Higher Bitrate MMF Systems using WDM

Application Note

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Summary

Multimode fiber (MMF) plays a central role in modern data center systems because of its compatibility with the high data rate VCSEL sources which have revolutionized communications. Both fiber/cable and laser are evolving as data rates continue to increase to support modern technology. The wide band multimode fiber (WB MMF) will make use of wavelength division multiplexing (WDM) to further increase the capacity of multimode systems.

Introduction

Modern data center systems running high data rates rely on vertical cavity surface emitting laser (VCSEL) sources and MMF cables for the many links which are too long to be feasible with copper and too short to be economical with typical single-mode lasers. There is a solid history of data rate growth, and it continues as shown in Figure 1 ([1] Appendix A, [2]), driven by the needs of modern technology. To achieve higher capacity, data centers are using faster VCSELs (25 Gb/s transceivers were launched commercially in 2015), parallel fiber, and multiple wavelengths. This white paper reviews the fiber requirements for the recently proposed four-wavelength WDM application, which in principle increases the capacity of a single multimode fiber by a factor of four. The total increase in the capacity of the system is the product of the VCSEL baud rate, the number of parallel fibers, and the number of WDM wavelengths. All three methods will be employed to meet the increasing demand for bandwidth in data centers.

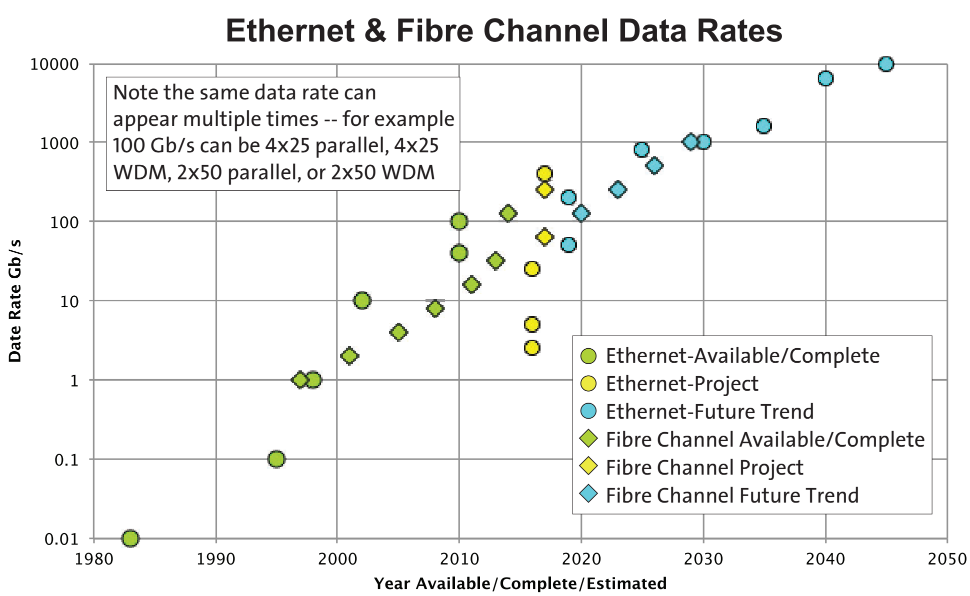

Figure 1. Chronological depiction of ethernet and fibre channel data rates.

History of Data Rates and Laser-Optimized Multimode Fiber

Multimode fiber continued to be used in data centers and campus links after it was replaced by single-mode fiber in very long terrestrial and undersea links in the 1980s [3]. During the late 1980s and early 1990s, a MMF with a higher numerical aperture (NA) of 0.275 and a 62.5 µm core diameter (OM1) was introduced to better capture the light from 1300 nm LED sources [4]. In the late 1990s, laser-based systems were introduced along with a higher modal bandwidth MMF with a 50 µm core diameter and a lower NA of 0.20. The early 1 Gb/s VCSELs had spot sizes slightly smaller than the LEDs and were designed to operate at 850 nm, which became the standard wavelength for these systems.

For LED-based systems, the modal bandwidth of the fiber had been characterized with a single overfilled launch (OFL) in which the light was launched over the entire core of the fiber with measurements taken at both 850 nm and 1300 nm wavelengths. For the 1 Gb/s systems, it was adequate to supplement the OFL bandwidth with a 'Restricted Mode Launch' (RML) bandwidth using light launched into a central portion of the core to simulate a VCSEL launch [Ref. 1, p.250]. As higher data rate 10 Gb/s VCSELs became available after 2000, a different approach was needed. A high resolution version of the differential delay measurement was used to measure the fiber mode group delays and estimate the performance for the mode power distribution (MPD) of a specific laser [5].

