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Signature Core™ Fiber Optic Cabling Systems

Multimode Fiber: Understanding Chromatic Dispersion

OM4 SIGNATURE CORE™

OM5 SIGNATURE CORE™

Fiber Future and Beyond

WHITE PAPER

The performance and reliability of networks within the data center are vital to the operation of today's enterprise. As the performance requirements of these networks have advanced to keep up with the data and virtualization explosion, the specifications on the constituent components have also become more demanding. For high-speed optical networks using laser-optimized multimode fiber (MMF) operating at 10/40/100 Gb/s today and 200 Gb/s in the near future, it is more critical than ever for network operators and designers to have an accurate knowledge of the performance specifications of the active and passive fiber optic components used to make up the network.

Traditionally, much of the focus on the performance of passive fiber optic components has been on the overall optical power loss or attenuation of the fiber cable and connectors. Although loss is a critical parameter for the fiber cable and connectivity, signal impairment related to the fiber bandwidth is also critically important for networks operating at gigabit data rates and above. Traditional techniques of minimizing signal impairments by minimizing the total dispersion have been built upon simplified system models that do not consider the interaction of the two primary types of dispersion in MMF networks: modal dispersion and chromatic dispersion. Panduit developed an advancement in MMF communications systems that compensates for both modal and chromatic dispersion, delivering extended reach over OM4 MMF industry standards to deliver verified system performance and signal integrity as well as design flexibility.

This white paper investigates the benefits of deploying Panduit's Signature Core™ Fiber Optic Cabling Systems in data centers, colocations, enterprise, and factory automation. After a review of singlemode and MMF, fiber bandwidth, and the role of bandwidth in chromatic dispersion, this paper explores the comparison between modal dispersion and chromatic dispersion. Finally, this paper demonstrates how Panduit's Signature Core Fiber Optic Cabling Systems can help compensate for the two types of dispersion, solving the problem of poor correlation between fiber bandwidth and system performance in much of today's laser-optimized MMF.

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Singlemode Fiber versus Multimode Fiber

A singlemode optical fiber is an optical fiber that carries a single ray (mode) of light transmission. A mode is the path the laser light travels down the fiber. For singlemode optical fiber, the fiber has a small core diameter which only allows one mode. With only one mode, the signal is free of distortion and therefore the fiber optic medium has extremely long reach; as such, singlemode fiber is used for high speed signal transmission over long distances.

MMF is optical fiber with a larger core than singlemode fiber and is designed to carry multiple light rays, or modes, simultaneously, each mode positioned at a slightly different reflection angle within the fiber core. For MMF, the light can take several paths at once. The larger MMF core makes it easy to capture light from a transceiver and to guide multiple modes at the same time, making it a cost effective alternative to singlemode fiber over shorter distances. MMF speeds up the modes traveling the longer paths and keeps the individual modes (pulses) aligned to reduce the effect of modal dispersion. Even though MMF today corrects for modal dispersion, MMF is used typically for short distances because the modes will still have a tendency to separate over longer lengths regardless of the modal dispersion compensation.

Singlemode optical fiber is good for long runs in data centers, for example, from the data center to telecommunications closets, and can be used to connect buildings on a campus and for telecommunications and cable systems. However, singlemode fiber has a smaller core than MMF, which makes it more difficult to use; also, tighter mechanical tolerances of connectors are associated with singlemode fiber, and the alignment of laser and lens mechanism is more challenging. These differences increase the cost of a singlemode link to two to three times the cost of a multimode link. MMF is ideal for use within data centers because the medium addresses specific network challenges such as limited space, tight bends, short distances, and low cost.

Fiber Bandwidth

Fiber bandwidth is a quantitative measure of how well the medium is able to support a given data transmission rate over a specified distance. Fiber with a higher bandwidth is able to support higher data rates over a longer distance than a fiber with a lower bandwidth. To illustrate the importance of fiber bandwidth, the most important (largest) power penalties for 10 Gb/s Ethernet networks that extend 300m are shown in Figure 1. [1] The intersymbol interference (ISI) power penalty, which is strongly related to the fiber bandwidth, is greater than both the connectors and splices power penalty and fiber attenuation power penalty combined.

