# Legacy fiber meets long-haul network needs

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When installing new systems, carriers must balance transmission technology and fiber infrastructure to maximize value. Standard SMF provides an advantage over alternative fiber types in an ultradense scenario because of its inherently high chromatic dispersion and relatively large effective core area.

Management planning for future long-haul fiberoptic networks requires assessment of which technologies to deploy and when it makes good business sense to deploy them. The key factors affecting these decisions include the anticipated rate of growth in bandwidth demand and the characteristics and capabilities of the installed legacy fiber network. Experience, fiber compatibility studies, and cost modeling drives the decision-making process within Sprint Corporation.

### MIGRATION FROM 2.5 TO 10 GBIT/S

Sprint's philosophy on increasing network capacity can be understood by examining how the company recently migrated from a line rate of 2.5 to 10 Gbit/s. Sprint initially satisfied the increased capacity demands by exploiting tighter carrier spacing (100 to 50 GHz) that standard single-mode fiber (SMF) or non-dispersion-shifted fiber (NDSF)/G.652 could support, unlike some newer fiber types. In addition, Sprint opted for the more cost-effective and proven 2.5-Gbit/s technology, deferring the adoption of 10-Gbit/s line rates until those technologies had more fully matured.

Sprint had a sizable investment and great confidence in managing 2.5-Gbit/s line rates. Early on, managing 10-Gbit/s links was a very expensive proposition.

Although 10 Gbit/s was introduced in the first half of the 1990s, it is only within the past three years that 10-Gbit/s systems have been accepted in long-haul networks and began shipping in volume. By taking this pragmatic view, Sprint realized substantial cost savings.

Sprint is now deploying mature 80-channel DWDM systems with 10-Gbit/s line rates and has a growing nationwide coverage. Therefore, it is reasonable to assume that to meet growing capacity requirements coupled with increased length demands, Sprint will initially favor ultradense WDM and the maintenance of 10 Gbit/s in the core, while adopting the position that standard SMF is the fiber of choice.

### WHEN TO ADOPT NEW TECHNOLOGIES

The metrics driving an adoption decision include the maximum bandwidth-length product and cost, measured in

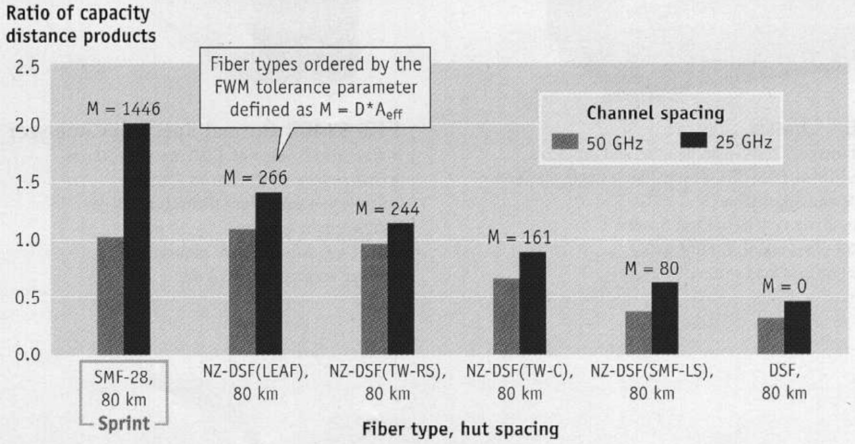

**FIGURE 1.** The relative capacity-distance products for system offerings from Vendor A are normalized to the product obtained for SMF-28 fiber with 80-km hut spacing and 50-GHz carrier spacing.

$/DS3/mile. The bandwidth-length product is based on a typical engineering rule that subtracts 1 to 1.5 spans from the maximum transmission distance per optical add/drop module (OADM) addition. The $/DS3/mile metric is calculated by simply using the loaded capital cost of the simple point-to-point DWDM system. Currently, a 40-Gbit/s offering will not compete with a 10-Gbit/s offering from the same vendor in terms of these metrics.

Equipment space savings may also be reviewed. Space savings translate into proportional savings in other capital and operational costs, which may include the costs associated with consuming floor space and purchasing new additions, cabling, required HVAC system additions, and the recurring utility expense.

