Selecting Small Form Factor Connectors for Fiber Optic Equipment and Infrastructures

The Advantages of a Hybrid PANDUIT FJ® / LC Solution

White Paper – 1/2004
Executive Summary
A thorough review of the designs and quality metrics of Small Form Factor (SFF) fiber optic connectors with respect to specific applications within the TIA/EIA-568-A Enterprise network model was performed.

A “House of Quality”\(^1\) approach to quantify the differences in the quality metrics among SFF connectors indicates the limitations of the MT-RJ connector solution and suggests the use of an alternate SFF interconnect solution. This solution includes a marriage of the robust Panduit FJ connector in bulkhead/outlet applications and the LC connector for the high densities required in closet and cross-connect applications.

The analysis presented herein highlights the weakness of the MT-RJ in infrastructure applications in terms of channel and return loss and its mechanical and reliability shortcomings in fiber-to-the-desk (FTTD) applications. These are the very areas where the combination of the FJ\(^{®}\) OPTI-JACK\(^{®}\) Module in FTTD and the LC Connector in infrastructure patching/cross connect excel.

Over the past several years, as an equipment connector, the MT-RJ has been popular in 100BASE-F applications, but is being overtaken in newer higher speed designs (1-10Gb/s) by the Lucent designed LC. Technical issues associated with driving transceiver costs down have limited the applicability of the MT-RJ at these higher data rates. Most high-speed transceiver vendors have standardized on the LC.

Both the FJ and the LC utilize familiar and proven fiber alignment designs (separate, independent ferrules and sleeves). The MT-RJ on the other hand uses a unitary “ferrule” that houses both fibers. Dimensional complexity handicaps the MT-RJ. Hence, compared to both the FJ and the LC, the MT-RJ is a substandard performer in terms of channel loss and channel loss variation.

In the sometimes harsh environment of FTTD, connectors are subject to mechanical shock and frequent moves, adds and changes (MACs) that are not usually present in equipment rack applications. This paper illustrates that the most robust connector for wall plate/bulkhead applications is the FJ Jack Module. It houses independent moving and separate fiber channels in a unitary plug and jack format that is familiar to end-users and very robust against mechanical shock.

MACs subject the connector interface to contamination that can seriously degrade channel loss. The MT-RJ is much more difficult to clean than either the FJ or the LC connector. Field repair of the pre-polished end of the MT-RJ is impractical in the case where contamination degrades the fiber surface (no field polish solution exists for the MT-RJ). With independent ferrule style connectors (FJ and LC), this is easy to do with simple polishing tools that are familiar to most installers.

Because of these and other issues highlighted in this paper, it is recommended that a “hybrid” solution of FJ/LC is used for Data Center and Enterprise interconnect.

The Small Form Factor
Widespread use of optical fiber in the Enterprise and particularly in Data Center applications has helped to drive the deployment of SFF fiber optic connectors. The primary goal in Enterprise applications is increased fiber termination count within existing and currently available facilities, or conversely, the reduction of the total interconnection envelope for an existing installation. Several designs for SFF are presently available. The SFF connectors examined in this paper (FJ: TIA/EIA FOCIS-6, LC: TIA/EIA FOCIS-10, and MT-RJ: TIA/EIA FOCIS-12) comprise three of the most popular systems used in Enterprise applications in the North American market.

SFF Connector History and Standards
Cabling standards organizations (IEC and TIA) have endorsed the use of diverse SFF connector designs by opening Enterprise infrastructure to all SFF connectors that satisfy applicable TIA/EIA and/or ISO/IEC standards. The ISO/IEC 11801 standard recommends using SC connectors at Telecommunications Outlets (TO), but also endorses SFF use in high-density applications such as Telecommunications Closets (TC) and Consolidation Points. SFF connectors are approved in any Enterprise location within a TIA-568 standardized network.
The fiber connector ports available on current system optoelectronics hardware should not influence the choice of a SFF connector for infrastructure. Optoelectronics gear (routers, switches etc.) is updated and changed out more frequently than infrastructure hardware (cable, cable management and connectors) and the interfaces on optoelectronics are not the deciding factor for the interconnect solution in infrastructure. ESCON and FDDI connectors were common optointerfaces, but never became important in infrastructure connectivity in this case because of low-density potential, large interconnect envelopes and cost. In the 80’s and early 90’s, both of these connectors enjoyed popularity as equipment interconnect but never replaced the installed base of Biconics, STs and SCs. A similar thing is happening today with the MT-RJ.

Today, FJs and LCs are in the cabling infrastructure as existing or newly installed interconnect. Looking at legacy applications versus new installs, a large number of new installs are occurring with these connector systems.

With respect to current SFF connectors for high-speed networking, both the ESCON and FDDI interconnect (particularly ESCON) are considered obsolete. In perspective, there have been almost 100 optical fiber connector designs in the last 20 years. Only about 5 or 6 have had significant market acceptance.