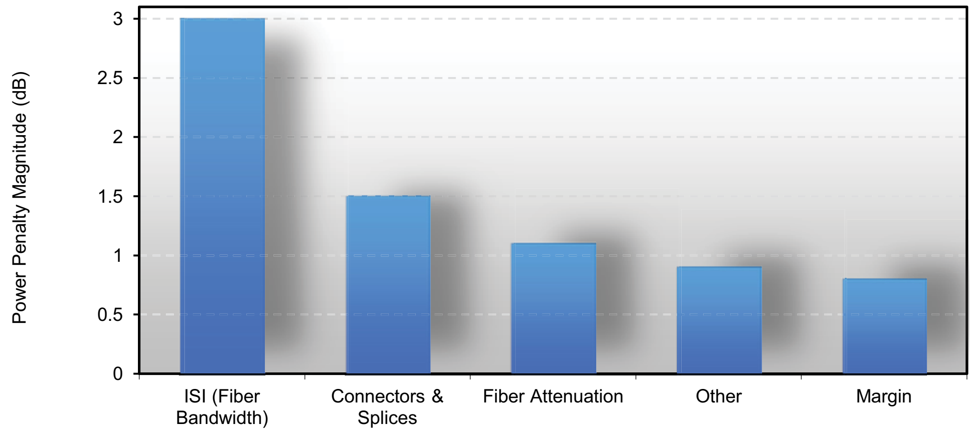


Figure 1. This figure illustrates the largest power penalties for 10 Gb/s Ethernet optical links that extend 300m (10GBASE-SR). [1]

Fiber bandwidth is impacted by two factors: fiber attenuation and dispersion. In communication systems that utilize MMF optic transceivers, information (data) is carried by light pulses generated by a laser transmitter called a Vertical Cavity Surface Emitting Laser (VCSEL), which is focused into the MMF. These lasers convert the electrical signals into laser light. As these light pulses travel through the fiber, the light lost at the connectors and from the attenuation of the fiber cable reduces the amplitude of the original signal and impairs the receiver's ability to reconstruct the transmitted data. Ultimately this causes bit errors and degrades the performance of the network. A bit error is where the receiver incorrectly interprets the received data bit; if a "one" was sent; the receiver interpreted it as a "zero" and vice-versa if a "zero" was sent.

Another system impairment, called dispersion, is the spreading out of light pulses in time which also degrades the original transmitted signal and may cause errors as well. Two types of dispersion exist, modal and chromatic; however, traditional laser-optimized MMF deployments are designed to minimize only one cause of dispersion: modal dispersion.

Modal Dispersion

The amount of light spreading in time based on the different modes taken is called modal dispersion and is measured for every laser-optimized multimode fiber with Effective Modal Bandwidth (EMB) and/or Differential Mode Delay (DMD) measurements (Figure 2a). In MMF, light pulses travel through the fiber in discrete paths, or modes, which have slightly different path lengths. In order for the pulses of light to arrive at the receiver at the same time, which is necessary for the signal to be reconstructed properly, the light traveling in the modes that have a longer path length (higher order modes) must travel faster than the light traveling in the modes that have a shorter path length (lower order modes).

This mode and speed "balancing", or simply speeding up and slowing down of the different components of the light pulse, is done by "grading" the refractive index of MMF and has been a primary focus of design and manufacturing improvements for more than 20 years. However, small imperfections are unavoidable in the manufacturing process and cause the light to have slightly unequal transit times for all the different modes. The increasingly stringent requirements on the maximum amount of modal dispersion, or minimum effective modal bandwidth, are defined within the fiber standards documents for the various classes of laser-optimized MMF: OM3 (EMB ≥ 2000 MHz·km) and OM4 (EMB ≥ 4700 MHz·km).

