visible to the naked eye. Check that the laser power is turned off completely or the fiber is disconnected from any laser source before inspection of the fiber end.

4. Fiber reliability

4.1 Limitations on Fiber Bending

The mechanical fiber reliability and failure probability are important factors to consider in COBO module use cases. Additionally, the bend loss has to be considered as well. The steady increase of switch ASIC bandwidth drives growth in the numbers of transceivers on a host board. Boards with a high density of on-board modules leave only narrow spaces and create challenges for fiber routing, notably the need for tight bends. Tight bending increases the probability of fiber breakage. Board design requires care to balance the considerations for on-board module layout, macro bending loss and fiber bend failure probabilities to guarantee COBO module operability, lifetime and reliability.

This chapter discusses fiber reliability under a bent condition. Macrobending loss for single-mode fiber is described in 3.1.1.

4.2 Reliability of Bent Fibers

Continual bending of an optical fiber will result in fatigue in the glass fiber due to the increased residual stress inside of the fiber cross section. During the fiber manufacturing process, the optical fiber is subjected to a proof test by applying a tensile stress in the longitudinal direction for a controlled period of time. This test screens out any faulty portion along the entire length of optical fiber. For example, proof stress level of 1% (measured as elongation under applied tensile stress; for 125 µm diameter fiber, 1 % corresponds to 0.69 GPa) is the screening condition used for conventional terrestrial optical fiber.

Based on this screening process, the fiber lifetime estimation adopted by IEC/TR 62048 [4] is used to assure mechanical reliability. In this document, the lifetime t_f is defined as where σa is bending stress, σp is proof stress, t_P is proof time, P is failure probability, L is the bent length, m is the Weibull form factor and n is a fatigue coefficient.

$$t_f = \{[\frac{\beta^{m_s}}{L} \ln\frac{1}{P} + (\sigma_p^n\, t_p)^{m_s}]^{\frac{1}{m_s}} - \sigma_p^n\, t_p\}\, \sigma_a^{-n}$$

FIGURE 4-1: EQUATION

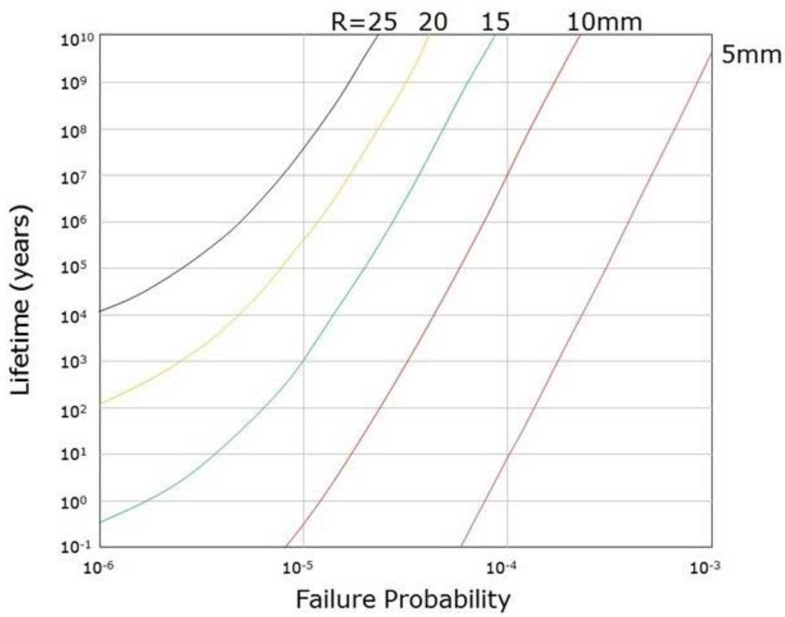


FIGURE 4-2 LIFETIMES PER BENT FIBER METER VS FAILURE PROBABILITY

Below are estimations using this formula and assuming parameter values of n=20, m=3, Np=1.0E-6 [/m] and tp =1 sec.

Below is the failure probability difference calculated result assuming the proof stress is applied by 1 % with a standard fiber cladding diameter of 125 µm. These results show that a smaller bend radius and long-term condition result in a worse failure probability, whereas the best probability is estimated to be larger bend radius and shorter-term condition.

It is important to note that Table 4-1 shows failure probability over a meter which is bent continuously at the bend radius specified. For typical OBO module applications, the fiber will only be bent at these radii for fractions of a turn to several turns. Probabilities shown do not account for the fact that a smaller bend radius turn occurs over a shorter length, e.g. a 30mm turn requires 0.18 m of fiber, but a 5 mm turn requires 0.03 m of fiber.

Bend Radius (mm)	Failure probability* (m^{-1})		
	20 years	5 years	3 years
30	2.5×10^{-12}	6.24×10^{-13}	3.74×10^{-13}
15	5.99×10^{-7}	3.04×10^{-7}	2.24×10^{-7}
7.5	1.49×10^{-5}	1.17×10^{-5}	1.06×10^{-5}
5	6.06×10^{-5}	4.79×10^{-5}	4.39×10^{-5}

TABLE 4-1 FAILURE PROBABILITY VS BEND RADIUS AND TIME

* For fibers with proof test 125 µm fiber cladding diameter

Below is the calculated bend radius failure probability difference by applied proof stress ranging from 1 % through 2 %, assuming 5 years span with a standard fiber cladding diameter of 125 μm. As can be seen, the fiber applied a higher proof stress gives lower failure probability because the higher proof stress can eliminate the weak portion of the fiber during its manufacturing process.

Bend Radius (mm)	Failure probability* (m^{-1})		
	1%	1.5%	2%
30	6.24×10^{-13}	-	-
15	3.04×10^{-7}	1.97×10^{-10}	6.24×10^{-13}
7.5	1.17×10^{-5}	2.28×10^{-6}	3.04×10^{-7}
5	4.79×10^{-5}	1.17×10^{-5}	3.85×10^{-6}

TABLE 4-2 IMPROVEMENT OF FIBER RELIABILITY UNDER BENDING BY PROOF STRESS

* For fibers with 25 μm fiber cladding diameter, over five years

Below is the calculated failure probability using different fiber cladding diameters. Compared to the standard fiber cladding diameter of 125 μm, fibers with smaller cross-sections have less residual stress when bent and therefore lower failure probability.

Bend Radius (mm)	Failure probability* (m^{-1})		
	125 μm	100 μm	80 μm
30	6.24×10^{-13}	7.22×10^{-15}	-
15	3.04×10^{-7}	7.40×10^{-9}	8.69×10^{-11}
7.5	1.17×10^{-5}	5.02×10^{-6}	1.86×10^{-6}
5	4.79×10^{-5}	2.22×10^{-5}	1.00×10^{-5}

TABLE 4-3 DEPENDENCE OF FIBER RELIABILITY ON FIBER CLADDING DIAMETER

* For fibers with 1% proof test, over five years

5. Fiber optic connectors

5.1 Connector Types in COBO Specification

There are three connector types listed in the COBO specification for fiber optic connectivity at the MDI. The best choice of connector type is primarily dependent on fiber count. In general, PMDs that use more than two fibers are best served by using a multi-fiber connector. Other connector types with similar fiber count may be considered as long as they meet the lane assignment requirements that are defined in the COBO specification.

All the existing connectors described in this section (both single and multi-fiber) share the same attributes at the fiber level. They differ in the mechanics to assure fiber alignment, but all require physical contact of the individual fibers. The next section describes alternatives which do not share this requirement for physical contact. Physical contact (PC) connectors represent the vast majority of fiber optic deployed solutions today. It is a mature technology with a wide range of non-proprietary solutions and interoperable vendors. PC also enables the best possible optical performance for most applications, although it can require considerable preparation and care to maintain yields at the factory and deploy in the field. To help minimize these trade-offs, the industry has adopted standardized processes to polish, clean, and inspect PC connectors.

5.1.1 MPO-12 and MPO-16 Connectors

Single and dual-row MPO-12 and MPO-16 are specified for MDI connections and can contain up to 32 fibers per connector. TIA-604-5 [8] , IEC 61754-7-1 [9], and IEC 61754-7-2 [10] specify the mechanical intermateability requirements of the plug, adapter and receptacle for the MPO-12 connectors. The optical plug, adapter and receptacle for the MPO-16 connector is defined by TIA-604-18 [11], IEC 61754-7-3 [12] and IEC 61754-7-4 [13].