Looking forward (and recognizing that even though this is not an infrastructure driver), the large majority of 10Gb/s transceiver manufacturers (Agilent, Finisar, Stratos Lightwave, Picolight, Molex, and Samsung) offer LC transceivers in the Small Form factor Pluggable (SFP) version only. Tyco Electronics, one of the MT-RJs original benefactors, now offers a singlemode and multimode LC-based SFP product line.

Also, IBM SFF transceivers have adopted the LC connector as the standard because of tolerances built into both the connector and transceiver aspects of the design.

**Typical TIA/EIA-568-A Cabling System**

For the Enterprise network, the recommendations of TIA/EIA-568-A include multiple wiring closets that are distributed in a star topology throughout the building(s) and/or floors (Fig. 1). This can be a vertical network (between floors) or horizontal (between satellite locations on the same floor). In each of these cases, multiple wiring closets branch from the Main Cross Connect (MC or MXC).

At the top of the network, and with the highest level of networking component functionality is the MC. Connected to the MC via fiber backbone cables (dashed lines) are intermediate distribution centers (IC) or telecommunications closets (TC). From the TC to the desktop workstations, long runs of fiber cable can be installed. The TC provides network administration (e.g. cross connect) and organization (storage, splices, etc.) and can contain the lower rungs of the terminating electronics (e.g. hubs, routers).

![Figure 1 – “Typical” Enterprise Network](image-url)
The LC Connector in Fiber Management and Transceivers

The LC connector system, standardized as TIA/EIA FOCIS-10, was designed specifically to address the needs of increasing network interconnect density.

In the past, fiber management systems (for D4, ST, FC and Biconic), have required twice as many individual connectors as copper systems, hence, crowding racks and closets (Fig. 2) with additional patch bays, management hardware and line terminating electronics. SFF connectors have either a unitary body design (FJ and MT-RJ) or a provision for clipping simplex connectors together to form a single SFF end (LC).

The LC connector provides the potential for twice the interconnect density in closets and racks when compared to a SC connector. Although, there is a point at which additional density cannot be utilized because of the difficulty in fiber routing inordinately large cable counts. Also at issue in these higher density racks, is the problem of disturbing adjacent circuits in MACs. Most important in fiber management, is the decreased footprint of the LC on electronics (hubs, switches, etc.) for fiber transceivers.

SFF Connector, SFP Transceivers and the march towards 10Gb/s Enterprise Networking

Original SFF transceivers (GBICs) on equipment have now been overshadowed by the SFP (“pluggable” versions of the SFF) transceiver. Equipment vendors are starting to offer SFP on switches/NICs for Gb/s Ethernet. The optical receptacle on the SFP for Fibre Channel and Gb/s Ethernet is the LC connector. Most major transceiver vendors, including early proponents of “MT-RJ-only” transceivers, now sell SFPs with the LC interface only.

On 200 pin XenPAK transceivers, only SFF options are specified in the Multi Source Agreement (MSA). Vendors have offered XenPAK with both SC and LC pigtails, but the majority offers “LC-only” XenPAK product lines. The LC is also used in competing transceivers such as XenPAK, X2 and XFP.

10Gb/s Standards are driving network planners to “future proof” infrastructure hardware (fiber, cable management and interconnect) and to prepare their network Storage Area Networks and Fiber Backbones to be able to utilize these new high-speed transceivers. Network planners are standardizing on the LC.

LC Market Acceptance

The LC is the market leader in SFF connectors. Press releases from the major vendors of LCs (Lucent) and MT-RJs (Tyco/AMP) in similar time frames (mid '01) indicate unit volumes of 20 million and 3 million respectively.

Table 1 – SFF Market Growth

<table>
<thead>
<tr>
<th>SFF Type</th>
<th>2001-2006</th>
<th>2006-2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>LC</td>
<td>60.1%</td>
<td>53.2%</td>
</tr>
<tr>
<td>MT-RJ</td>
<td>26.4%</td>
<td>23.7%</td>
</tr>
</tbody>
</table>

Source: Electronicast, May 2003

According to the Fiber Optic Connector/Mechanical Splice Global Market Report by Electronicast, the North American Market for private network use of SFF connectors is expanding quite rapidly. In this report, the multimode LC is estimated to grow at double the rate of that of the multimode MT-RJ (Table 1). The difference embedded in the Electronicast data is the creation of new installations (LC) versus the support of existing facilities (MT-RJ).

The multimode MT-RJ found early support in 100BASE-F applications. In spite of this, the LC is becoming the optoelectronics interconnect solution for 1-10Gb/s applications. The emerging 10Gb/s market has forced transceiver vendors to evolve toward pluggable designs with the LC as the primary choice of interconnect.
The FJ® Connector in FTTD Applications

The PANDUIT® FJ connector system (Fig. 3), specified as FOCIS-6, was designed specifically for FTTD and FTTZ (Fiber-To-The-Zone) interconnect.

