Is standard single-mode fiber the fiber to fulfill the needs of tomorrow's long-haul networks?

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Abstract

To meet increased fiber capacity and transmission distance demands, ultra-Dense Wavelength-Division Multiplexing (DWDM) is preferred by Sprint because of its compatibility with Sprint's legacy fiber plant, composed primarily of standard Single-Mode Fiber (SMF). This paper focuses on long-haul transmission efficiencies and fiber compatibility. The trade-offs between bandwidth efficiency, transmission distance and implementation/operation costs are considered. We compare system performances on standard SMF against Non-Zero Dispersion Shifted Fiber (NZDSF) by means of a full-fidelity fiber link modeling tool developed at the University of Kansas. Using this model, the effects of different carrier spacings, channel rates, modulation formats, amplifiers, and filtering schemes are compared. A comparative assessment is also provided by surveying DWDM vendor offerings across various fiber types.

In ultra-dense WDM systems, nonlinear crosstalk is considered a major source of performance degradation. Our results clearly demonstrated the advantages of using standard SMF because of its high local dispersion. From a strategic planning perspective, we remain confident that Sprint will continue to extract value from its existing fiber plant into the foreseeable future.

Introduction

Sprint is actively pursuing an overlay network to more efficiently support growing capacity-length demands (internet and data traffic) and offer varying levels of wavelength protection. To satisfy demands for increased data capacity, the Sprint network has favored dense WDM as opposed to increased time-division multiplexing (TDM).

To meet growing capacity requirements coupled with increased length demands, Sprint will favor initially ultra-dense WDM in the core, while adopting the position that standard SMF is the fiber of choice. This direction is consistent with one Sprint employed previously in migrating from 2.5- to 10-Gb/s line rates. In the past, Sprint satisfied increased capacity demands by tactically exploiting a tighter carrier spacing (100 GHz to 50 GHz) that standard SMF could support, unlike some newer fiber types. In addition, Sprint opted for the more cost effective and proven 2.5-Gb/s technology, deferring the adoption of 10-Gb/s line rates until those technologies had more fully matured. Sprint had a sizable investment and great confidence in managing 2.5-Gb/s line rates. Early on, managing 10-Gb/s links was a very expensive proposition. Although 10 Gb/s was introduced in the first half of the '90s, it is only within the past three years that 10-Gb/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-Gb/s line rates and has a growing nationwide coverage.

The metrics driving an adoption decision include the maximum bandwidth-length product[1] and cost, measured in $/DS3/mile. The $/DS3/mile metric is calculated simply using the loaded capital cost of the simple point-to-point DWDM system. Today, a 40-Gb/s offering will not compete with a 10-Gb/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

[1] A typical engineering rule is the subtraction of 1 to 1½ spans from the maximum transmission distance per OADM addition.

system additions, and the recurring utility expense. Historically, by migrating from 2.5 Gb/s to 10 Gb/s, Sprint quadrupled the system capacity within the same footprint (going from 100 Gb/s realized in 2 bays to 800 Gb/s in 4 bays) and while doubling the system reach. And while the initial 40-Gb/s/100 GHz (0.4 b/s/Hz) spectrally efficient systems being offered today may double the capacity within the same footprint, new 10-Gb/s/25 GHz (0.4 b/s/Hz) spectrally efficient systems may offer comparable savings.

On reaching maturity and acceptance in long-haul networks, 40-Gb/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 (see OFC 2002) and is clearly aimed at improving the efficiency of 40-Gb/s systems. Moreover, when these techniques are brought to bear, we fully expect to see similar 10-Gb/s design rules and margins restored. Impractical link budget margins exist today for 40-Gb/s links. For 10-Gb/s, the chromatic dispersion tolerance in standard SMF is about ±32 km; today, at 40 Gb/s, that figure should be 16 times less, or ±2 km. The polarization-mode dispersion (PMD) tolerance at 10 Gb/s is about 12-15 ps; at 40 Gb/s, that plummets to about 4 ps. Turning up 40-Gb/s links today will require far more stringent qualification testing. Carriers fully expect greater diagnostic tools and test equipment embedded within more advanced transport systems, wanting to reduce the cost of test equipment while improving efficiency.

