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Supporting Tomorrow’s Data Rates Depends on Overcoming Fiber-Optic Dispersion

The demand for bandwidth continues to increase unabated, driven most recently by artificial intelligence (AI) and machine learning (ML) applications. AI clusters are the first to use high-speed transceivers; they have more high-speed inter-rack cabling and consume more fiber cable than traditional data center networks1. New 800G and 1.6T transceivers with 200G lanes will be standardized in the IEEE 802.3dj task force, with publication expected in 2026.

The 802.3dj standard will include parallel singlemode fiber applications with intensity modulation and direct detection transceivers (IMDD) like 800G-DR4, 800G-DR4-2, 1.6T-DR8 and 1.6T-DR8-2. Duplex singlemode fiber applications that use wavelength division multiplexing (WDM) like 800G-FR4-500, 800G-FR4 and 800G-LR4 will also be included.

These future data rates will become available to your data center soon, and fiber parameters must be re-evaluated for these higher baud rates. Fiber impairments must be considered with these high-speed transceivers, and chromatic dispersion is the largest concern. This article will discuss chromatic dispersion and what steps the standards bodies and CommScope have taken for these fibers to support these new data rates.

What is fiber-optic dispersion, and why is it important in fiber-optic communication systems?

Dispersion is anything that causes some parts of an optical signal to travel faster or slower than other parts. This leads to signal distortion and limits the bandwidth and reach of fiber-optic links.

There are different types of dispersion, including modal, chromatic and polarization mode dispersion. In multimode fibers, each mode travels at a different speed; we call this “modal dispersion.” With polarization mode dispersion, the two polarizations of an optical signal travel at slightly different speeds. Singlemode fibers are primarily concerned with chromatic dispersion where each wavelength in a signal sees slightly different glass properties and consequently travels at a different speed. Each of these types of dispersion will close an eye diagram and increase the bit error ratio (BER).

Fiber dispersion contributed to the adoption of PAM4 modulation. Each of these types of dispersion has a larger penalty at higher speeds or baud rates. With higher modulation formats like PAM4, you can double the bit rate compared to non-return-to-zero (NRZ) modulation while maintaining the same baud rate or symbol rate. Data throughput increases without increasing the dispersion penalty. This is particularly important with chromatic dispersion, since that penalty quadruples with each doubling of the baud rate.

How does fiber-optic dispersion influence the design and deployment of long-distance communication networks?

In the past, chromatic dispersion was a major area of concern in long-haul and undersea networks. These networks typically would follow a span of singlemode fiber with a span of special fiber with negative dispersion to cancel out chromatic dispersion. About a decade ago, coherent transceivers were introduced with powerful digital signal processors (DSPs) that can mathematically remove the impact of dispersion.

Unlike these long-haul networks, data center links are much shorter and operate near 1310 nm, where chromatic dispersion is negligible and hasn't been a major concern. However, as we get to 200G lanes, the impact of chromatic dispersion can't be ignored.

Two parameters are used to determine the chromatic dispersion at a given wavelength: the zero-dispersion wavelength and the slope at zero-dispersion. The three-term Sellmeier equation uses these two parameters to calculate the dispersion at an operating wavelength.

The ITU-T in standards G.6522 and G.6573 sets the range of dispersion values allowed in G.652.D, G.657.A1 and G.657.A2 fibers. The permitted zero-dispersion wavelength is from 1300 – 1324 nm and the slope at zero dispersion is in the range 0.073 – 0.092 ps/(nm^2*km).

In the past, Ethernet standards used both extreme zero-dispersion wavelengths (1300 or 1324nm) and maximum slope (0.092 ps/nm^2*km) to determine the range of dispersion values for testing wavelength channels. The shortest operating wavelength would assume 1324 nm zero dispersion wavelength, and the longest would assume 1300 nm.

The dispersion at a given wavelength will vary from fiber to fiber. Figure 1 graphs the dispersion in ps/(nm*km) for two different extreme fibers, one with a zero-dispersion wavelength of 1300 nm and slope of 0.073 ps/(nm^2*km), and another with zero-dispersion wavelength of 1324 nm and slope of 0.092 ps/(nm^2*km). Of these two extreme fibers, Fiber 1 has nearly double the dispersion at 1264.5 nm and half the dispersion at 1337.5 nm compared to Fiber 2.