The FJ connector envelope, standardized in 1996, was the first such of all SFF designs. It is based on the familiar RJ45 form factor and is a true duplex (unlike the LC which uses a duplexing clip).

The adapterless FJ is easily field terminated with common fiber optic tools, and is designed around regular zip cord cable. Of all of the connectors destined for FTTD applications, it’s the one that looks the most familiar to the average installer (based on proven and user-friendly 2.5mm ferrule technology, with a termination process similar to STs and SCs).

Benefits intrinsic to this design that make it the most appropriate of the three SFF connectors (FJ, LC and MT-RJ) for wall plate applications include the provision of visual (color-coding) and mechanical (integrated key) differentiation, thus providing network security for military, government, financial and educational applications. This feature also serves to limit access to highly sensitive, classified, or segregated networks. The standardized color-coding scheme on the connector bodies prevents unintentional insertion into adjacent ports and assures network continuity.

By design, this is a very physically (and optically) robust connector system that is ideally suited to the sometimes harsh environment of FTTD. In this setting, the mated FJ plug and jack can be subject to the everyday, unintentional, bumps and knocks of the workplace.

Quick terminating variants of the female jack for 900 micron through 3.0mm fiber cable for Behind The Wall (BTW) application are available for connections to consolidation points or wiring closets, as is the hybrid assembly cordage required to make the connection from the wall plate to workstation NICs.

One of the largest long distance carriers in the world chose the FJ for FTTD in their corporate campus, using 300,000 duplex FJ connector sets (singlemode and multimode). At ground breaking, this campus was the largest construction project in North America and the largest Fiber-to-the-Desk installation in history.

Millions of fibers have been terminated worldwide with FJ in FTTD applications.
Connector Design Comparison

Design characteristics of the FJ and LC connectors include large fiber pitch (required for low cost transceiver design – FJ and LC pitch only vary by 10µm), precision fiber alignment, simple connector cleaning and duplex configuration. These design features insure excellent performance and long life for field or factory-terminated connectors. A connector design comparison, summarizing these characteristics (Table 2 below), shows that the FJ and LC connectors are the optimum interconnect solutions for FTTD and equipment/closet applications, respectively.

<table>
<thead>
<tr>
<th>Design Feature</th>
<th>FJ</th>
<th>LC</th>
<th>MT-RJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber Pitch</td>
<td>6.35mm</td>
<td>6.25mm</td>
<td>0.75mm</td>
</tr>
<tr>
<td>Mating</td>
<td>“Elastic Contact”</td>
<td>“Elastic Contact”</td>
<td>Undefined</td>
</tr>
<tr>
<td>No. of ferrules</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Simplex Availability</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Channels</td>
<td>Physically Independent</td>
<td>Physically Independent</td>
<td>Conjoined</td>
</tr>
<tr>
<td>Keying / Security</td>
<td>Multiple - with master key for troubleshooting</td>
<td>BTW Keying</td>
<td>Male/Female Keying</td>
</tr>
<tr>
<td>Channel I.D. Polarization</td>
<td>Both; color-code for I.D.</td>
<td>Polarization only</td>
<td>Polarization only</td>
</tr>
<tr>
<td>Configuration</td>
<td>Plug-Jack</td>
<td>Plug-Adapter-Plug</td>
<td>Plug-Adapter-Plug; Plug-Jack</td>
</tr>
<tr>
<td>Ferrule Material</td>
<td>Zirconia Ceramic</td>
<td>Zirconia Ceramic</td>
<td>Plastic</td>
</tr>
<tr>
<td>Physical Contact</td>
<td>Yes</td>
<td>Yes</td>
<td>Unreliable</td>
</tr>
<tr>
<td>Alignment</td>
<td>Precision Sleeve and Ferrule</td>
<td>Precision Sleeve and Ferrule</td>
<td>Pins and Ferrule</td>
</tr>
<tr>
<td>Latch style</td>
<td>1 RJ Latch</td>
<td>2 RJ Latches</td>
<td>1 RJ Latch</td>
</tr>
<tr>
<td>Ferrule size</td>
<td>Ø 2.50mm</td>
<td>Ø 1.25mm</td>
<td>2.5 x 4.4mm</td>
</tr>
<tr>
<td>Cleaning</td>
<td>Easy (with simple tools)</td>
<td>Easy (with simple tools)</td>
<td>Difficult (with simple tools)</td>
</tr>
<tr>
<td>Fiber cable</td>
<td>Duplex Zip</td>
<td>Duplex Zip</td>
<td>Duplex/Ribbon</td>
</tr>
<tr>
<td>Jumper / Pigtail Field Termination</td>
<td>Yes – Anaerobic or Heat Cure</td>
<td>Yes – Anaerobic or Heat Cure</td>
<td>No</td>
</tr>
<tr>
<td>BTW Field Termination</td>
<td>Yes – Anaerobic, Heat Cure or Pre-terminated Fiber Stub</td>
<td>Yes – Anaerobic, Heat Cure or Pre-terminated Fiber Stub</td>
<td>Yes – Pre-terminated Fiber Stub, Pigtail</td>
</tr>
</tbody>
</table>
Fiber Pitch