Historically, by migrating from 2.5 to 10 Gbit/s, Sprint quadrupled the system capacity within the same footprint (going from 100 Gbit/s realized in two bays to 800 Gbit/s in four bays) while doubling the system reach. Although the initial 40-Gbit/s systems with a 100-GHz carrier spacing (yielding a 0.4-bit/s/Hz spectral efficiency) being offered today may double the capacity within the same footprint, new 10-Gbit/s systems with a 25-GHz carrier spacing (yielding a comparable spectral efficiency) may offer comparable savings. Thus, from a spectral efficiency point of view, there is not yet a compelling reason to migrate from 10 to 40 Gbit/s.

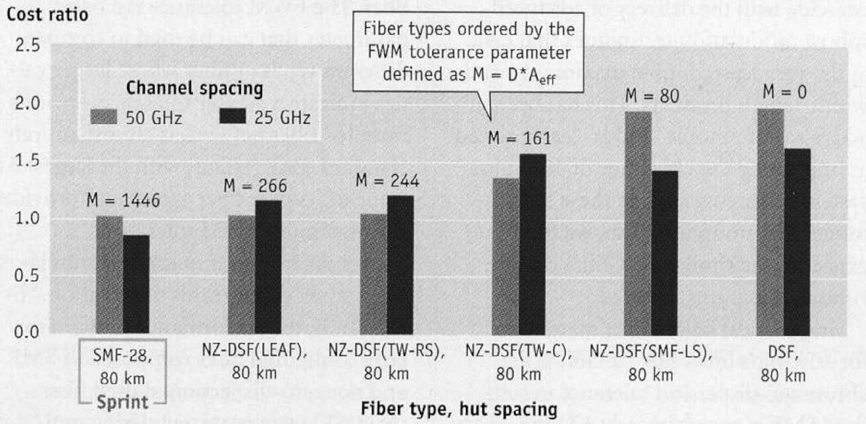

**FIGURE 2.** The costs for Vendor A ($/DS3/mile) are normalized according to the cost obtained for an SMF-28 fiber plant with 80-km hut spacing and 50-GHz carrier spacing.

Transport efficiencies are to be gained by increasing line rates to 40 Gbit/s, but what innovations does the future hold and when does this transition make sense? On reaching maturity and acceptance in long-haul networks, 40-Gbit/s links will likely coincide with the delivery of advanced, robust modulation techniques that can, at the very least, double maximum bandwidth-length products. This has been an active research topic and is clearly aimed at improving the efficiency of 40-Gbit/s systems. Moreover, when these techniques are brought to bear, we fully expect to see similar 10-Gbit/s design rules and margins restored.

Impractical link budget margins exist for 40-Gbit/s links. For 10-Gbit/s, the chromatic-dispersion tolerance in standard SMF is approximately ±32 km; today, at 40 Gbit/s, that figure should be 16 times less, or ±2 km. The polarization-mode-dispersion (PMD) tolerance at 10 Gbit/s is approximately 12 to 15 ps; at 40 Gbit/s, that plummets to approximately 4 ps.

Turning up 40-Gbit/s links today will require far more stringent qualification testing. Carriers fully expect better diagnostic tools and test equipment embedded within more-advanced transport systems, wanting to reduce the cost of test equipment while improving efficiency. A cost-avoidance approach of stand-alone high-speed bit-error-rate (BER) testers and optical-spectrum analyzers used in daily operations is realizable.

### FIBER DISPERSION AND CORE EFFECTIVE AREAS

| Fiber Type | ITU | Dispersion @ 1550nm (ps/nm/km) | Dispersion slope (ps/km/nm$^2$) | Effective area ($A_{eff}$) (μm$^2$) | M |
|---|---|---|---|---|---|
| SMF-28 | NDSF/G.652 | 16.70 | 0.06 | 86.6 | 1446 |
| DSF | DSF/G.653[CTA1] | 0 | 0.063 | 45.3 | 0 |
| LS | NZNDSF/G.655 | -1.60 | 0.075 | 50 | 80 |
| TW Classic | NZNDSF/G.655 | 2.90 | 0.07 | 55.42 | 161 |
| TW - RS | NZNDSF/G.655 | 4.40 | 0.042 | 55.42 | 244 |
| LEAF | NZNDSF/G.655 | 3.67 | 0.105 | 72.36 | 266 |
| TERALIGHT | NZNDSF/G.655 | 8.0 | 0.058 | 63 | 504 |

## LEGACY NETWORKS AND FWM

In WDM optical systems, cross-phase modulation and four-wave mixing (FWM) are considered major sources of nonlinear crosstalk between channels. Although crosstalk induced by cross-phase modulation can be significantly reduced by proper dispersion compensation, FWM depends only on the local dispersion value of each fiber spool in the system.[1, 2]