Chromatic Dispersion

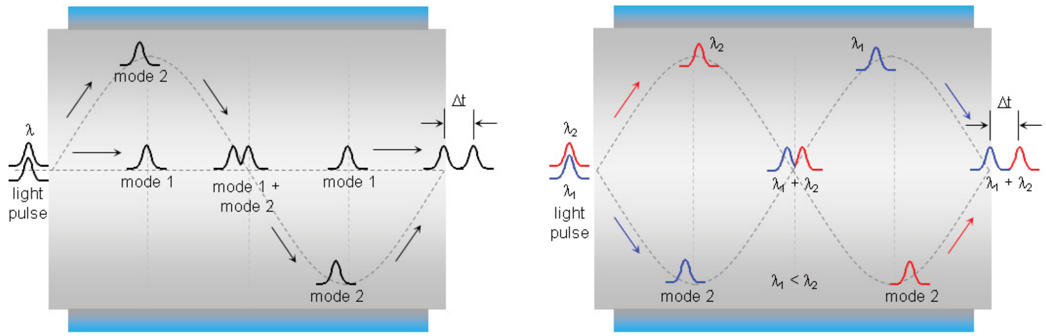
The other type of dispersion important in MMF communication systems is the spreading out of light due to the slightly different colors or wavelengths of light that make up the optical signal. This type of dispersion is called chromatic dispersion. Light generated from typical VCSELs is actually not a single wavelength but is made up of several closely spaced discrete wavelengths around 850nm.[1] The speed at which the light travels through the fiber depends on the wavelength, therefore the individual wavelength components of the light pulse travel at slightly different speeds with the shorter wavelengths traveling at slower speeds compared to the longer wavelengths.

This slight difference in the speed that the various wavelengths travel through the fiber results in unequal transit times, which results in signal distortion. The wavelengths cause the laser pulse to spread out which makes it harder to interpret the data stream at the receiving end and limits reach while increasing Bit Error Rate (BER). The concern for chromatic dispersion increases as the speed of the data rate increases. Chromatic dispersion effects are even more important to control at higher data rates because the difference in transit times and chromatic dispersion is proportional to the difference in wavelengths emitted by the VCSEL, and the limitations on the spectral widths of VCSELs increased from 10 Gb/s Ethernet to 40/100 Gb/s Ethernet (Figure 2b).[2] [2]

[1]VCSELs typically utilized in short reach communications systems have fiber coupled emission spectrums that are multimode and have RMS spectral widths > 0.1 nm.
[2]IEEE 802.3™ – 2008 and IEEE 802.3ba™ – 2010 specify the RMS spectral width for 10GBASE-SR transmitters <0.45 nm and the RMS spectral width for 40/100GBASE-SR4/10 transmitters <0.65 nm.

VCSEL to Fiber Coupling

While exploring the causes of dispersion to develop a fiber optic cabling system that minimizes both modal and chromatic dispersion, Panduit researchers discovered that there is a radial-dependent wavelength that couples into MMF. This coupling ultimately results in a radial dependence of both modal and chromatic dispersion.



2a) pulse spread from modal dispersion

2b) pulse spread from chromatic dispersion

Figure 2. Simplified representation of 2a) modal dispersion and 2b) chromatic dispersion in MMF.

In 2a) only two different fiber modes are shown. The path length of mode 2 is greater than mode 1 so the light in mode 2 must travel faster than mode 1 to arrive at the end of the fiber at the same time as mode 1. The spreading out of light signals, Δt, due to path length differences is called modal dispersion.

In 2b) only two wavelengths, λ1 and λ2, where λ1 < λ2, are shown passing through the fiber in mode 2. Because shorter wavelengths travel slower than longer wavelengths, λ2 arrives at the end of the fiber before λ1. The spreading out of lights signals, Δt, due to their wavelengths is called chromatic dispersion.

The basic configuration of a typical VCSEL Transmitter Optical Sub-Assembly (TOSA) used in multimode transceivers is shown in Figure 3. The optical sub-assembly couples light emitted from the VCSEL into the MMF using a lens and precise optical alignment between the VCSEL, lens and fiber. The light emission characteristics of VCSELs are known to emit longer wavelengths with small angles and shorter wavelengths at larger angles (from the optical axis). [3] Consequently, the TOSA will generally couple longer wavelengths into fiber modes near the center of the fiber core with shorter path lengths (lower order modes). It will also couple shorter wavelengths emitted into larger angles that emit into fiber modes nearer the edges of the fiber core with longer path lengths (higher order modes). The following section describes how these findings were incorporated into the Signature Core™ Fiber Optic Cabling Systems.