Fiber cables come in a variety of form factors. Because of the 750 micron spacing of the fiber holes in the MT-RJ ferrule, the design is best suited to ribbon cable construction with 250 micron coated fibers. FJ and LC connectors, in contrast, were designed to be compatible with existing multi-channel indoor cable and jumper cordage designs. With fiber spacing of 6.35mm and 6.25mm respectively, the FJ and LC connectors are utilized for their compatibility and ease of installation on standard cable designs with buffered fiber sub-units.

Some authors\textsuperscript{2} have described high-speed transceivers by designing around the tight fiber spacing of the MT-RJ design. This is not without design challenges:

- Tolerance Build Up – By having a unitary ferrule structure (2 fibers in a block), the budgeting of the fiber to device alignment becomes a design and process challenge. Instead of dealing with two separate, smaller alignment problems (circular single channel alignment for the LC), the alignment problem now deals with more than two-fold the critical alignment parameters. The optoelectronics alignment (emitter and photo detector must also be aligned with respect to each other for the MT-RJ). An excellent assessment of a tolerance build-up in the transceiver alignment problem for the LC and MT-RJ is offered in an engineering report\textsuperscript{3} by Methode Inc.

- Cross Talk – In order to minimize cross talk between outgoing and incoming signals, some manufacturers have resorted to exotic wave guiding or bulk optical component approaches in the OSA (Optical Sub-Assembly). This serves to complicate the assembly process and drive transceiver cost up.

- Additional Optical Components – In contrast to the MT-RJ, the LC enables direct coupling of the fiber ends to the transceiver devices. MT-RJ design approaches add optical components (loss), and complexity (cost).

- Shielding Effectiveness – The cross sectional area of the opening presented by the connector is much less in OSAs designed for use with the LC than for that of the MT-RJ. At high data rates, small openings in the front of the OSA that do not have a short path to ground become potential conduits for RF leakage. MT-RJ OSAs are hence intrinsically more difficult to design for good shielding effectiveness.

With the move to multi-Gb/s transmission, the cost and performance benefits of high-speed transceivers designed around duplex independently ferruled connector (the LC) becomes apparent.

Cleaning

In order to maintain the ongoing performance measures of the connector system, quality cleaning is necessary (after MACs, for instance). Debris in the connector interface (present after polishing or accumulated by multiple mating cycles) must be removed to assure robust channel margins. Cleaning FJ and LC connectors is a simple task, even with simple hand-held tools. Efficacious cleaning around the base of the alignment pins in the male side of the MT-RJ connector is very difficult. Also, the female side alignment holes act as debris receptacles.

Both FJ and LC connectors present easier to clean interfaces with less expensive cleaning options.

Channel Configuration

Applications such as the fiber version of IEEE 1394 (Firewire) and cross connect patching demand simplex connectors. The only connector of the three mentioned in this paper that supports a simplex configuration is the LC. Both of the FJ and MT-RJ connectors are duplex by design. The difference (as mentioned before) is that the MT-RJ does not use separate, free-floating and independent ferrules. The LC connector is a simplex connector configured as a duplex design. Also, both the FJ and LC connectors totally eliminate the need to re-terminate to correct polarization errors.
Fiber Alignment Method

Insertion loss in fiber connectors is strongly affected by dimensionality of the fiber connector, specifically the business end of the connector, the ferrule. The FJ and LC are independent ferrule, circular contacts that rely on a few key ferrule dimensions (hole diameter, concentricity) to centrate the fiber with respect to the alignment datum (the ferrule O.D.). Proper fiber alignment is assured through precision machining of the Zirconia ceramic ferrules. The nature of this precision is so refined that it pushes the “state-of-the-art” sub-micron metrology used to define it.

In the injection molded MT-RJ body, fiber positioning and alignment is fundamentally difficult, with requisite alignment of two fibers and two mating pins.