With the advent of 10 Gb Ethernet systems, the laser-optimized OM3 fiber with an effective modal bandwidth (EMB) of 2000 MHz•km at 850 nm became the standard. However, as 10 Gb/s VCSELs were commercialized, it was found that the spectral width and other laser specifications needed to be relaxed to allow the large scale production from GaAs wafers without individually testing each laser. To ensure robustness to broad operating conditions and the full lifetime of the link, OM4 fibers with a higher EMB of 4700 MHz•km were introduced. OM3 fibers had an initial reach goal of 300 m [6a] while OM4 targeted 550 m. Due to the broader spectral width and the need to guarantee performance over the full spectral range of the 850 nm VCSELs, the standardized reach for OM4 was later reduced to 400 m [6b].

In 2013, transceiver manufacturers began to develop VCSELs with line rates of 25 Gb/s, and the VCSEL spectral width requirement was increased to 0.60 nm. This larger spectral width reduces the theoretical reach of OM4 to 100 m, even when using forward error correction (FEC) [6c]. The 100 G SR4 Gigabit Ethernet (GbE) standard is based on 4x25 Gb/s parallel links. Figure 2 shows the link length limitation for 100G-SR4 using the assumptions in the IEEE link model [6c]. As the assumed bandwidth increases, the reach plateaus at a maximum reach between 110 and 115 m, even if the modal bandwidth of the OM4 fiber exceeds 40,000 MHz•km. The reach limitation is not due to the modal bandwidth of the MMF, but rather is due to the interplay between the high spectral width of the transceiver and the chromatic dispersion of the fiber at shorter wavelengths.

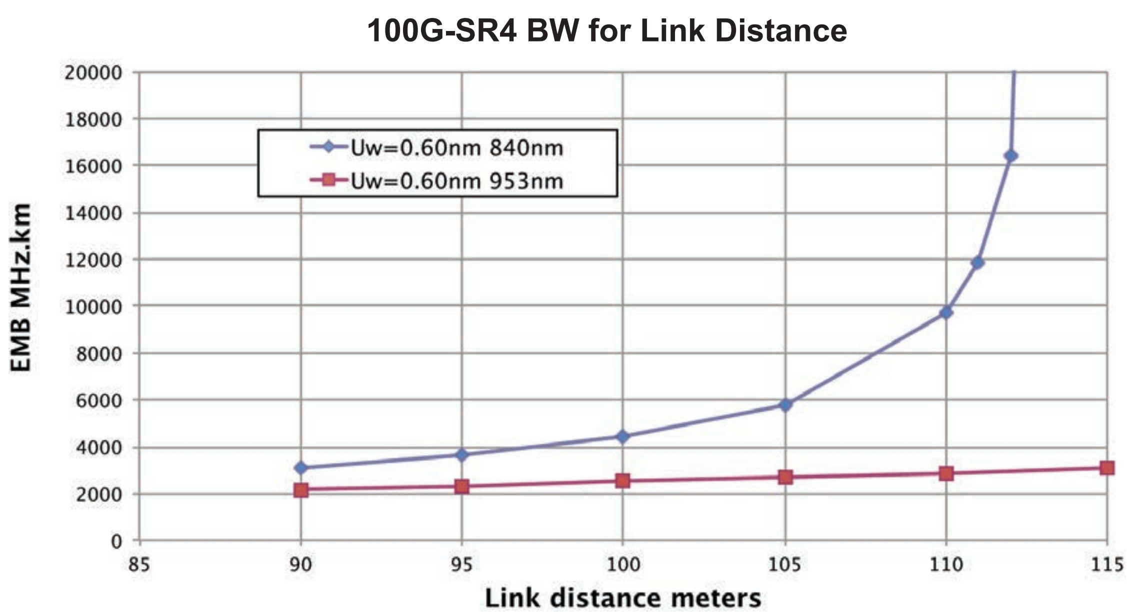

Figure 2. Required EMB versus link distance. The system reach at 840 nm is limited by the spectral width of the transceiver combined with chromatic dispersion, not by the bandwidth and intermodal dispersion. At 953 nm with reduced chromatic dispersion there is no limitation to distance in this range.

To summarize the motivation for WB MMF, (a) the data rates are still increasing (Figure 1); (b) the MM links need to take advantage of the capability of high speed VCSEL sources; c) at shorter wavelengths, the reach is limited by the broad spectral sources and the chromatic dispersion of the fiber (Figure 2).