In dispersion-compensated WDM optical systems, if we consider FWM as the only source of nonlinear crosstalk, the FWM tolerance (*M*) of the transmission optical fiber can be shown to be related by simply using $M = D \cdot A_{eff}$, where *D* is the local dispersion and $A_{eff}$ is the effective cross-sectional area of the fiber. The FWM tolerance is a basic parameter that can be used to compare different types of fiber where larger values indicate a greater tolerance. Sprint's installed fiber network is almost entirely standard SMF (NDSF, with the largest *M* value of its peer fiber types) and provides the maximum FWM tolerance.

Results from our numerical simulations study support this observation.[3] In this study, the performance of two similarly configured links composed of SMF and nonzero-dispersion-shifted fiber (NZDSF) were evaluated. Using optimized launch powers, the maximum link lengths for the two 10-Gbit/s links were compared. With a 50-GHz carrier spacing, the maximum link length for the SMF link was comparable to that of the NZDSF link at 950 km. However, with a 25-GHz carrier spacing, the maximum link length for the NZDSF link decreases to 525 km, while that of the SMF link remains at 950 km. This difference is attributed to the effects of FWM, which are significantly less in the SMF link because of its superior FWM tolerance.

## TECHNOLOGY ASSESSMENT

Sprint recently surveyed state-of-the-art 10-Gbit/s system offerings across a number of fiber types for 80-km spans. We compared these offerings in terms of both performance and cost across fiber types from a given vendor. (PMD was not considered a limiting factor for 10-Gbit/s systems.[4]) Rather than comparing vendors and their product offerings, we have instead used this data to assess the capabilities of the legacy network with state-of-the-art technologies from both a technology and business viewpoint.

Only a few vendors responded with 40-Gbit/s systems with a 100-GHz carrier spacing (0.4-bit/s/Hz spectral efficiency). The performance and cost of these systems on NZDSF and standard SMF was similar, but not superior to our baseline reference system (for example, a 10-Gbit/s system with 50-GHz carrier spacing on standard SMF with 80-km hut spacing).

While all of the vendors surveyed offered 10-Gbit/s systems with 50-GHz carrier spacing, only two (vendors A and B) offered 10-Gbit/s systems with 25-GHz carrier spacing as well. (Recently other vendors have announced products with 25-GHz carrier spacing.) Vendor A and B offerings are EDFA and Raman amplified (RA) systems, respectively.

Fiber types evaluated include SMF-28, LEAF, True-Wave-Reduced Slope (TW-RS), True-Wave-Classic (TW-C), SMF-LS, and dispersion-shifted fiber (DSF) (see table). An evolutionary trend from high-dispersion (NDSF or standard SMF), then zero-dispersion (DSF), and back to high-dispersion (Teralight) fiber can be seen in this chronological listing of fiber types.

Fig. 1 shows the relative capacity-distance products for Vendor A's offerings, normalized to the product obtained for our baseline reference. A value of 2, for example, would be interpreted as having twice the capacity-distance product of the baseline reference. The fiber types on the horizontal axis of Fig. 1 have been arranged according to their FWM

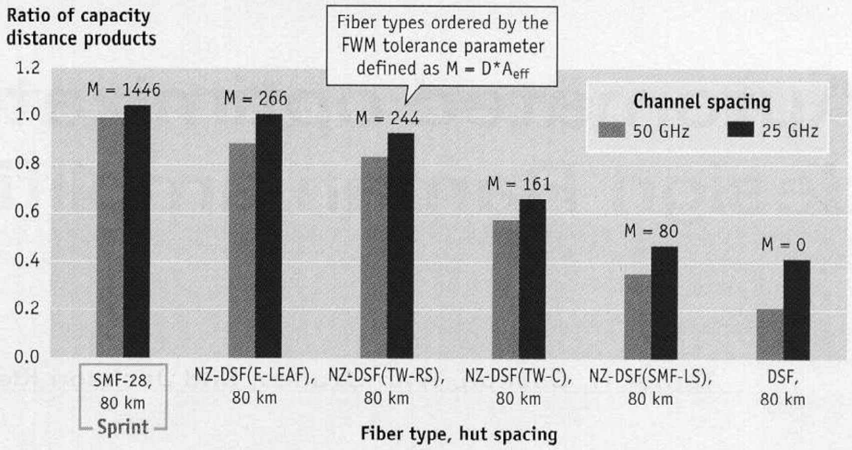

**FIGURE 3.** The relative capacity-distance products for system offerings from Vendor B are normalized to the product obtained for SMF-28 fiber with 80-km hut spacing and 50-GHz carrier spacing.