A simple Geometric Dimensioning and Tolerancing (GD&T) assessment of the design datum(s), feature (fiber hole) sizes and feature positions across the three connector systems is presented in Table 3 below:

<table>
<thead>
<tr>
<th>DIM.</th>
<th>FJ</th>
<th>LC</th>
<th>MT-RJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Datum(s)</td>
<td>Simple - Ferrule O.D.’s &amp; Sleeve I.D.’s</td>
<td>Simple - Ferrule O.D.’s &amp; Sleeve I.D.’s</td>
<td>Compound - defined by male Pin O.D.’s., pin separation, pin/hole projected tolerance zones, female hole I.D.’s, hole separation</td>
</tr>
<tr>
<td>Feature Sizes</td>
<td>Simple - Ferrule hole I.D. &amp; circularity</td>
<td>Simple - Ferrule hole I.D. &amp; circularity</td>
<td>Simple - Ferrule Hole I.D. &amp; circularity</td>
</tr>
<tr>
<td>Feature Positions</td>
<td>Simple - Concentricity with respect to datums</td>
<td>Simple - Concentricity with respect to datums</td>
<td>Compound - True positions of features with respect to simulated datums (represented by alignment feature medians)</td>
</tr>
</tbody>
</table>

With design and process simplicity in mind, a direct comparison of the precision of the manufacturing process (machining versus molding) and the count of critical control dimensions between independent, circular contacts (FJ, LC) and a unitary duplex design (MT-RJ) weighs in favor of the later. Better dimensional control in the FJ and LC connectors (compared to MT-RJ) equals decreased variability and increased predictability of channel loss.

Field Installation

The field installation process of MT-RJ connectors generally necessitates pre-polished, crimp-on or cam-on fiber stub style connectors or fusion splicing of MT-RJ pigtails. No field polish solution exists for the MT-RJ. The BTW solutions available are designed around a pre-polished fiber stub that yields inherently higher insertion losses than a field polish solution (and higher than FJ and LC fiber stub BTW connectors). The losses of the MT-RJ in actual usage (jumper connector to BTW connector) can exceed the limit specified in the TIA/EIA 568 standard (0.75dB maximum). Although these are quick terminating options, they have the potential to put the installers link budget at risk (1000BASE-SX applications, working with a 2.5dB total budget can be especially risky with MT-RJs).

The FJ and LC connectors both have maximum insertion losses of roughly 0.3-0.35dB (with 0.15-0.20dB as a typical result) for multimode fibers terminated in the field. Installation of these connectors with anaerobic adhesive and quick polish techniques can typically be done in 2-3 minutes.

Some vendors now offer stub-equipped BTW LCs. The independent body/independent ferrule design of these LCs offers better mechanical integrity than their MT-RJ counterparts, but is not without risk. Stub-equipped FJs, with a unitary body/independent ferrule design are the most physically robust outlet/BTW solution.
The Fiber Optic “Elastic” Contact

Independent, spring loaded fiber optic contacts (ferrules) have proven themselves in all performance aspects through years of field use. Duplexing independent FO contacts does not change the level of performance that has been historically demonstrated and accepted in single FO contacts. Physical fiber contact (an “elastic contact”) in these connector systems is a key Figure of Merit (FOM), critical to low insertion/return loss and environmental stability. Preferably, the physical contact described is near spherical with a precisely prescribed and controlled radius, which is centered on the axis of the fiber.

As a side note, physical contact of circular fiber/ferrule contacts has been described frequently through the use of Hertz Stress formulations6).

While intimate physical contact of fibers is easily (and regularly) achieved with the FJ and LC connectors, it is significantly more of a challenge with the MT-RJ. In the MT-RJ, the contact can be described by two slightly deformed parallel cylinders (both larger in the middle) that abut each other face to face. The line of contact is along the axis defined by the fiber pair. Small displacements from nominal fiber protrusion or small increments of connector surface tilt (especially in the direction of the long axis) disturb the balance of the contact and prevent the fibers from achieving full seating. Material “polishing hardness” difference in the MT-RJ (between the composite ferrule block and the fiber) manifests itself in wide variations of the finished surface geometry.

This impacts insertion loss only marginally, but return loss can be impacted catastrophically. The “close, but not touching” scenario is the worst case for singlemode and multimode, physical contact connectors. The cavity can become a source of “multiple beam interference” and may actually exceed the normal Fresnel related reflections of mated fibers with an air gap (Fresnel for two fibers = -14dB, worst case with interference = -8.8dB).

Spring-loaded independent ferrules on FJ and LC connectors ensure full physical contact by design.

Channel Loss

Channel loss performance is a prime driver in interconnect selection because power budgets are shrinking. The 10-12dB budgets for legacy 10Mb/s and 100Mb/s applications now give way to new applications with much more stringent budgets. Both 1 and 10Gb/s Ethernet have 2.5dB loss budgets for 2,000Mhz-km fiber to as low as 1.6dB (200MHz-km fiber). These standards allocate two connection losses at 0.75dB each.