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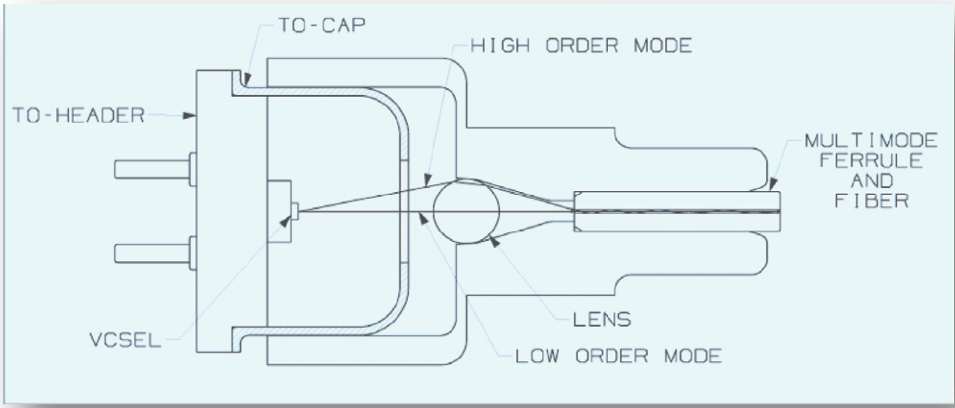

Figure 3. Transmitter Optical Sub-Assembly (TOSA) showing the spectral dependant coupling from VCSEL to MMF, where longer wavelengths are coupled into the lower order modes while the shorter wavelengths are coupled into the higher order modes.

Compensating Modal and Chromatic Dispersion

Shorter wavelengths travel slower than longer wavelengths and this speed difference needs to be “corrected” or compensated in order for the total light pulse to arrive at the receiver at the same time. Since the shorter wavelengths are coupled towards the edge of the fiber, this compensation may be performed by intentionally speeding up the modes at the extremities of the fiber. Therefore the difference in speed due to the various colors of the light (chromatic dispersion) may be effectively compensated by a difference in speed of the different modes (modal dispersion). This is the basic concept behind Signature Core Fiber Optic Cabling Systems, which are specifically designed to compensate for both modal and chromatic dispersion, providing the highest system performance.

Although the effects of modal dispersion and chromatic dispersion are well understood, traditional systems models oversimplify their interaction and therefore do not correctly account for how these two effects may add or subtract from one another. Traditional laser-optimized MMF is designed to only minimize the effects of modal dispersion, thus ignoring the effects of chromatic dispersion. However, because VCSELs preferentially couple different wavelength components into different areas of the fiber, improved system performance is achieved by designing the fiber to “balance” or reduce the effects of chromatic dispersion with some amount of modal dispersion.

It is important to understand why these effects must be considered together rather than separately. For example, consider a hypothetical fiber that supports only two modes where one of the modes has a longer path length than the other and an optical signal that consists of two different wavelengths where one wavelength is longer than the other (remembering that shorter wavelengths travel slower than longer wavelengths in "normal" fibers). In this simplified situation there can only be two different combinations of modes and wavelengths. The first is when the shorter wavelength light travels through the longer path length mode. Consequently, this part of the optical signal will take much longer to pass through the fiber than the part of the signal comprised of the longer wavelength that takes the shorter path length mode. In the other combination the shorter wavelength light travels through the mode with the shorter path length and the longer wavelength light travels through the mode with a longer path length. In this later case, the light that travels faster must travel a longer path length and may be designed to have a similar arrival time as the light that travels a bit slower, but takes a shorter path length.

From this simplified example, it is easy to understand how these chromatic and modal effects must be considered together because they only influence the velocity of the light pulse as it passes through the fiber. However, the fiber coupled wavelength distribution of VCSEL TOSAs was not considered within systems models – only the magnitude of their effects was considered. Therefore, these models are not able to predict how modal and chromatic effects may be combined to reduce the total dispersion which will provide improved system performance. These models also are unable to predict how modal and chromatic effects may be added together, which will increase the total dispersion and significantly degrade system performance more than traditional systems models.

Although the simplified example used above is useful for illustrative purposes, the large number of VCSEL wavelength components that make up the light signal (~20), their fiber coupled distribution, and the large number of fiber modes (~400) make the analysis of a real transceiver and fiber combination quite involved. Detailed simulations of thousands of VCSEL transceivers and fiber combinations have been computed to optimize the design of Signature Core Fiber Optic Cabling Systems and quantify the benefits of compensating modal and chromatic dispersion.