To ensure proper orientation at the MDI between the OBO and the patch cord, both MPO-12 and MPO-16 OBOs use aligned keys. For both connector types, this means the optical connector is orientated such that the keying feature of the MPO receptacle is towards the top of the OBO.

5.1.2 Dual LC Connector

The Dual LC optical patch cord and OBO receptacle, which is specified in TIA-604-10 [14] and IEC 61754-20 [15] , can also be used in COBO designs. It is two individual single-fiber connectors often ganged together into a dual (or “duplex”) configuration.

5.1.3 CS Connector

The CS optical patch connector and receptacle is a new PC-type connector. The first version of this connector specification [16] was issued in late 2017 by the QSFP-DD MSA. CS will be specified in TIA-604-19. At the time of this white paper, TIA was in the process of being written with a 2019 target publish time frame. CS is a two-fiber connector, which can be paired at the OBO for a total of four fibers.

5.2 Alternative and Emerging Multi-fiber Connectors

Alternatives to PC connectors include expanded beam (EB). Multimode multifiber EB connectors have been used in service provider and high performance computing applications for over a decade. Other EB variants are used extensively in the military/aerospace industry. The COBO specification is forward-looking and targets expansion to future applications. In recent years, the fiber optic connector industry has put effort into addressing some desires for improvement. Additional emerging technologies that may be particularly relevant to multifiber communications including COBO-compliant designs include single-mode EB and single-mode or multimode Air Gap (AG). These are currently proprietary to individual connector manufacturers, but may offer positive trade offs for certain applications. Figure 5-1 illustrates the difference between PC and expanded beam (EB) and Air Gap (AG) connectors.

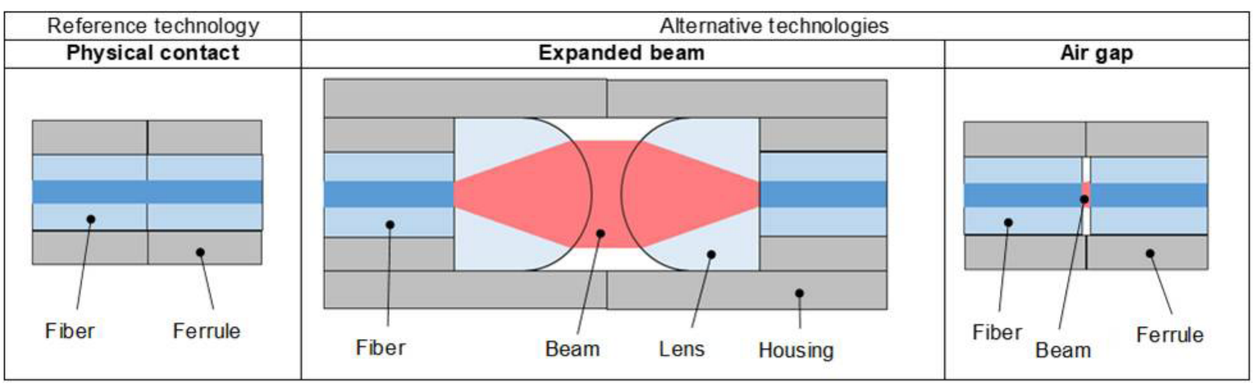


FIGURE 5-1 PHYSICAL CONTACT FIBER CONNECTION AND ALTERNATIVES

Section 5.2.1 describes the issues they seek to address. Sections 5.2.2 and 5.2.3 discuss in detail the EB and AG approaches and the improvements they offer. Section 5.2.4 describes some performance criteria that should be considered and finally section 5.2.5 and Table 5 2 summarize the comparison between PC, EB and AG. Note that single-mode and multimode applications have different sensitivities. Care should be taken to make the comparison for the appropriate type of connector for the user's application.

5.2.1 Desired Improvements

Lower connector spring force may be a desirable improvement for applications such as multi-fiber connectors with greater than thirty-two fibers per port and blind mate mid-plane/backplane connections, especially those with multiple ports (e.g. ganged connectors).

The fibers in PC connectors are precision-aligned, polished to a smooth finish (see Figure 5-2), and then mated with enough force to planarize both endfaces. The Endface Geometry requirements are specified in standard EN 50377-15-1:2011 [17] and IEC 61755-3 family of standards [18] [19] [20]. This eliminates any air gaps between fibers, and in the ideal case, creates a continuous propagating media where light can travel as if inside a single optical glass fiber. The challenge is that the force required is roughly proportional to the number of fibers (at a rate of about 1 N per fiber).

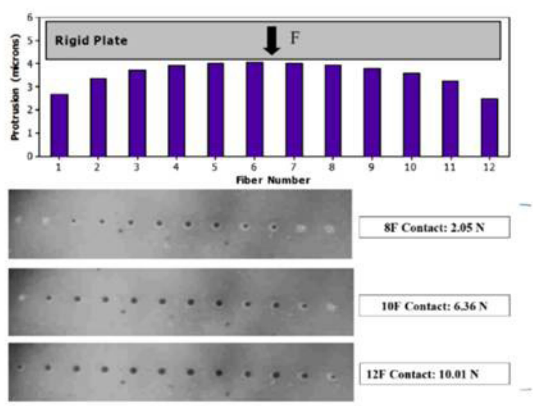


FIGURE 5-2 ENDFACE GEOMETRY FOR MT CONNECTOR

Another area where improvement is sought is the impact of debris on the connector endface. PC connectors require a clean endface. Debris can occlude light but furthermore lack of proper physical contact can also degrade insertion loss or back reflectance performance. In most installations, PC connectors are inspected and cleaned to ensure proper physical contact and that no permanent damage is induced onto the endface.

In the case of multi-fiber connectors, this issue gets compounded by the laws of probability. For some installation environments, an alternative connector solution may be desired. Examples include installation sites not equipped to perform adequate cleaning/inspection, harsh environment installations, and mid-plane / backplane connections where accessibility to cleaning may be limited (especially in the field).

5.2.2 *Expanded Beam Multifiber Connector*

One possible emerging technology is expanded beam (EB) connectors. Millions of multimode EB connectors (not including lensed receptacles inside pluggable transceivers) have been deployed over the past decade. While this is a mature industry, it is still largely proprietary and their volumes are still dwarfed by PC connectors. At the time of this white paper, single-mode EB connectors are emerging as well. Per their name, EB connectors have a larger light beam in the region between connectors than in the fibers. By doing so, the portion of light blocked by dust particles is smaller than in the conventional physical contact case, and so is the degradation of the signal itself.

EB solutions do not require physical contact between the fibers and are insensitive to variation in the location of the light beam in all three axes. Connector insensitivity in the x and y-axes (i.e. orthogonal to the direction of the light) can be helpful in applications with high vibration or side load requirements. Connector insensitivity in the z-axis (i.e. parallel to the direction of the light) can be helpful in sites with significant debris. EB connectors also eliminate the need to polish fibers and measure endface geometry.

The reduced effects of dust are sketched in Figure 5-3 where the cross-sectional area of a fiber in a PC connector is compared to an EB (16 times larger beam area). The same dust particle is overlaid on both cross-sections, intuitively showing how the same particle blocks a significant portion of the optical signal in the multimode 50 μm PC case, while it blocks an insignificant portion of the EB signal. The enhanced insensitivity to debris is proportional to the area of the beam.