Published specifications relevant to the MT-RJ include:

- Mechanical Splice insertion loss = 0.15 mean; ≤ 0.3dB (for reference, one for each channel in BTW MT-RJ)7)
- Factory Pot and Polish MT-RJ insertion loss = 0.2dB average (no maximum stated)6)
- Fiber Stub Style MT-RJ insertion loss = 0.3dB typical (no average or maximum stated)9)

These specifications have been validated in testing (completed by Avaya4)) of channel attenuation in a statistical study of LC and MT-RJ concatenated jumpers. The results of this particular study showed that the LC channels had nearly half of the insertion loss and standard deviation of the MT-RJ channels. The FJ connector system yields similar insertion loss statistics to the LC5).

The FJ and LC connectors both provide added channel margin and hence offer the potential to support future infrastructure reconfiguration (adding additional connectors).
Quality Framework for SFF Connector Families

In the Harvard Business Review, David A. Garvin proposed eight key dimensions of quality that can provide a framework for benchmarking quality differences among SFF connector families. Below, these Figures of Merit (FOMs) are applied to the case of SFF fiber optic connector options for use in equipment and bulkhead applications. These FOMs, as described by Garvin, comprise four customer “required” dimensions and four “desired” dimensions.

Table 4 below summarizes the key Quality FOMs and their associated quality characteristic(s) for the FJ, LC and MT-RJ connector systems in both equipment and infrastructure applications. A discussion of the preferred connector choices in each of these applications follows (gray area in table suggests the best performing connector for the stated FOMs).

<table>
<thead>
<tr>
<th>Quality FOM</th>
<th>Characteristic(s)</th>
<th>Equipment/Closet</th>
<th>Infrastructure (FTTD)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. PERFORMANCE</strong></td>
<td>Channel Loss</td>
<td>⭐⭐⭐⭐</td>
<td>⭐⭐⭐⭐</td>
</tr>
<tr>
<td><strong>2. CONFORMANCE</strong></td>
<td>SM 10Gb/s Operation, Multiple Applications</td>
<td>⭐⭐⭐⭐</td>
<td>⭐⭐⭐⭐</td>
</tr>
<tr>
<td><strong>3. RELIABILITY</strong></td>
<td>Mechanical Shock, Side Loading</td>
<td>⭐⭐⭐⭐</td>
<td>⭐⭐⭐⭐</td>
</tr>
<tr>
<td><strong>4. DURABILITY</strong></td>
<td>Repeatability, Repeated Mating</td>
<td>⭐⭐⭐⭐</td>
<td>⭐⭐⭐⭐</td>
</tr>
<tr>
<td><strong>5. SERVICEABILITY</strong></td>
<td>Troubleshooting Ease, Maintenance</td>
<td>⭐⭐⭐⭐</td>
<td>⭐⭐⭐⭐</td>
</tr>
<tr>
<td><strong>6. FEATURES</strong></td>
<td>Security Config’s, Installation Time</td>
<td>⭐⭐⭐⭐</td>
<td>⭐⭐⭐⭐</td>
</tr>
<tr>
<td><strong>7. AESTHETICS</strong></td>
<td>Construction, Color Choices</td>
<td>⭐⭐⭐⭐</td>
<td>⭐⭐⭐⭐</td>
</tr>
<tr>
<td><strong>8. PERCEIVED QUALITY</strong></td>
<td>Construction, Life Cycle Costs, History</td>
<td>⭐⭐⭐⭐</td>
<td>⭐⭐⭐⭐</td>
</tr>
</tbody>
</table>

Note 1 - FJ equipment applications limited to interconnect/bulkhead (non-transceiver)

“Required Qualities” - Quality dimensions that the connector must possess:

1. PERFORMANCE

The primary operating characteristics of the connector system describe its performance. For various connector solutions, typical performance characteristics are insertion loss, return loss and termination time. Because this quality dimension involves measurable attributes, the various connectorization solutions can be graded objectively with respect to demonstrated performance. Overall rankings of performance are usually harder to generate, because they may involve benefits that are not required by all customers (e.g. Return loss is a non-issue in FDDI and Fibre Channel applications and cable retention may not be important in BTW applications).

Preference - With respect to loss characteristics, circular/independent ferrule connectors are favored over unitary ferrule, multi-fiber connectors. MT-RJ technology, by design, and in any format (pot/polish or fiber-stub), simply cannot match the repeatable high tolerance characteristics of the ceramic ferrules native to both the LC and FJ designs. MT-RJ alignment relies primarily on the true position of two, sometimes non-circular holes, in reference to a compound datum defined by the spacing and size of two pins (or holes for the female side). When you contrast this to simple concentric circular, independent channel connector alignment, it is no surprise that MT-RJs in some studies show double the insertion loss and insertion loss variation compared to their FJ and LC counterparts.
2. CONFORMANCE

The extent to which physical and optical characteristics of the interconnect meet the standards espoused by vendors and/or accepted as industry normative. Two frequently used metrics in conformance failure are factory defect rates (producers risk) and the rate of field install failures (consumers risk). Missing parts or instructions, that do not necessarily lead to service calls or factory corrective action are considered deviations from standard, but are not considered here.