These advanced fiber optic cabling systems are standards compliant and counterbalance the dispersive effects of both modal and chromatic dispersion, therefore minimizing total dispersion. The systems deliver signal integrity far beyond the requirements for 10/40/100 Gb/s Ethernet, and 8 and 16 Gb/s Fibre Channel, providing the ultimate in design flexibility which allows implementation of complex data center architectures, and verified optical performance. They improve MMF performance by increasing modal bandwidth. In addition, Signature Core Fiber Optic Cabling Systems ensure consistent performance and reliability of critical systems, delivering the ability to deploy more connectors in the channel, which simplifies moves, adds, and changes.

Figure 4 shows the benefits delivered by Signature Core™ Fiber Optic Cabling Systems fiber, as compared to traditional MMF that does not compensate for modal and chromatic dispersion. The average improvement is 30% compared to the bandwidth of traditional multimode fiber. This improved bandwidth can be used to provide greater reach, or add more connectivity, or realize improved system performance (lower bit error ratios) for 10G, 40G, and 100G MMF systems.

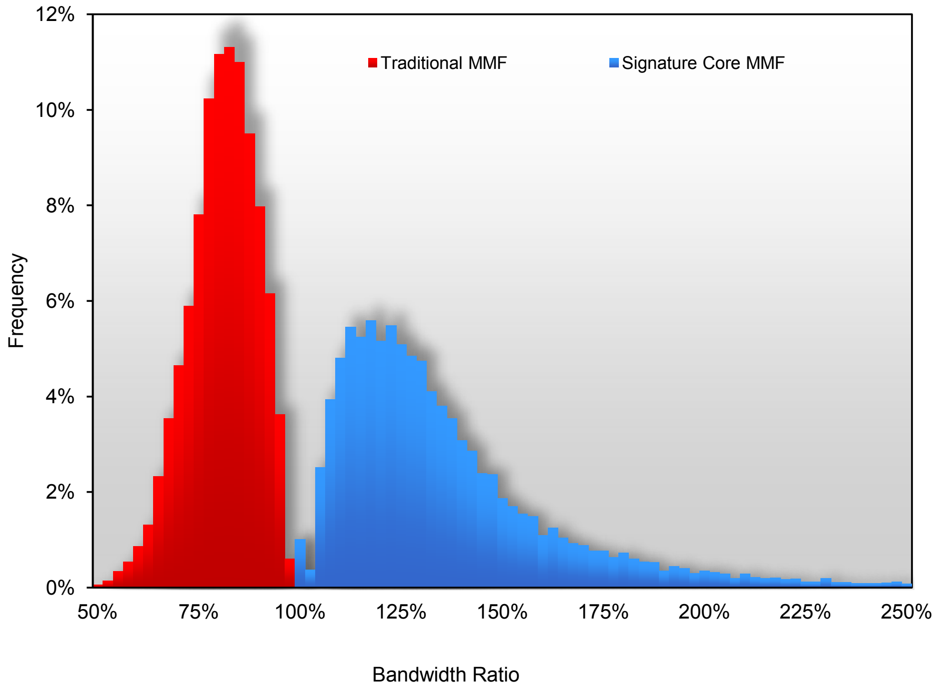

Figure 4. Modeled benefit, in terms of bandwidth ratio of Signature Core Fiber Optic Cabling Systems compared to traditional MMF that does not compensate modal and chromatic dispersion.

The bandwidth ratio is the bandwidth calculated considering modal and chromatic dispersion collectively divided by the traditional modal bandwidth. Bandwidth ratios >100% represent an improvement and bandwidth ratios <100% represent a degradation. Improvements or degradations in bandwidth will improve or degrade system performance compared to the performance that traditional system models predict. Signature Core Fiber Optic Cabling Systems provide improved system performance for approximately 98% of transceivers with an average improvement of 30%. The 2% balance of these transceivers incurs a bandwidth degradation of about 1%.

Conversely, traditional fiber realizes a reduction in bandwidth by approximately 20% compared to the bandwidth predicted by traditional models that do not collectively consider the effects of model and chromatic dispersion. This reduction in bandwidth has the dangerous effect of reducing the reach, connectivity budget and system performance.

Another way to take advantage of the Signature Core Fiber Optic Cabling Systems' enhanced performance is with the deployment of a fabric based switching architecture. By using the Signature Core Fiber Optic Cabling Systems to connect the leaf and spine switches, the fabric architecture can be enlarged to cover more area within the data center.