Current/Near-Future Approaches for Increased Data Rates

Below are listed four current approaches to increasing the data rate over MM links. In combination, these provide a variety of ways to address the need for more capacity as links evolve from 10 G to 100 G and eventually to 400 G and beyond.

1. Serial: the baud rate of VCSELs has increased from 1 G to 10 G to 25 G over a single multimode fiber. 25 Gb/s VCSELs became commercially available in 2015, and line rates of 40-60+ Gb/s have been demonstrated in the laboratory [8].
2. Parallel: Higher data rates can also be achieved by increasing the number of fibers transmitting data from a transceiver. For example, a 100 Gb/s data stream can be divided into data streams over 10 fibers at 10 Gb/s or 4 fibers at 25 Gb/s.
3. Wavelength division multiplexing (WDM): The WB MMF is designed to take advantage of this technique, where data streams with different wavelengths are transmitted simultaneously down the same fiber. For example, the Bi-Di approach proposed by Cisco [7] uses two wavelengths to increase the capability of a single fiber to 40 Gb/s of bidirectional bandwidth. In that approach, 20 Gb/s signals are transmitted in one direction at 850 nm and in the return direction at 900 nm.
4. Increased bit rate: The conventional modulation format is non-return-to-zero (NRZ), which has two symbols, one for each bit 0 or 1, that represent voltage levels. In this case, the baud or symbol rate is the same as the bit rate. Pulse amplitude formats such as PAM4 encode more than two bits in one transmission interval (symbol), which results in a bit rate which is a multiple of the baud rate of the laser.

The use of WDM and multiplexing through parallel fibers are approaches which can be combined for 100 G, 200 G, 400 G and higher capacities. As four-wavelength WDM is commercialized using the WB MMF, various options will be explored for achieving higher capacity.

Key Parameters Driving Functionality at High Data Rates

The data rate of a MM link is limited by the modal bandwidth of the MMF and the effect of chromatic dispersion, which both vary significantly with wavelength. Operation near 850 nm with large spectral width VCSELS limits the functionality of the link even when the MMF has very high modal bandwidth. As the wavelength shifts toward 950 nm, the absolute value of the chromatic dispersion decreases and the effect of large spectral width sources becomes less important (the zero dispersion wavelength is between 1296 to 1328 nm). Figure 3 shows the dependence of chromatic dispersion on wavelength. The absolute value decreases about 40% from 850 nm to 950 nm. Figure 3 includes a curve for the chromatic dispersion assumed in the current IEEE 100G SR4 and Fibre Channel 32G FC link models ([6c],[6d]) as well as a curve based on improved estimates of material properties. Updated values were agreed to by the TIA WB-MMF project team following a 2015 industry round-robin and have been incorporated into TIA draft standards for WB-MMF fiber.

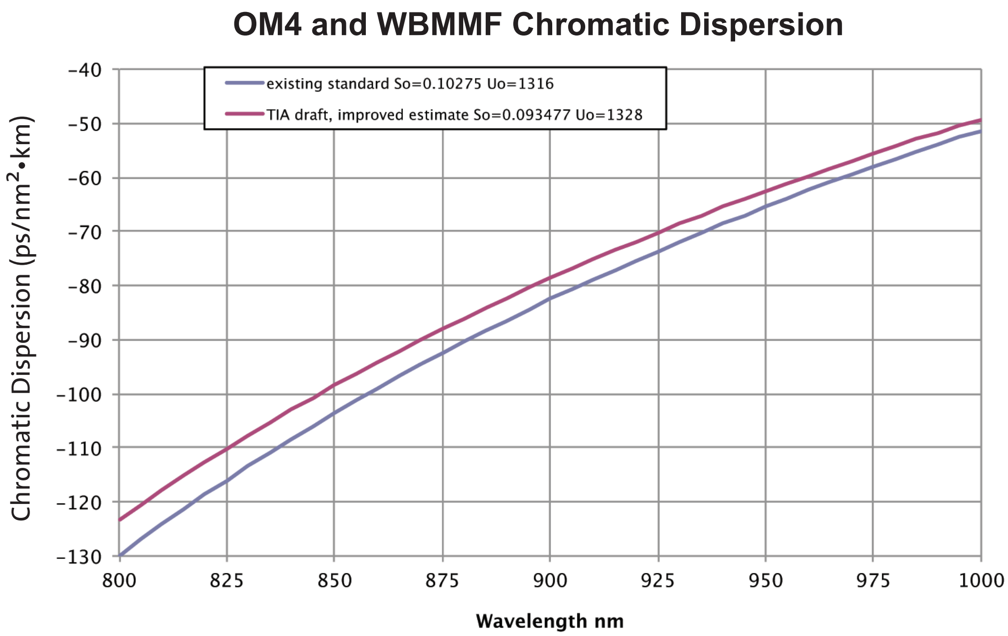

Figure 3. The Chromatic Dispersion penalty of a MM fiber is proportional to the dispersion and the spectral width of the transmitter. Improved estimates of chromatic dispersion in OM4 and WB MMF fibers enable longer distances at 850 nm with the same laser.