Preference - Several authors\(^2\)\(^{11}\) have claimed MT-RJ return loss of no less than 28dB and 40dB for multimode and singlemode operation, respectively. Practical experience in the field has shown that this is difficult to attain\(^2\)\(^{12}\) (without resorting to angled polishing). These authors have shown it to be possible to realize this level of performance in the lab. Numerous others have found these return loss values to be difficult to achieve in typical installation environments.

3. RELIABILITY

Reliability is connector performance degradation likelihood or probability of failure within a specified time. Measures of reliability for an installed connector system are the Mean Time to Failure (MTTF), Mean Time Between Failures (MTBF) and failure rate per unit time (inverse of MTBF). These reliability metrics require the connector to be installed for a specific time and are therefore more relevant to connectors that are installed behind the wall (or panel/bulkhead) than to highly cycled interconnect (as in cross connect patching).

Preference - If a failure is considered to be any change that brings the subject connector system outside of specifications, the ability of the MT-RJ to survive in the harsh environment of the FTTD environment is in question. This environment opens the connector mounted to the outside of the wall to all sorts of physical abuse. The MT-RJ is intrinsically more side loading sensitive than the FJ in this application. A quick look of the length of the lever arm formed by the edge of the ferrule in the widest direction of the MT-RJ indicates the possibility of endface separation when a side load is applied.

4. DURABILITY

Durability has technical and economic implications. Technically, interconnect durability is defined by mating cycles achieved before the insertion loss deteriorates to a prescribed level. It can also be defined by the useful life of a connector system before failure and replacement is necessary. Durability directly impacts Total Cost of Ownership (TCO) for installations that have high incidence of MACs.

Preference - Circular/independent ferrules constructed with Zirconia ceramic ferrules are intrinsically more robust as “elastic” contacts. The endface morphology of ceramic physical contact connectors is known to be unchanged through hundreds of connector mating cycles (the compressive strength of Zirconia is over 10x that of the material used in the MT-RJ). No such published morphological data exists for MT-RJ connectors.

It was found that MT-RJ endfaces become permanently deformed to match the connectors they are mated to. Repeated cycling using the same connector pair (per FOTP-21) can yield good insertion and return loss values. But, when another connector is swapped in, the return loss values can be catastrophically bad (this is not a good situation in practice for MACs).

Additionally, the MT-RJ alignment technique of metal pins in composite material holes is a balancing act of precision fits, usability and damage control. If the dimensions are “line-on-line”, the connector system becomes difficult to mate and the potential for damage of the alignment holes exists (potentially impacting durability with debris). If the dimensions are too sloppy, insertion loss could suffer and/or alignment hole damage can occur.

Compared to the LC, the FJ is more robust against breakage simply because its ferrules have much larger section moduli (e.g. more resistant to fracture in mishandling of the connector).
“Desired Qualities” - Quality dimensions that the connector should possess:

5. SERVICEABILITY
Serviceability is directly related to the speed/ease of repair and troubleshooting of the interconnect system. Users are interested in installation efficiency and the time it takes to troubleshoot and correct interconnect problems during MACs.

Preference - features in the FJ include a “key” which only allows certain connectors to be plugged into certain outlets. The FJ keying option includes a “master” connector that allows connection to the key style on any FJ outlet. This allows for quick troubleshooting of circuits and precludes the need for the service person to carry connector cordage with all styles of keys. These features are not present in either the LC or the MT-RJ.

6. FEATURES
Features are secondary performance aspects of the connector system, the "bells and whistles" design details that complement or enhance basic function (Anti-snag features, tethered protective caps, ergonomics, etc.). The line that delineates primary from secondary connector features can be tough to define. Crucial in differentiation among connectors and their features, is the demonstration of measurable and objective attributes that translate into quality differences.

Preference – On the FJ connector system, the provision of visual (color-coding) and mechanical (integrated key) differentiation provides network security for FTTD applications. This feature also serves to limit access to highly sensitive, classified, or segregated networks. Color-coding identifies different network ports to help prevent unintentional insertion of connectors into segregated network ports.

7. AESTHETICS
A subjective dimension of quality of the connector system is the aesthetics. How the connector system looks or feels in the user's hands is subject to the installer/end user's judgment and is a manifestation of his/her personal preference. The choice of the materials and surface finishes used in the construction of the connector may impact the aesthetics more than the functional aspects of the system. Securing aesthetic preference while fulfilling the functional dimensions of quality can be a challenging job.

Preference – The FJ connector system includes more body color choices than either the LC or the MT-RJ. Not only are these colors functional (as for matching FTTD cordage to the correct outlet jack), but also they can serve to match the aesthetics on the existing office or home environment (by color matching existing or planned decor).