Sprint believes that supporting services (e.g. OC-768c router interface) will naturally drive increased line rates, for it is the overall cost structures that are important with an emphasis on cost per service. The delivery of OC-768c router interfaces will likely be commensurate with increasing line rates to 40 Gb/s. Traditionally, router interfaces have lagged behind optical interfaces in terms of SONET/SDH speeds (e.g. 2.5 to 10 Gb/s).

Clearly, transport efficiencies are to be gained by increasing line rates to 40 Gb/s, but what innovations does the future hold and when does this transition make sense? This paper weighs the technology option of ultra-dense WDM transmission as a competing cost alternative to increased TDM. This paper addresses some considerations in the selection of the most efficient approach through (i) an academic study examining fiber compatibility and (ii) vendor inputs that survey the state-of-the-art DWDM offerings across fiber types and leading to a competitive assessment. Both showcase the standard SMF fiber plant, emphasizing its key strengths.

Numerical Modeling Study

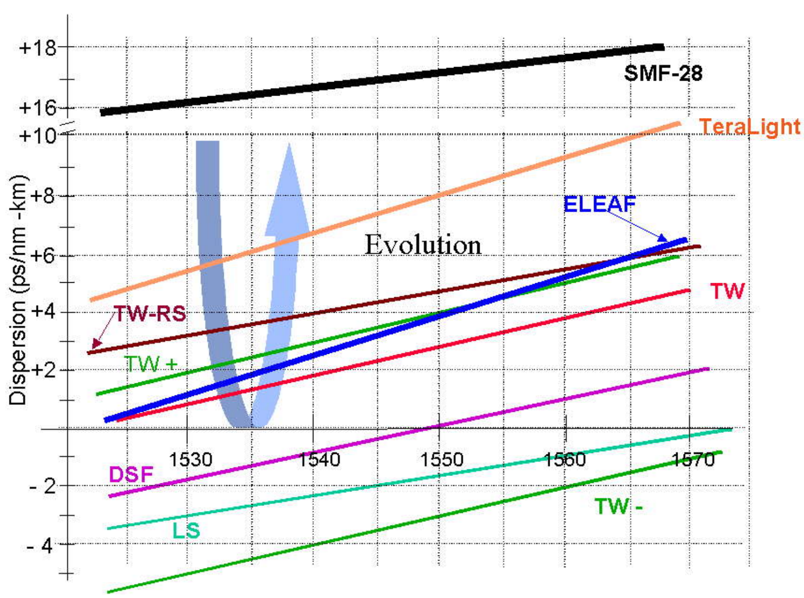


Figure 1. Evolution of fiber dispersion characteristics

Figure 1 shows typical dispersion vs. wavelength characteristics for several major fiber types that have been offered for long-distance links. This figure shows the evolutionary trend from high dispersion (NDSF or standard SMF), then zero (DSF), and back to high dispersion (Teralight) fiber.

To model the effects of fiber dispersion on network performance for DWDM systems, we considered the link configuration shown in Figure 2. Here, 25 equally spaced NRZ-modulated carriers are launched down a fiber link consisting of repeating spans. Each span consisted of a 75-km length of either standard SMF or NZDSF, followed by an amplifying/dispersion-compensating module.

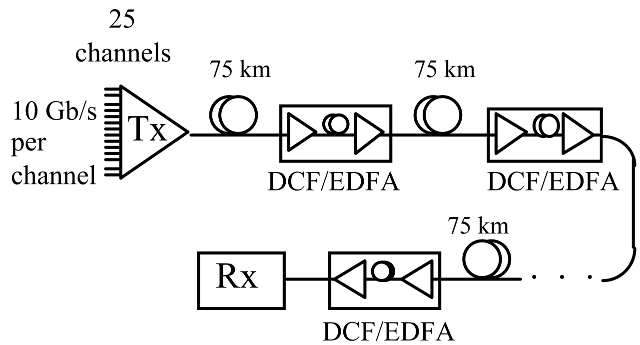


Figure 2. Span configuration for standard SMF, NZDSF comparison.

WDM inputs were formed by multiplexing 25 NRZ-modulated carriers. Each waveform was modulated at 10 Gb/s, using standard on-off keying with an electrical bandwidth 7.5 GHz. For all of the cases considered, the carriers were equally-spaced (in frequency), and the lowest carrier wavelength was 1528 nm.