Figure 4 shows the dependence of the effective modal bandwidth (EMB) on wavelength for some modeled example fibers. For a given reach of 100 m, a lower bandwidth is needed near 950 nm compared to 850 nm because the absolute value of chromatic dispersion of the fiber is lower, as will be seen in Figure 5. Current estimates suggest that an EMB of 2470 MHz•km at 953 nm is needed to achieve 100 m reach. (A) The blue curve shows a model EMB vs. wavelength curve for an example OM4 fiber – in this case the fiber meets OM4 requirements at 850 nm, but the EMB at 953 nm is borderline for the 953 nm application. (B) The red curve is an example of an OM4 fiber with a very high EMB optimized for the OM4 design wavelength of 850 nm. However, at 953 nm the EMB still falls below the 2470 MHz•km suggested by the 32G FC link model [6d] assuming zero margin but improved chromatic dispersion and attenuation (Figure 5). (C) The example WB MMF depicted by the green curve here is similar to the example OM4 fiber but the wavelength of peak bandwidth is shifted toward 950 nm. This raises the EMB at 953 nm above the level where the technical consensus suggests it is adequate. On the other hand, the 850 nm EMB is now lower because of this shift. The fiber must be carefully designed to be compatible with all legacy OM4 applications as well the 850 nm to 953 nm requirements for the WDM application.

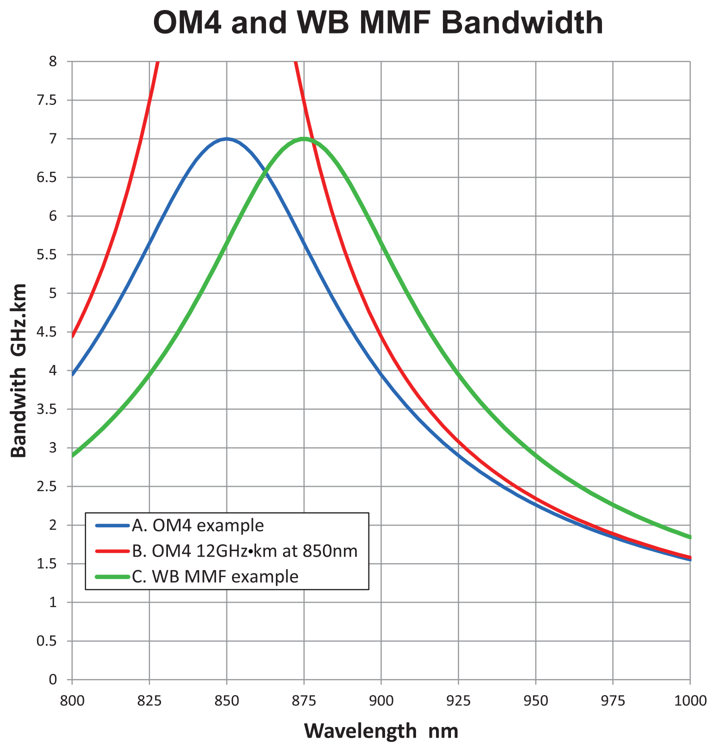

Figure 4. Bandwidth versus wavelength for three modeled fibers that illustrate the characteristics needed for a WB MMF.

Figure 5 plots the required bandwidth vs. wavelength in the 32G FC link model [6d] being used by the TIA WB-MMF project. This requires a slightly higher bandwidth than the IEEE link model for 100G-SR4 [6c]. The required bandwidth at each wavelength is estimated using the default 32 FC link model [6c] and varying the input wavelength, adjusting the effective modal bandwidth (EMB) to achieve exactly zero margin. The green dots represent the results calculated from the spreadsheet with the existing values for chromatic dispersion (U_O = zero dispersion wavelength, S_O = dispersion slope at U_O), while the yellow dots use the values of U_O and S_O from Figure 3 that are included in the WB-MMF draft based on round-robin results, as well as an improved attenuation assumption of 3.0 dB/km compared to 3.5 dB/km previously.