8. PERCEIVED QUALITY
Installers and system designers of fiber interconnect usually don't have comprehensive data regarding a particular interconnect solution’s quality attributes (outside of the manufacturers data and spec. sheets). Indirect measures of “quality” sometimes are the only available comparison basis for connector series or styles. For instance, through everyday use the user cannot directly quantify the durability of a particular connector; it is usually inferred from a combination of tangible and intangible product elements. Sometimes, trade magazine articles/advertising and brand recognition (associations or inferences about quality rather than the reality itself) – are the deciding factors in connector selection. “Word of Mouth” can be a powerful tool in driving connector selection (rumors of low installation yields can have a dramatic impact on the longevity of a connector system).

Preference - The FJ connector is perceived by the user to be of rugged construction and users are more confident in mating the FJ plug to the jack than less mechanically robust LCs and MT-RJs. A visit to Internet message boards frequented by installers such as the BICSI Forums, gives a good flavor of installation issues and particularly “perceived quality”. Many of the threads in these boards relate to “perceived” quality issues with the MT-RJ.
SFF Connector Choice for Equipment/Closet

The LC connector is proving to be a popular choice in Gb/s Ethernet GBICs. It is the standard for Fibre Channel Host Bus Adapters (Agilent, Adaptec, Atop Tech, Emulex, LSI Logic, etc.). The LC is offered by Intel in its range of Gb/s Ethernet server adapters and 1000BASE-SX and 1000BASE-LX transceiver cards. Server adapters for Gb/s Ethernet with LC SFPs are also manufactured by Emulex, Ramix, and many others. A multitude of vendors are now producing LC equipped, 10Gb/s transceivers (in XPAK and XFP formats), targeted at the burgeoning NIC market.

In equipment/closet applications, the required FOMs usually drive connector choice.

SFF Connector Choice for FTTD

In choosing SFF interconnect for FTTD, designers understand that system electronics have a life cycle of two or three years, and that their choice of interconnect at the wall can be free of the constraints of the optoelectronics interconnect that was selected for the equipment. With shrinking channel loss budgets and data rates that continue to increase, system designers need to ensure that the FTTD SFF interconnect system chosen has characteristics that “future proof” their installations. The FJ offers similar channel loss performance to the LC.

With respect to required FOMs, the SFF connector for wall plate and surface mount box applications should have robustness as its key required FOM. The environment in the proximity of the end user is fraught with the potential for damage to interconnect. Accidental bumps or pulls to the cordage connected to the bulkhead can wreak havoc on less stable designs. The FJ offers side loading insensitivity with its uni-body construction and independent ferrule design. Neither the LC nor MT-RJ offers both of these design features.

In FTTD (wall plate) applications, the desired FOMs (particularly aesthetics) usually have a strong influence on connector choice.

Conclusion

LC interconnect offers marked advantages over the MT-RJ in equipment and high-density closet/rack applications. This is based on the market migration of high-speed optoelectronics to the LC and the superiority of the LC in performance and fiber management. The LC supports simplex operation, essential in cross connect and specialty applications, and provides much better channel loss characteristics that aid in “future proofing” the fiber cable infrastructure. LC based interconnect is easier to maintain (cleaning), and provides better reliability and durability (mating cycles) than the MT-RJ.

The continued evolution of Enterprise LC-based optoelectronics is evidenced through the sheer number of SFP transceivers becoming available equipped with the LC interface. The LC is the SFF choice for 10Gb/s transceivers.

Typically infrastructure designs and particularly passive optical interconnect, have a usable life of 2 times that of the 10 years referenced in the international cabling standards (ISO 11801). Superior channel performance is a must to satisfy these types of forward planned designs.

The FJ connector is the most physically robust design for FTTD applications. Its combination of user features, superior channel loss and rugged, unitary plug and jack design, and its similarity to the RJ45 design, make it a solid choice for bulkhead and wall outlet applications.

The FTTD choice of the FJ is synergistic with the LC because of the similarity of the technologies and materials used in design. Ceramic ferrules and traditional alignment techniques are simply better with respect to the required FOMs of Enterprise interconnect. Installers use the same techniques and tool sets for termination for both the FJ and LC.

A combination of the reliable FJ in FTTD applications and the LC in equipment and closet/rack applications satisfies cabling infrastructure requirements and assures ongoing support for multi-Gb/s applications with excellent end-user characteristics, easy serviceability and long life.
PANDUIT® develops and manufactures fiber optic connectors, patch cords, optical component modules, enclosures, and cable management. PANDUIT supplies connectors and patch cords that include FJ® OPTI-JACK® Modules and Plugs, SC, LC and ST connectors. OPTI-CRIMP® FJ Jack Modules, SC and ST connectors are also available for pre-polished crimp termination.

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