Conclusion

For high-speed data center, colocation, and enterprise optical communication networks, basic optical loss and dispersion – the spreading out of optical signals – are the most important factors that will determine overall network performance. Utilizing high performance (low loss) connectivity and fiber cable as well as following industry standardized practices of cable routing (e.g. maintaining bend radius control) are the best ways to minimize signal impairments from excessive optical loss. Traditional techniques of minimizing signal impairments by reducing the total dispersion have been built upon simplified system models that do not consider the interaction of the two primary types of dispersion in MMF networks: modal dispersion and chromatic dispersion. The net effect is that these simplified systems models do not accurately provide a worst case estimate of network performance as they were intended, and the transceiver and fiber have been optimized independently, thereby ignoring potential performance improvements by designing them as a system.

By considering both modal and chromatic dispersion together, customers can experience significant improvements which result in a better system model that can more accurately predict performance. The Signature Core™ Fiber Optic Cabling Systems fiber was designed to account for the interaction of modal and chromatic dispersion and compensate for these effects to provide a communication system (transceiver and fiber combination) with minimum total dispersion. These systems provide the best of both performance improvements by compensating modal and chromatic effects while simultaneously eliminating the potential combination of chromatic and modal dispersion, which can cause a significantly degraded system performance. While the average length within the data center is below 100m and can make on some occasions the impact of the compensated chromatic and modal dispersion insignificant, the headroom Signature Core fiber provides can allow a more complex architecture system and more connectivity and at the same time deliver the required bandwidth and performance for the link.

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Signature Core™ Fiber Optic Cabling Systems are the only MMF to correct modal and chromatic dispersion because it is designed to counterbalance both of these dispersive effects and therefore minimize total dispersion. This fiber is 100% OM3 and/or OM4 standards compliant and therefore fully backwards compatible with all other standards compliant laser-optimized OM3 and OM4 cable. [4,5] For those channels that are the most demanding in terms of reach, connectivity budget or performance requirements. The Signature Core Fiber Optic Cabling Systems MMF provides network designers and operators with the highest performance fiber available to meet the most demanding applications and data center architectures.

References

[1] IEEE Std 802.3™ - 2008.

[2] IEEE Std 802.3ba™ - 2010.

[3] S. Gronenborna, H. Moenchb, M. Millerc, P. Gerlachc, and J. Kolbb, "Dynamics of the Angular Emission Spectrum of Large-area VCSELs," Vertical-Cavity Surface-Emitting Lasers XIV, SPIE Proc., vol. 7615, pp. 76150I-76150I-12 (2010).

[4] TIA-492AAAC-B, Telecommunications Industry Association standard "Detail specification for 850-nm laser-optimized, 50-µm core diameter/125-µm cladding diameter class 1a graded-index multimode optical fibers," November 2009.

[5] TIA-492AAAD, Telecommunications Industry Association standard "Detail specification for 850-nm laser-optimized, 50-µm core diameter/125-µm cladding diameter class 1a graded-index multimode optical fibers suitable for manufacturing OM4 cabled optical fiber," September 2009.

Since 1955, Panduit's culture of curiosity and passion for problem solving have enabled more meaningful connections between companies' business goals and their marketplace success. Panduit creates leading-edge physical, electrical, and network infrastructure solutions for enterprise-wide environments, from the data center to the telecom room, from the desktop to the plant floor. Headquartered in Tinley Park, IL, USA and operating in 112 global locations, Panduit's proven reputation for quality and technology leadership, coupled with a robust partner ecosystem, help support, sustain, and empower business growth in a connected world.

For more information

Visit us at www.panduit.com/signaturecore

Contact Panduit North America Customer Service by email: cs@panduit.com
or by phone: 800.777.3300

PANDUIT US/CANADA
Phone: 800.777.3300

PANDUIT EUROPE LTD.
London, UK
cs-emea@panduit.com
Phone: 44.20.8601.7200

PANDUIT SINGAPORE PTE. LTD.
Republic of Singapore
cs-ap@panduit.com
Phone: 65.6305.7575

PANDUIT JAPAN
Tokyo, Japan
cs-japan@panduit.com
Phone: 81.3.6863.6000

PANDUIT LATIN AMERICA
Guadalajara, Mexico
cs-la@panduit.com
Phone: 52.33.3777.6000

PANDUIT AUSTRALIA PTY. LTD.
Victoria, Australia
cs-aus@panduit.com
Phone: 61.3.9794.9020