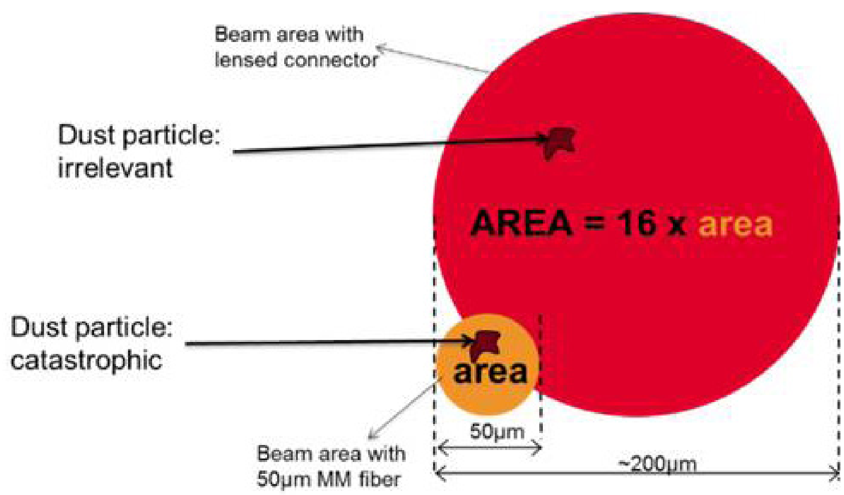


FIGURE 5-3 CROSS-SECTIONAL COMPARISON OF DUST PARTICLE AND OPTICAL BEAMS IN MULTIMODE PC AND EB CONNECTORS

Another advantage of EB connectors is lower mating force (< 3 N total). Because it does not require a PC connection, the EB connector mating force is independent of the fiber count per port. This enables the use of multi-fiber connectors in applications where board-level components or connections could get damaged by larger mating forces. For the same reason, expanded beam technology also reduces tooling or mechanical features that might be required to latch/engage high fiber count and/or ganged connectors. Additionally, a lower mating force generally results in less debris generation during mate-demate cycles, which can greatly reduce the need to clean the connector endface. As mentioned in 5.2.1, this can result in less debris generation between mating cycles, which can enable high density ganged connector designs. It can also significantly reduce installation time in the field.

The technical tradeoff with EB connectors is that they typically exhibit worse insertion loss and return loss performance compared to PC. Manufacturers are actively working to improve EB performance with the goal to achieve similar performance as PC.

5.2.3 Air Gap Multifiber Connector

Another possible emerging technology is air gap (AG) connectors. It does not require PC between fibers and intentionally applies a controlled micron (μm) air gap between the fiber endfaces of mated connectors. AG connectors can use an angled endface option to achieve low optical reflectance performance similar to that of angled physical contact (APC) connectors. AG connectors can achieve low insertion loss due to the small gap distance applied between mated connectors.

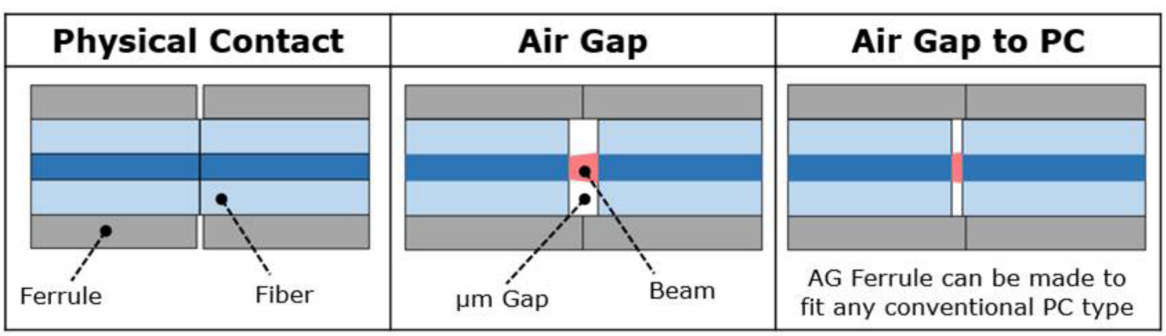


FIGURE 5-4 COMPATIBILITY OF AIR GAP AND PC CONNECTORS

AG connectors have a low mating force (3 N) requirement independent of the fiber count per port. As mentioned in Section 5.2.1, this can result in less debris generation between mating cycles, which can enable high density ganged connector designs.

The AG connector can mate to either another AG connector or to a standard PC connector as shown in Figure 5 4. For AG compatibility with conventional PC type connectors, the AG side should have the appropriate gap, polarity and compatible connector type. The optical performance for AG to PC is proprietary to the vendor.

The technical trade off is that the light beam for the AG connector is about the same diameter as for PC connector type. Therefore, the loss of AG connector is more sensitive to dust than EB. Compared to PC however, the AG connector should be easier to clean since debris is less likely to be pressed between the fibers.

5.2.4 Connector Performance

Note that designs must account for the worst-case loss that can be anticipated for any given mated pair solution.
Worst Case Insertion Loss = Specified Insertion Loss (Max) + Change in loss from service conditions (Max)
Service conditions that should be specified include:

- Frequency of cleaning, test and inspection.
- Number of mate-demate cycles between cleaning/inspection
- Thermal Cycles (number and operating temperature range)
- Aging (which is simulated by accelerated thermal and humidity exposure)
- Dust conditions.

Specifiers should consider using existing industry standards to define use qualification requirements, including ANSI/TIA-568.3-D [21], GR-1435-CORE [22] or GR-326-CORE [23]. These standards serve as a good reference point, even if the user or Original Equipment Manufacturer chooses to relax or tighten the specifications for their specific application or product. See also Section 7.0 for relevant standards specifying tests, recommended performance criteria as well as reliability tests for connectors.

These tables reflect a general summary of standards requirements. Users should consult the standards themselves for specific details about qualification testing and application of standards.

There exist multiple grades of optical performance, with some typical criteria levels shown in Table 5-1.

Typical Industry Requirements		Maximum Insertion Loss (dB) New Product	During test, not under load	During test, under load	End of test, not under load	Suitability PC	EB*	AG*
Service Provider	SM Standard Performance	0.70	0.80	1.20	0.80	✓	✓	✓
	SM High Performance	0.50	0.60	1.00	0.60	✓	✓	✓
	SM Ultra Performance	0.35	0.45	0.65	0.45	✓	?	?
	Multimode	0.70	1.00	1.20	1.00	✓	✓	✓
Datacom	Single-mode	0.75	1.05	1.05	0.75	✓	✓	✓
	Multimode	0.75	0.95	0.95	0.75	✓	✓	✓
	MM Ultra Performance	0.35	0.45	0.65	0.45	✓	?	?

Typical Industry Requirements		Maximum Reflectance Loss (dB) New Product	During test, not under load	During test, under load	End of test, not under load	Suitability PC	EB*	AG*
Service Provider	SM Standard Performance	-55	-50	-50	-50	✓	✓	✓
	SM High Performance	-60	-55	-55	-55	✓	✓	✓
	SM Ultra Performance	-65	-60	-60	-60	✓	?	?
	Multimode	-20	-20	-20	-20	✓	✓	✓
Datacom	Single-mode	-35	—	—	-35	✓	✓	✓
	Multimode	-20	—	—	-20	✓	✓	✓

TABLE 5-1 EXAMPLE MODULE DESIGN USING FULLY INTEGRATED OPTICAL SUBASSEMBLY

High optical reflectance can cause optical transmission devices like lasers to operate incorrectly. The specified maximum reflectance for the connector should be less than that required by the optical transmission device. It should be noted that legacy analog broadband requirements have driven the telecom industry to standardize on max reflectance of -55 dB, but many transmission devices will perform suitably at higher reflectance.

5.2.5 Multi-Fiber Connector Selection Considerations

Assuming that the optical performance of one of these alternative connector types is suitable for the application, the decision to use an alternative connector type will be primarily driven by the desire to reduce mating force or cleaning requirements. Table 5-2 provides a summary of the how the alternative connection types compare with physical contact connections.

Criteria	PC	EB	AG
Technology maturity (as of 2019)	Mature (20+ years) Billions deployed	MM: Mature (10+ years) Millions deployed SM: Emerging	Emerging
Physical contact of mated fibers	Yes	No	No
Optical interface specified in standards	Yes	No	No
Enables low force ganged connectors	No	Yes	Yes
Mating force	10 N for 4f to 16f* ferrule 20 N to 16f* to 32f ferrule	≤3 N per ferrule and indpendent of fiber count	
Connector debris created by high number of mate / de-mate cycles	High	Low	Low
Sensitivity to displacement in z-axis	High	Low	Medium
Supply chain options	High	MM: Medium SM: Low	Low
MM Beam diameter	Approximately 50µm	Vendor Defined	Approximately 50µm
MM sensitivity to dust in the optical path	High	Lowest	Medium
SM Beam diameter	Approximately 50µm	Vendor Defined	Approximately 50µm
SM sensitivity to dust in the optical path	Highest	Low	High
Cleaning for dust particles	Hardest	Easiest	Easiest
Cleaning type for dust particle	Tape and/or wet	Canister Air Blow, Tape, Wet	
Inspection and cleaning cycle between mattings for random dust in a controlled environment	Before every matting	MM: Medium SM: Low	As needed

TABLE 5-2 SUMMARY OF CONNECTOR TYPES

**At the time of publication of this white paper, the TIA standard specifies 20N for 16f PC ferrules while the IEC is unpublished.*

5.3 Faceplate Density and Breakout

COBO offers several options for faceplate connectors that provide the ability to design the faceplate for easier breakout or for faceplate density.