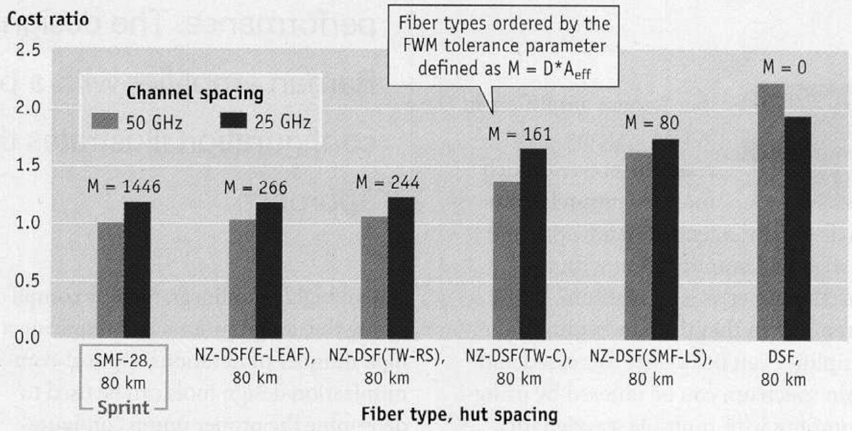

**FIGURE 4.** The costs for Vendor B ($/DS3/mile) are normalized according to the cost obtained for an SMF-28 fiber plant with 80-km hut spacing and 50-GHz carrier spacing.

*M*-value tolerance. As can be seen, there is a clear migration towards lower capacity-distance products as the *M*-value decreases for both 50- and 25-GHz carrier spacing. More important, the slope of this trend is more pronounced for the tighter carrier spacing, which agrees well with our numerical simulations.[3] Clearly, the best dense-WDM performances are obtained on SMF-28 fiber.

We also compared vendor offerings with respect to cost, measured in $/DS3/mile. These values are shown in Fig. 2 for Vendor A. Here, the costs are normalized according to the cost for an SMF-28 fiber plant with 50-GHz carrier spacing. A value of 2, for example, would be interpreted as double the cost of a reference modeled system obtained for SMF-28 with 80-km hut spacing and 50-GHz carrier spacings. This figure shows that system costs generally rise with decreasing *M*-values. The lowest overall costs are obtained for SMF-28 fiber for either carrier spacing, with the lowest cost obtained at 25-GHz carrier spacing.

Similar capacity-distance and cost comparisons are shown for Vendor B in figures 3 and 4, respectively. Vendor B's offering is a Raman-amplified system. Performances were once again ordered according to our FWM tolerance, *M*. Here, the performance benefit on transitioning from 50-GHz to 25-GHz carrier spacing seems marginal as if trading-off distance for capacity for all fiber types.

## TECHNOLOGY DEPLOYMENT

In keeping with its proven strategy of paced technology introduction, the Sprint long-haul network should opt for a more scalable and cost-effective established 10-Gbit/s technology, and look toward 40-Gbit/s systems after they mature in two to three years. Currently, this means 10-Gbit/s systems offering 50-GHz carrier spacing with 25-GHz carrier spacing on the horizon as an in-service upgrade.

Based on numerical simulations, we have shown that standard SMF has a definite advantage over alternative fiber types in an ultradense scenario because of its inherently high chromatic dispersion and relatively large effective core area. Data provided by vendors support this claim. The record of fiber-type evolution seems to be a testament to the admitted capabilities of standard SMF and that the future is not unfolding as many had thought.

Many technologies have emerged that appear promising to a carrier with a legacy standard SMF network. Recently, much interest has been paid to the study of advanced modulation formats for better optical bandwidth efficiency and longer transmission distance. No matter what modulation format is used, increasing optical bandwidth efficiency implies tighter WDM carrier spacing.

Since FWM efficiency is inversely proportional to the square of the carrier spacing, FWM-induced crosstalk is still a major concern in this type of advanced optical system. In addition, the effect of FWM is cumulative, and for longer nonrepeated transmission distance, the FWM effect intensifies and it cannot be reduced by dispersion compensation. **WDM**

### REFERENCES

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