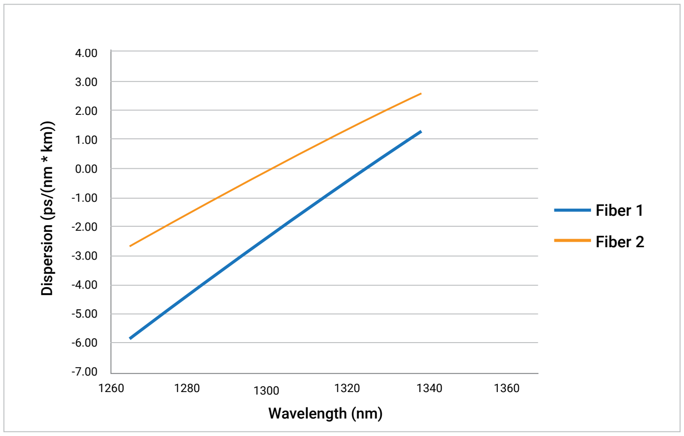

Figure 1: Dispersion vs. wavelength for two extreme fibers. Fiber 1 has the longest zero-dispersion wavelength and maximum slope; Fiber 2 has the shortest zero-dispersion wavelength and minimum slope.

This approach to dispersion effectively requires each transmitter to tolerate the most extreme fibers allowed by ITU-T standards at maximum reach. For 800G-FR4, this would lead to a dispersion range of -11.7 to +6.6 ps/nm over 2 km. For 800G-LR4, the range would be -28.1 ps/nm to +9.3 ps/nm over 10 km. A statistical approach to chromatic dispersion has the potential to require transceivers to comply with less dispersion while representing realistic fiber links.

What steps have been taken to address chromatic dispersion for 200G lanes?

The IEEE 802.3dj task force has taken a statistical approach to fiber chromatic dispersion for 200G lane applications like 800G-FR4 and 800G-LR4. In the past, each transceiver was tested with the worst-case fiber. The ITU-T conducted a study with data from eight fiber manufacturers to understand the statistical distributions of fiber dispersion for G.652 and G.657 fibers. The results were published in the 2024 version of G.652. This is useful data that IEEE can reference.

CommScope also compiled a data set using millions of fibers in CommScope cables over the past 10 years. This CommScope data set—which I compiled and graphed myself in Figure 2— showed good agreement with the ITU-T data set, confirming that dispersion has remained consistent over time.

Knowing the likelihood of encountering a fiber with both an extreme zero-dispersion wavelength and maximum slope is key to developing a statistical model for link dispersion. Figure 2 plots a bivariate histogram of the data set for zero-dispersion wavelength and slope. Fibers with the most dispersion would be located in the top two corners of the graph (1300, 0.092) and (1324, 0.092). Nearly all the fibers are within a small distribution with moderate wavelength and slope, and very few fibers have both an extreme zero-dispersion wavelength and slope. This indicates that the approach taken with previous generations requires transmitters to be designed and tested to work with fibers displaying dispersion characteristics that are rarely seen in practice.

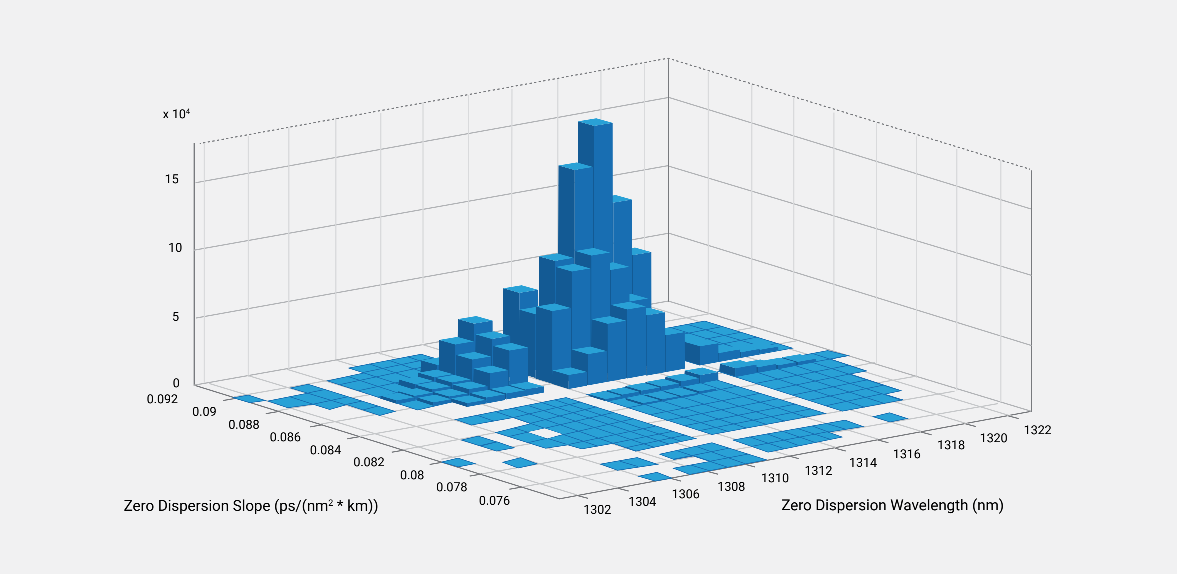

Figure 2: Bivariate histogram of fibers in the CommScope data set for zero-dispersion wavelength and slope.