There are several factors that are important in the selection of the connector. The first factor is the COBO engine type, which is specified as either an independent 400G engine, dual 400G independent engines or a 2x 400G integrated engine. The choice of the engine is determined by whether the switch design is being optimized for easier breakout or for faceplate density.

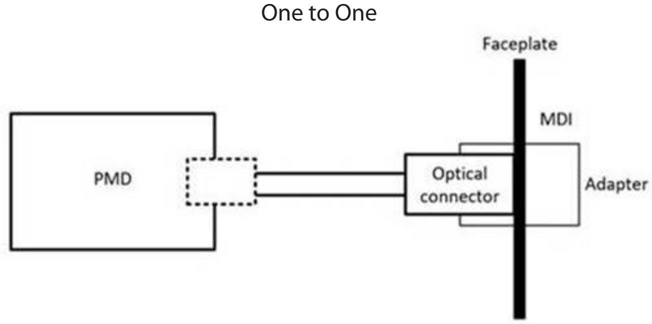
Both the standalone independent 400G engine and the dual independent 400G engines require an OBO for each 400G port. This will require two medium dependent interfaces (MDIs) on the faceplate each supporting a bank of eight data lanes with a connection from each MDI back to the OBO. This means more faceplate connections to support a given level of connectivity when compared to the integrated engine.

The dual integrated 400G engine utilizes a single OBO connection from the MDI supporting two banks of data lanes. This results in fewer faceplate connections for the same amount of connectivity as an independent engine, but also requires a fanout to separate the data lanes in the two banks. It's important to note that having more open area at the faceplate results in more airflow through the system delivering better performance.

5.3.1 Fiber Management Inside a Coherent COBO-compliant OBO

The multiple breakout options can be described as OBO configurations. In this section, the configurations are named in terms of the number of OBOs to connectors, e.g. a 1-to-4 configuration has four connectors per OBO, a 4-to-1 configuration has four OBOs sharing a single connector. Table 5-3 describes some configurations and their pros and cons.

Table 5-4 and Table 5-5 give the system implications in terms of applicable types and required numbers of front-panel connectors. The difference between the tables is the size of OBO - with both tables designed for switches with sixteen OBOs, utilizing a different system capacity, and assuming each OBO lane is running at the same speed.

Configuration Type	Attributes
One to One 	✔ Applicable for pigtailed and connectorized modules ✔ Easy to replace module or fiber assembly ✔ Easy to handle fibers properly ✔ Easy to clean end face by removing connector ✖ No seperation of fibers per bank or application (100G, 200G)

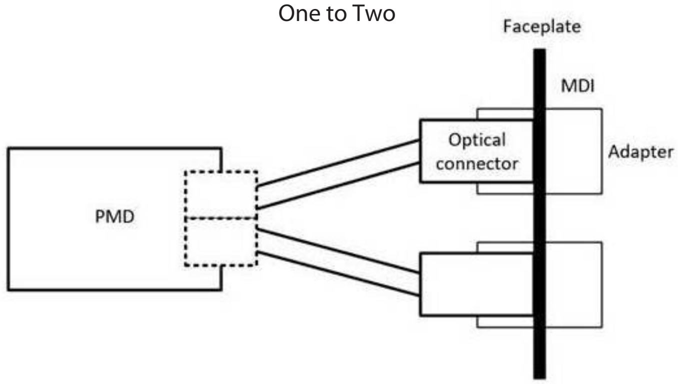
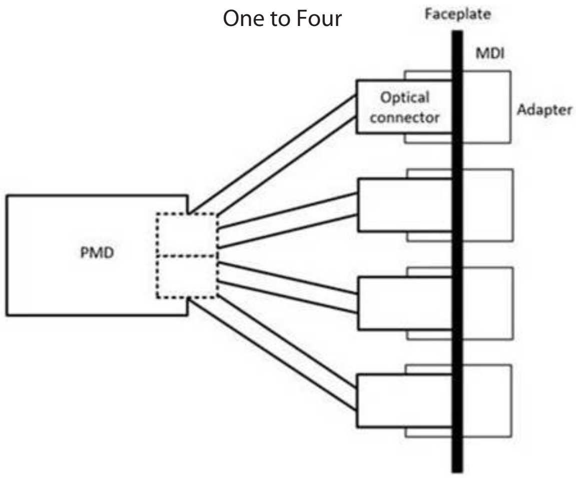
Configuration Type	Attributes
One to Two 	✔ Applicable for pigtailed and connectorized modules ✔ Fan-out integrated on-board (no external fan-out required) ✔ Fibers from each bank or each application (100G, 200G) can be seperated into each connector ✖ High footprint at faceplate ✖ Difficult to handle fibers and connectors properly ✖ Difficult to clean end face by removing one connector ✖ Replacement of all connectors and all fibers if damaged

TABLE 5-3 CONNECTIVITY OPTIONS

<table>
<tr><th>Configuration Type</th><th>Attributes</th></tr>
<tr><td>

One to Four



</td><td>

- ✅ Applicable for pigtailed and connectorized modules
- ✅ Fan-out integrated on-board (no external fan-out required)
- ✅ Fibers from each bank or each application (100G, 200G) can be seperated into each connector

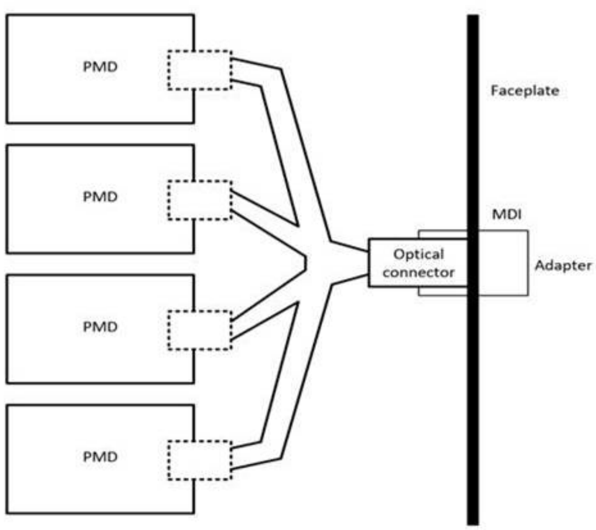
- ❎ High footprint at faceplate
- ❎ Difficult to handle fibers and connectors properly
- ❎ Difficult to clean end face by removing one connector
- ❎ Replacement of all connectors and all fibers if damaged

</td></tr>
</table>

<table>
<tr><th>Configuration Type</th><th>Attributes</th></tr>
<tr><td>

Four to One

Example configuration, other configuartions are possible (2 to 1, 8 to 1, etc.)



</td><td>

- ✅ Applicable for pigtailed and connectorized modules
- ✅ Very low footprint at faceplate
- ✅ Low number of connectors results in low chance of contamination
- ✅ Improved airflow with reduced footprint at faceplate
- ✅ Easy to handle fibers properly with no entaglement of multiple fibers/cables
- ✅ Using a low profile multi-fiber flex plane may reduce the hinderance of airflow

- ❎ A defect at the faceplate connector affects all connected modules
- ❎ Replacement of all connectors and all fibers in case of damage
- ❎ No seperation of fibers per module, bank or application (100G, 200G) - an external fan-out cable assembly may be required

</td></tr>
</table>

TABLE 5-3 CONNECTIVITY OPTIONS (CONT.)