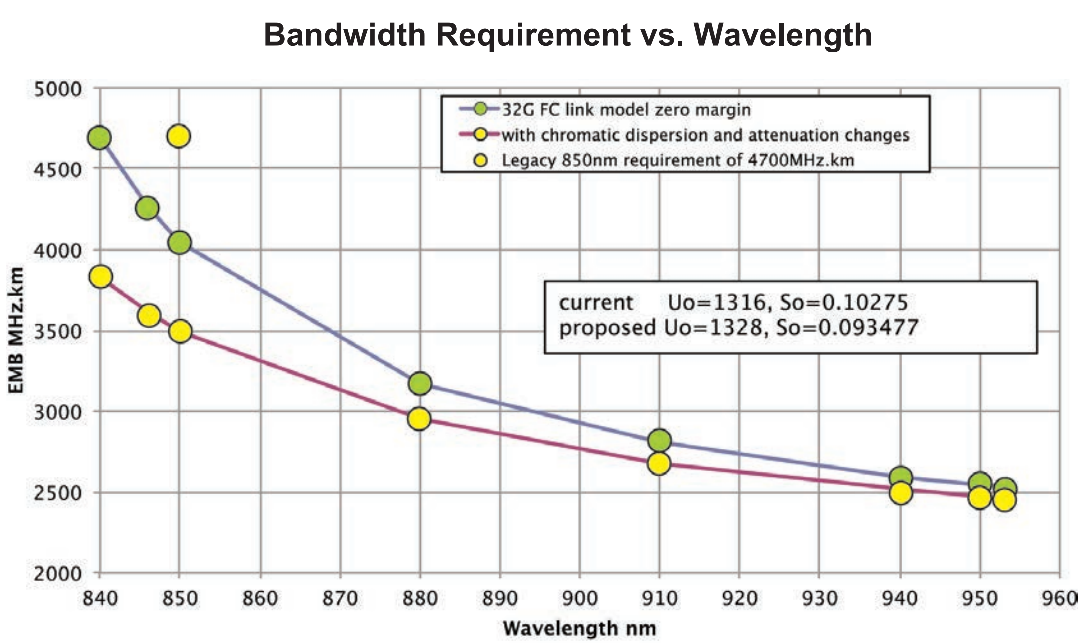

Figure 5. Required bandwidth versus wavelength in IEEE 100G-SR4 link model for two different chromatic dispersion parameters.

The support of OM4 applications is ensured by continuing a requirement that the 850 nm EMB be >4700 MHz•km (single dot), well above the requirement suggested by link models once the improved chromatic dispersion and attenuation are included. For WDM applications this capability is further matched at the intermediate wavelengths up to 953 nm. For WB MMF each 50/125 µm fiber will be characterized at 953 nm, in addition to 850 nm.

Advantages of WB MMF

The primary advantage of WB MMF is that it increases the information-carrying capacity of each fiber by 4x by using WDM; this can either be viewed as enabling 100 GbE on a single fiber or as enabling an upgrade to 400 G from a 4x25 Gb/s parallel link without installing new fiber.

Another evolution supported by WB MMF is a migration from shorter wavelengths where the 0.60 nm spectral width of the VCSELS limits the data rate and reach. Eventually this might enable 10 GbE and 25 GbE operation at longer wavelengths where the chromatic dispersion of the fiber is lower and has less impact on the system performance. The impact of operating VCSELS at longer wavelengths will be to allow longer transmission distances, assuming the same spectral width.

Cabled Fiber Requirements for WB MMF

The plan in the TIA project is that WB MMF will be specified using the EMBc technique developed for 10 GbE [3], both at 850 nm and 953 nm. These will characterize the fiber at both ends of the wavelength range and enable accurate estimates of performance with VCSELs over the entire wavelength range. At 850 nm, a higher modal bandwidth is needed to compensate for the effect of chromatic dispersion. To remain consistent with legacy OM4 specifications, the 850 nm EMB is 4700 MHz•km. The requirement at 953 nm is 2470 MHz•km.

Conclusion

As MM links evolve to support higher data rates, the links take advantage of the highest serial rate available. This is leveraged by a combination of multiplexing over parallel lanes, multiplexing over multiple wavelengths in the same fiber, and potentially using different modulation formats. These approaches are all combined to achieve the most practical implementation. The proposed WB-MMF will enable usage compatible with OM4 and further increase the capability by 4x using WDM. System requirements will dictate the optimal choice to meet the competing needs of installation cost, system capability and future upgrade potential.

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