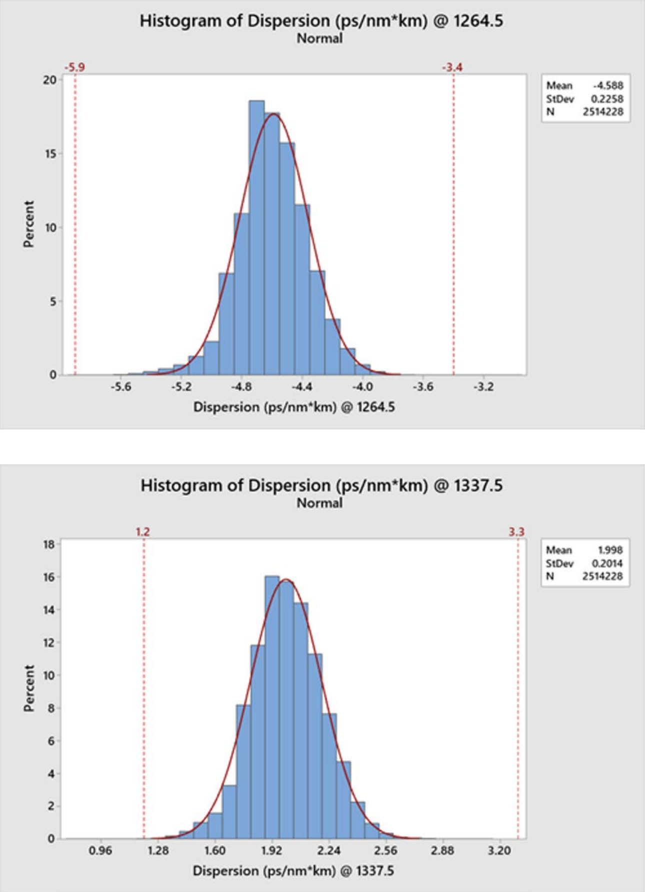

Figure 3: Histogram of per km dispersion for 800G-FR4 wavelengths at (a) 1264.5 nm and (b) 1337.5 nm. Worst-case dispersion is marked by vertical red lines.

Figure 3 includes histograms for per-km fiber dispersion in ps/(nm*km) for the two extreme 800G-FR4 wavelengths: (a) 1264.5 nm and (b) 1337.5 nm. The vertical red lines indicate the most extreme fiber dispersion allowed by ITU-T standards. The vast majority of the fibers in the data set have much less positive dispersion at 1337.5 nm and less negative dispersion at 1264.5 nm. Since very few fibers in the data set have both an extreme zero-dispersion wavelength and maximum slope, it is very rare to see a fiber that would have worst-case dispersion at these wavelengths.

What's in store for the future?

The results from the CommScope data set and the ITU-T study mean that a new singlemode fiber standard is not needed for IMDD WDM transceivers with 200G lanes. The next step will be to determine what is needed for 400G lanes and 1.6T transceivers like 1.6T-FR4 and 1.6T-LR4. The New Ethernet Applications Ad Hoc Ethernet for AI Assessment in IEEE 802.3 hosts a consensus-building activity where participants discuss whether tighter chromatic dispersion specifications are needed for 400G signaling.

Why does CommScope pay attention to transceiver standards and specifications?

We understand that our customers use the passive components they buy from us with active equipment to build their networks. It's very important that we understand these standards and specifications to enable our Fiber Performance Calculator tool and our SYSTIMAX® Application Assurance™ warranty. We want to be a trusted partner for our customers as they design and build their networks.

By Earl Parsons, Director,
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This article was originally published as a chapter in CommScope's 2026 Data Center eBook, available for free here.

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[1] E. Parsons, "Cabling considerations of AI data centers," CommScope white paper, 2023.

[2] G.652, "Characteristics of a single-mode optical fibre and cable", ITU-T, 2024.

[3] G.657 "Characteristics of a bending-loss insensitive single-mode optical fibre and cable", ITU-T, 2016.

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