Fibers[a] per OBO	Connector Type	Connector at Faceplate per OBO	OBO Configuration type[b]	Connectors per switch with 16 OBOs
1+1	Dual-LC, CS	1	1-to-1	16
2+2	Dual-LC, CS	2	1-to-2	32
	MPO-12[c]	1	1-to-1	16
4+4	MPO-12	1	1-to-1	16
8+8	MPO-12 (two row) MPO-16[c]	1	1-to-1	16

TABLE 5-4 CONNECTIVITY OPTIONS

a) Tx and Rx b) # OBOs to # connectors, see Table 5-3 c) or other 12- and 16-fiber connector

Fibers[a] per bank	Fibers[a] per OBO with 2 banks	Connector Type	Connector at Faceplate per OBO	OBO Configuration type	Connectors per switch with 16 OBOs
Separate Optical Ports of Bank 1 and 0					
1+1	2+2	Dual-LC, CS	2	1-to-2	32
2+2	4+4	Dual-LC, CS	4	1-to-4	64
		MPO-12[c]	1	1-to-1	16
4+4	8+8	MPO-12	2	1-to-2	32
8+8	16+16	MPO-12 (two row) MPO-16[c]	2	1-to-2	32
Combined Optical Ports of Bank 1 and 0					
1+1	2+2	Dual-LC, CS	2	1-to-2	32
2+2	4+4	MPO-12	1	1-to-1	16
4+4	8+8	MPO-12 (two row) MPO-16[c]	1	1-to-1	16
8+8	16+16	MPO-12 (two row)	1	1-to-1	16

TABLE 5-5 OBO CONFIGURATION TYPES FOR 16-LANE OBO AND TOTAL NUMBER OF CONNECTORS FOR A 16 OBO SWITCH

a) Tx and Rx b) # OBOs to # connectors, see Table 5-3 c) or other 12- and 16-fiber connector

5.4 Future Color Coding Decisions

With the current pluggable transceiver applications, the module handles (also called tabs) or bails are color coded to identify the types of optics or reaches. Examples of tabs implemented on QSFP-DD pluggable modules are shown in Table 5-6. In this example, single-mode 2 km reach and multimode 10 m reach are denoted by the green and beige colors respectively. Note that these colors apply across a variety of speeds, with 200G and 400G denoted explicitly by text on the handle. Table 5-6 lists the color-coding defined in the OSFP MSA Specification.

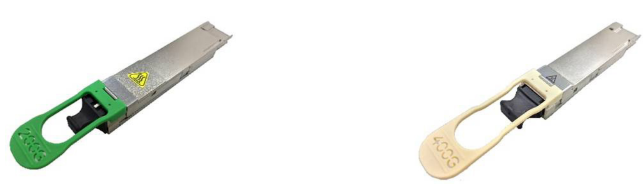


FIGURE 5-5: TRANSCEIVER TAB COLOR CODING COLOR EXAMPLES

Product Type	Example PMD	Color
Copper Cables	400G-CR8	Black
AOC Cables	400G-AOC	Grey
850nm solutions	400G SR8, SR4	Beige
1310nm solutions for up to 500m	400G DR4	Yellow
1310nm solutions for up to 2km	400G FR4, FR8	Green
1310nm solutions for up to 10km	400G LR8	Blue
1310nm solutions for up to 40km	400G ER8	Red
1310nm solutions for up to 80km	400G ZR8	White

TABLE 5-6: EXAMPLE OF PLUGGABLE TRANSCEIVER CODING COLOR ON TABS
SOURCE: OSFP MSA

For the COBO module use in the switch applications, the same color coding can be made by the optical adapter housing colors. However, there could be a conflict between existing pluggable color coding, and optical connector and adapter housing color coding by the fiber types. TIA-568.3-D defines the color of the optical connector and adapter housings based on fiber types, and this has been adopted and accepted widely.

Cable Type	Color
Multimode 850nm 50/125µm fiber (OM3/OM4)	Aqua
Multimode 850nm 50/125µm fiber (OM5)	Lime
Single Mode	Blue
Single Mode APC (angled)	Green

TABLE 5-7: MMF + SMF CONNECTOR AND ADAPTER IDENTIFICATION
SOURCE: TIA-568.3-D

A potential conflict can occur with the use of blue and green colors. For pluggable transceivers, these colors identify 10km and 2km reaches that typically do not use APC connectors. TIA uses blue and green to identify between non-APC and APC connectors. If we use the color coding of the existing pluggable modules for COBO switch applications, cable installers who are familiar with TIA standards might have confusion between SMF color coding of fiber reach vs. non-APC and APC connections.

[i]MM OM1 and OM2 color coding options are excluded to Annex as grandfathered content, and not recommended for new installations.

5.5 Dense and Highly Engineered Interface Technology

Optical backplane connectors allow the connection of optical fibers through blind mating interfaces in similar fashion to electrical backplane connectors. These dense and highly engineered interfaces have been utilized successfully for decades to enable scalable systems for applications in core routing, optical switching and telecommunications. As with front panel optical connections OBO modules are easily interfaced to optical backplane connectors through standard multi fiber cabling or shaped ribbon fiber pigtails attached to OBO modules where the specific connector hardware supported by the optical backplane connector is attached.

Optical flex planes can also be utilized to connect optical backplane specific connection elements to OBOs. Optical FlexPlane is a circuit constructed via individual machine routed fibers laminated onto a flexible substrate forming point-to-point, shuffle or logical connectivity patterns. Input /output leads which are typically of a ribbon fiber type construction can be directly terminated with optical connectors and/or fusion-spliced to connectors and OBOs. In this manner very dense and highly complex fiber port mapping can be accomplished within the system elements. Hardware designers and system architects are attracted to these interface technologies for a variety of aspects:

- Freeing up front panel space for increased airflow and client or networking ports
- Enabling faster system deployments, upgrades and repairs by eliminating manual installation of front panel cabling connections
- Increasing interconnect density and easing cable management beyond traditional front panel optical connectors, transceivers
- Allowing for greater modularization of system components via built in system specific connectivity configurations such as optical shuffling which standardizes line cards and drawers thus enabling use of standard structured cabling external to the chassis

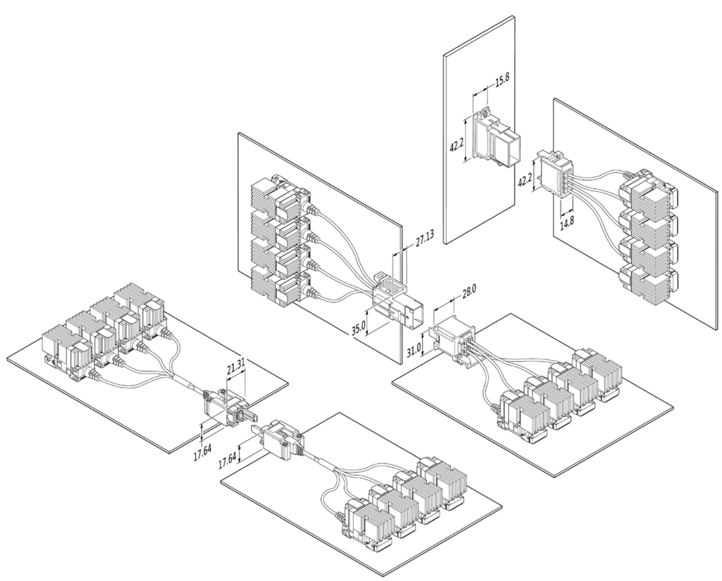


FIGURE 5-6: COPLANAR, ORTHOGONOL, AND STANDARD OPTICAL BACKPLANE CONNECTOR CONFIGURATIONS

The given dimensions and values in Figure 5-6 are applicable for only one connector manufacturers type as an example and is included to provide information about the possible size (indicatory).

5.6 Types of Optical Backplane Connectors

Ceramic ferrule based optical backplane connectors were first to market decades ago and for the most part based on industry standard connectors for the user side such as the MU, SC and LC with a with several custom termini based versions for vendor specific applications.

Ceramic single fiber ferrule interconnects utilize a cylindrical ferrule on each side of the interface aligned within a ceramic split sleeve held in a mating housing normally mounted on the backplane. The board side of the interface is a customized housing mounted to the PCB holding a ferrule designed for proper mating alignment into the backplane housing.

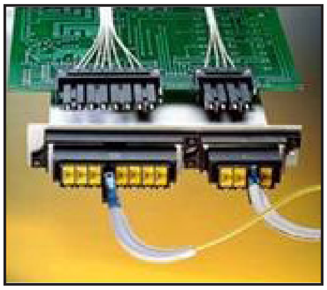
Optical performance and density mimicks the standards-based connector with additional dimensional overhead for latching and mounting features. Port counts typically range from 2 to 8 connectors utilizing either 1.25mm or 2.5mm ferrules. Cleaning and inspection is more standardized and well supported due to wide adoption of the standards based connectors. Today the LC blind mating interface is most predominant in 2, 4, and 8 port counts supporting multimode and single-mode fiber.

Multi-fiber MT ferrule based optical backplane interfaces are most common and achieve vastly higher fiber density than ceramic single fiber ferrules by incorporating multiple fibers per ferrule and multiple ferrule ports per connector. Port counts typically range from one 1 to 8 MT type ferrules enabling up to 384 fibers per connector in a 16x55mm area when using 48 fiber per ferrules.

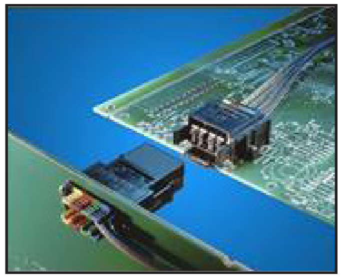
These interfaces are available from several manufacturers in a number of configurations and mounting styles addressing card cage styles and system specific mechanical and packaging needs. MT type ferrules utilize precision molded polymer ferrules aligned via metal guide pins in a male/female configuration.

Their incorporation within an optical backplane connector housing requires detailed consideration for mechanical alignment and containment for proper operation.

Optical Backplane Connector Manufacturer Images:

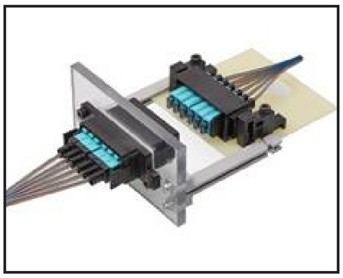


MOLEX: BLC

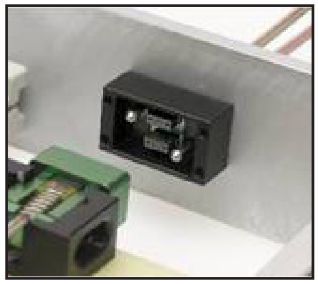


MOLEX: HBMT

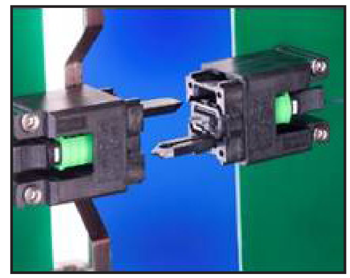
MOLEX: VFI FAMILY



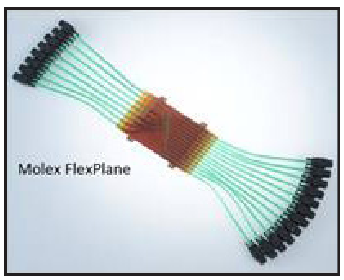
USCONEC: MXC FAMILY



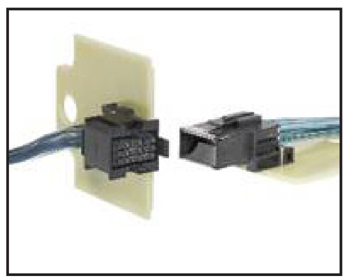
MOLEX: VITA 66.1



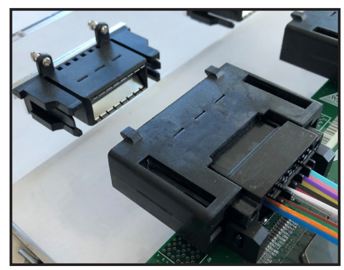
MOLEX: MTP-CPI



MOLEX: FLEXPLANE



MOLEX: ORTHOGONAL OPTICAL



SENKO BACKPLANE CONNECTOR

FIGURE 5-7 VARIOUS OPTICAL BACKPLANE CONNECTORS

5.7 Optical Backplane Connector Mechanical Overview

Early engagement between system architects and optical backplane connector engineers is critical as needs of the system architecture, mechanical enclosure, connector interface and system fiber connectivity scheme are tightly interactive. The number of fibers connected throughout the system can be immense numbering in the thousands making for a complex set of mechanical, optical device, cable management, thermal and usage considerations. It is nearly impossible to add optical backplane connectors to a system design after the fact or to change across different types of interfaces due to mechanical mounting, card pitch and chassis design requirements.

One aspect that is very flexible is fiber count per connector due to the many options available in multi fiber MT ferrules and optical connectors supporting multiple MT ferrule ports (see section 5.0 for ferrule types and configurations). The trade off becomes optical performance which decreases with an increase in the number of fibers per ferrule and fiber management where a single optical backplane connector can have hundreds of fiber connections.

Mechanical design and mounting needs of optical backplane connectors greatly influences the design of the chassis due to mating geometries and nuances in latching and holding force required dependant on the type of connector. As ferrules are individually spring loaded, these forces must either be accounted for in the optical backplane connector or the card front panel latches. Spring forces per MT ferrule ranging from 10 N for 12 fiber ferules to 20 N for 24+ fibers per ferrule is multiplied for each ferrule port of the connector.

Considering an optical backplane connector with eight 24 fiber MT ferrule ports and 4 connectors per card builds up to a required holding force of 640 N per card. Optical backplane connectors come in two types, self-latching or non-latching, which in the case of the latter card latches and chassis/backplane structure must compress the ferrule springs and hold the cards and connectors in a mated condition.

Self-latching optical backplane connectors offer additional Z axis travel or float easing card to backplane design tolerances. The trade-off between the two versions is somewhat dependent on individual connector design and affects density, connector complexity and cost as latches add additional size, design complexity and component count. This is one reason expanded beam ferrule interfaces are attractive as they greatly reduce spring forces required to hold the ferrules in contact often by a factor of 5 to 10x less force and independent of fiber count (see section 5.2 for further details).

Optical backplane connectors are typically mounted to a backplane which has cut-outs for the connector to mount within letting the fibers/cables pass through to the backside of the chassis. As with electrical backplane connectors there are versions of optical backplane connectors supporting midplane, co planer and orthogonal card cage designs as well as newer rack scale drawers/sled architectures all having unique mounting methods and mechanical requirements. Mounting methods include screws, rivets, clips or snap fits and require mechanical float of the connector housing to accommodate mating tolerances of the card or drawer assembly to the backplane / chassis.

If the mechanical tolerance of the card cage or rack is not within the range supported by the connector, guide pins are often utilized to increase mating precision. Because optical connectors are typically longer or first to mate in the mating sequence, electrical connectors cannot be utilized as guidance features. Additionally, electrical connectors have no float therefore the optical connector must have float to eliminate binding of the multiple interfaces. These aspects must be carefully considered by the mechanical designer and considered in connector selection.

Testing and qualification criteria for mechanical and environmental performance is established within Telcordia GR-1435 covering multi fiber connectors. Durability and performance of these connectors is primarily governed by the ferrule performance where optimal optical performance can be maintained well over the defined 50 mating cycle requirements. See section 7.0 for further details. System specific mechanical and cable management validation is key throughout the development process.

One unique aspect to optical backplane connectors is there are very few industry standards driving harmonization or intermate ability across types or vendors. Limited standardization efforts primarily within VITA and ARINC organizations focused mainly rugged / aerospace applications with a few vendors being intermatable but not harmonized fully in design.

Across optical backplane connector manufacturers design approaches taken to protect and secure ferrules on the cable and within connector housings differs greatly with each trying to achieve a trade-off between density, robustness and usability. Some low density versions utilize the industry standard MPO style interface as the mating connector while most use proprietary clips and connectors making inter vendor compatibility mostly non-existent. For system designers and end-users it is important to understand how optical ferrules are held within mounting clips for their installation and removal process from the main connector housing during manufacturing and maintenance, and how potential inspection or cleaning processes will be implemented in the intended system.

Alternative multi-fiber ferrule solutions are in development to address end user robustness and usability aspects with a goal of reducing total cost of ownership. These ferrules also provide benefits as to reduced sensitivity to dust/debris, lower spring forces, different mechanical mating and alignment benefits. As with any physical mating interface maintaining cleanliness for unabated fiber to fiber contact at the ferrule surface is critical to optical performance and preventing fiber surface damage. This is especially critical in optical backplane connectors where access to the ferrule interface for cleaning and inspection is more difficult. Ferrule and fiber debris drives interest to ferrule interfaces that do not require fiber to fiber physical mating such as expanded beam and fiber gap ferrules (see Section 5.2 for details). When alternative multi-fiber ferrules are based on the industry standard MT ferrule footprint they can be implemented in any MT ferrule based backplane connector broadening the connectors application space and reducing total cost of ownership.

5.8 Cleaning and Inspection

As optical backplane connectors are often seated deep within a chassis or rack or on narrowly spaced cards, inspection and cleaning aspects of fiber optic interfaces are greatly aggravated due to restricted access to the interfaces. Safety shutters are often utilized on the backplane side of the interface and while helpful for eye safety, complete dust prevention is often not possible. Cleaning and inspection products are developed by various industry suppliers supported by the connector manufacturers or the OEM equipment supplier works to develop their own methods and equipment.

These can be implemented on system dummy cards with cleaning or inspection equipment properly mounted and positioned for the specific chassis implementation. Much care is taken to ship the system elements with factory inspected, cleaned and protected interfaces enabling first time installed system bring up rates to very high levels where long-term repair and inspection takes more effort.

Cleaning and inspections approaches can be examined in section 6.0 and these are often adopted or modified for specific systems vendors applications. These challenges are strong drivers to increased interest in expanded beam and alternate ferrule technologies (e.g air gap) as they ease many aspects of inspection, cleaning and end user cost of ownership.

5.9 Future Connector Roapmap Needs and Challenges

Roadmaps for optical backplane connectors should include several aspects:

- Versions supporting new applications such as rack scale architectures incorporating greater mechanical tolerances and robustness for large heavy drawers and/or sleds
- Versions with low mating forces per ferrule or fiber for economical card and backplane designs
- Incorporation of alternative multi-fiber ferrule technologies easing deployments and usage while reducing cleaning and inspection burdens thus reducing total cost of ownership, see section 5.2
- Improvements in cleaning and inspection technologies
- Support for new fiber types to increase density, reduce fiber bulk, see section 3.1.3
- Potential standardization efforts providing supply side security and increasing volumes through wider adoption

6. Cleaning of connector faces

6.1 Importance of Connector End Face Cleanliness

Cleanliness of the connector end face is critical to having a good link in an optical network. Optical signals in single-mode fibers have a beam diameter of only roughly 9 μm. Any small particles of dust at any connectivity point of an optical link may cause excess reflection, excess insertion loss or even fiber damage.

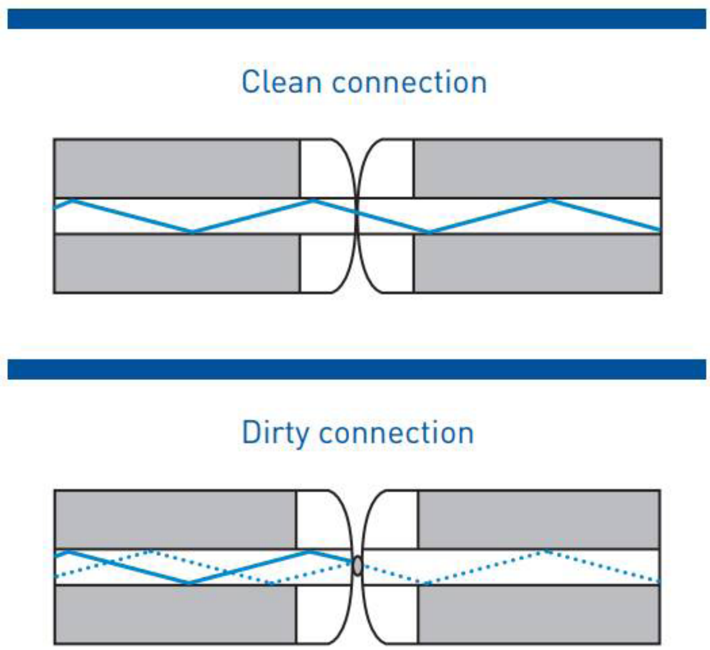


FIGURE 6-1: CLEAN VS DIRTY CONNECTION

6.2 Standards for Connector End Face Cleanliness

The IEC 61300-3-35 [24] standard outlines the pass/fail threshold level for the visual requirements for the end face quality of polished fiber for multiple return loss grades. This specification covers inspections of the core, the cladding, the adhesive and the contact and mandates the size and number of scratches and defects that are acceptable. The specification covers PC-polished connectors (for both single-mode and multimode fiber) and angle-polished connectors (single-mode fiber).

6.3 Cleaning Methods

Removing contaminants from optical fiber and bulk heads without damaging the fiber requires special optical cleaning tools. Two categories of tools have been established: dry cleaning tools and wet cleaning tools. Below is an overview of these tools and cleaning techniques, but complete details can be found in IEC TR 62627-01 [25]

6.3.1 Cleaning Types/Tools

Pen Cleaners - Pen cleaners have a reel of cleaning cloth that rotates at the tip of the cleaner when it is pressed against a connector in a bulk head adapter or directly onto a connector if a fitting is placed onto the tip. This instrument with a "push and click" mechanism cleans the ferrule end faces removing dust, oil and other debris without nicking or scratching the end face. There are three main types of pen cleaners suitable for 2.5 mm, 1.25 mm and MPO connectors.

Cartridge Cleaners - With this tool, a small window is opened to expose the cleaning cloth when the lever is pressed. This will also turn the cleaning cloth so that a clean cloth section is used for every clean. The connector end face is pressed and wiped against the cloth. For a more effective clean, specially treated cleaning cloth that prevents electrostatic charge buildup can be used.

Lint Free Wipes - Lint-free wipes are not usually used to clean connector end face. The operation of wiping the connector end face with a lint free wipe requires delicate skill to avoid damaging the connector end face.

Lint Free Swabs - Lint free swabs can be used to clean the internal barrel of a bulkhead adapter or the connector end face which is terminated in a bulkhead adapter.

Adhesive-Backed Cleaner - Adhesive-backed cleaners have a sticky tip with a soft backing at the top of the cleaner. This cleaner is pressed onto the end face of a bare connector or when terminated in a bulkhead adapter. The soft adhesive removed dust and other particles.

Compressed Air - Compressed air or air duster is used to blow air through the nozzle to get rid of dust on the connector end face. To maintain purity and pressure in the canned air, special material such as difluoroethane or trifluoroethane is used. It is advisable to select a material which has a lower Global Warming Potential (GWP) index

6.3.2 Dry Cleaning vs Wet Cleaning

In most cases, the cleaning tools above can be used dry. Dry cleaning is the most common and fastest cleaning method used in connector manufacturing. In situations when contamination on connectors is unable to be cleared by dry cleaning alone, wet cleaning is necessary. This is usually required when contaminants on a connector end face are left uncleaned for a long period of time. If wet cleaning is required, the same dry cleaning tools above are used but with an application of 99.9% isopropyl alcohol.

Multiple wet cleanings may be required to fully clean a connector end face and must always be followed by a final dry clean to remove isopropyl alcohol residue. See Figure 6-2 for more information about when to use dry and wet cleaning.

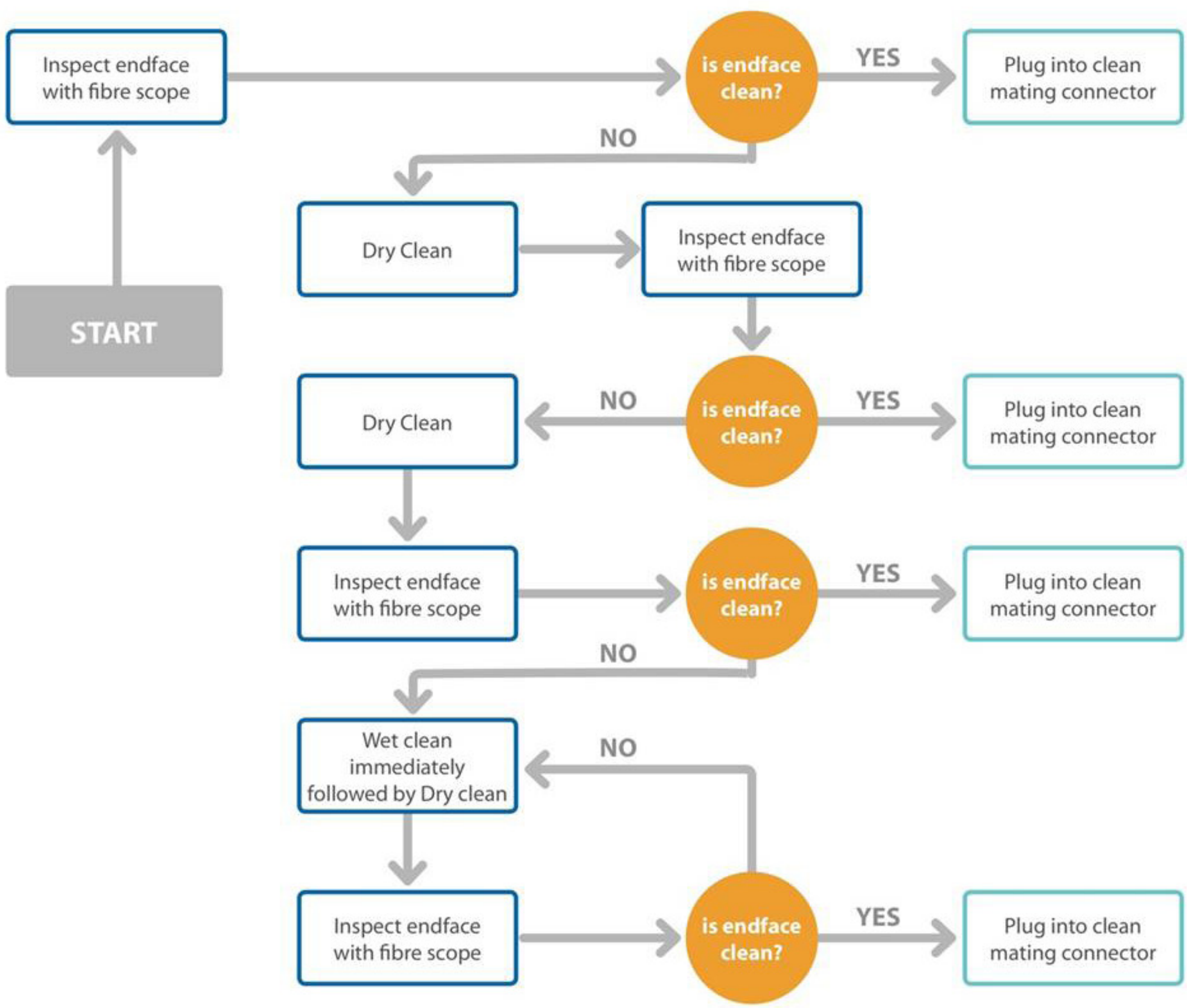


FIGURE 7-2 DRY-WET CLEANING DECISION CHART

7. Connector reliability and performance standards

International standards were developed to assure connector reliability and performance stability. IEC is the international standardization organization for electrotechnical products including fiber optics. IEC and TIA are widely known standardization bodies, and they provide connector performance requirements, test parameters and test procedures. Those test specifications from IEC and TIA are widely used for many market applications.

Telcordia is the standards body responsible for connector quality and it has issued two generic requirements documents that cover both single-mode and multi-fiber single-mode connectors and jumper assemblies.

7.1 Service Environment Categories

The IEC 61753 series [26] defines the tests and the recommended severities and performance criteria for different performance categories or general operating service environments for different products. The different performance categories are defined in IEC 61753-1 [27] as the following:

Performance Category	Description	Operating Service Environment
C	Indoor controlled environment	-10 ºC to +60 ºC
OP	Outdoor protected environment	-25 ºC to +70 ºC
OP+	Outdoor protected environment with wider temperature range	-40 ºC to +75 ºC
I	Industrial environment	-40 ºC to +70 ºC
E	Extreme environment	-40 ºC to +85 ºC

TABLE 7-1: PERFORMANCE CATEGORIES FOR FIBER OPTIC CONNECTORS, PASSIVE OPTICAL COMPONENTS

* For C, OP, OP+ and I, seperate categories with higher upper temperatures exist for locations where active electronics generate heat (e.g. C^{HD})

Standards with minimum initial test and measuremen
t severities and requirements are specified for example in IEC 61753-021 series [28] for single-mode connectors and in IEC 61753-121 series [29] for simplex and duplex cords with single-mode fibers. These performance tests do not guarantee the performance of a lifetime.

Reliability testing is not included in the IEC 61753 series [26]. The IEC 62005 series [30] , defines suitable reliability tests for fiber optic interconnecting devices (connectors) and passive optical components. IEC 62005-9-2 [31] includes reliability qualification of single fiber optic connector sets for single-mode fibers.

7.2 Single-mode Fiber – Telcordia GR-326

GR-326 [23] is a rigorous and complete standard for these connectors expressing the required features and characteristics of these connectors. Issue 4, the current version, includes updates covering endface geometry, connector reflectance, samples after salt spray exposure.

7.3 Single-mode Multi-Fiber – Telcordia GR-1435

GR-1435 [22], similar to GR-326 [23], spells out the desired features and characteristics for multi-fiber connectors. GR-1435 is on issue 2, which includes standards for an expanded number of cable media types, updated optical performance criteria for certain applications, alignment of environmental tests with GR-326 with updates for controlled and uncontrolled environments, revised mechanical tests and updated extended service section. The requirements in this document were developed for single-row MT ferrules, and additional considerations may be needed for multi-row ferrules. In addition to single-mode requirements, GR-1435 contains supplemental information on multimode multi-fiber connectors in the Appendix.

7.4 Cabling for Customer Premises - ISO/IEC 11801 Series

The ISO/IEC 11801 [7] series specifies requirements of the communication cabling of customer premises that supports a wide range of services including voice, data and video. That includes performance requirements to the cabled fibers and optical connectors as well as the connecting hardware types at specific interface locations.

7.5 Optical Cabling and Components - TIA-568.3

This standard specifies the requirements for optical fiber cabling and components. TIA 568.3 [21] contains both single-fiber and multi-fiber connector requirements. Unlike General Requirement specifications, this document specifies single-mode and multimode connectors. As GR-326 does not define the multimode fiber case, TIA 568.3 is referred for the tests on single-fiber connectors with multimode fiber.

7.6 Connector Performance Stability

A key issue that can cause high insertion and return losses is poor intermateability between connectorized fiber-optic jumpers from different manufacturers. Even with defined standards, there can be differences in tolerances that create inconsistencies between products from different (and sometimes the same) manufacturers. IL specifications are set by GR-326 and should be a mean of 0.25 dB and a max of 0.5 dB. Replicating this in the field is a challenge.

For example, when Random Mating patch cord without using Master Patch cords (as outlined in the IEC 61300-3-34 [32] or IEC 61300-3-45 [33] measurement procedures), a company can replicate the IL results it can expect in the field. In these cases, it is possible to have a total IL of more than 1.0dB, even when using products that comply with GR-326. Table 7-2 shows the attenuation grades specified in IEC 61755-1 [34]:

	Attenuation of randomly mated connectors	
Attenuation grade	≥97%	Mean
A[n]	–	–
B	≤.25 db	≤.12 db
C	≤.50 db	≤.25 db
D	≤1.0 db	≤.50 db

TABLE 7-2: ESTIMATED FAILURE AND FIT RATE AS A FUNCTION OF BEND RADIUS

a Attenuation grades at 1310 and 1550 nm
b Attenuation measurement according to IEC 61300-3-34 for mated connectors with single fiber ferrules and IEC 61300-3-45 for mated connectors with multi-fiber ferrules
c Reserved for future aplication

When choosing a connector to minimize IL in a random mating application, look for manufacturers that categorize their connectors to the IEC 61755-1 grades.

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Some useful links for obtaining standards documents: https://webstore.iec.ch/?ref=menu
https://www.itu.int/ITU-T/recommendations/index_sg.aspx?sg=15.
https://standards.globalspec.com/
https://www.cenelec.eu