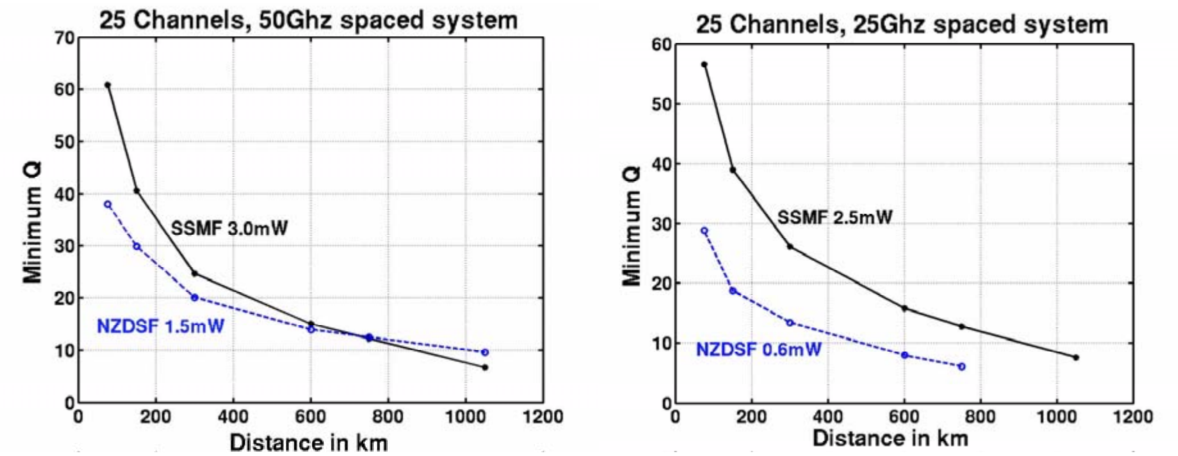
The standard SMF fibers considered had a dispersion and dispersion slope of +17 ps/nm/km and 0.09 ps/km/nm^2 at the band center, respectively, an effective area of 80 μm^2, and a loss of 0.25 dB/km. The NZDSF had a zero dispersion wavelength of 1507 nm, a dispersion slope of 0.1143 ps/km/nm^2, an effective area of 72 μm^2, and a loss of 0.25 dB/km.

The dispersion compensating fiber used in the amplifying/compensating modules was chosen to yield a residual dispersion of approximately +10 ps/span at the lowest wavelength and under 80 ps/span at the largest wavelength. For the standard SMF spans, the DCF in each compensating module had a dispersion and dispersion slope of -106 ps /nm/km and -1 ps/km/nm^2 respectively, and a length 12 km. For the NZDSF spans, the DCF had a dispersion and dispersion slope of -70.496 ps /nm/km and -1 ps/km/nm^2, respectively, and a length of 2.4 km. The module gains were chosen to exactly compensate for the previous span loss (not including the DCF loss), with noise figures of 6 dB that accounted for the DCF loss.

At the receiver, the demultiplexing optical filters were set to 16-GHz bandwidths and the electrical bandwidths of the detectors were 7.5 GHz. System quality factors (Q) were calculated from the receiver eye diagrams and the system noise parameters, which included the amplified spontaneous emission (ASE) noise from the EDFAs, along with the resulting signal-spontaneous noise at the detector [1].

The numerical simulations for this study were performed using a fiber link modeling code developed at the University of Kansas. This code uses the split-step Fourier transform technique (SSFT) to solve the nonlinear Schrödinger equation [2], and predicts the distortion of the WDM optical envelope as it progresses through the network. All dispersive and nonlinear effects were modeled during these calculations, including first- and second-order dispersion, self- and cross-phase modulation, four-wave mixing (FWM), and delayed Raman response. Both the carrier spacings and the launch power per channel were varied to see their effects on the system Q.

Figure 3a shows the minimum (i.e., poorest) channel Q vs. accumulating standard SMF or NZDSF span lengths when the carrier spacings were 50 GHz. The launch power levels (3 mW/channel for standard SMF and 1.5 mW/channel for NZDSF) used to generate these curves were chosen to produce the highest possible Q values out to distances of at least 750 km. As can be seen, both the standard SMF and NZDSF spans maintain Q values greater than 8 (corresponding to BER $\approx 10^{-15}$) out to distances of 950 km. Although the standard SMF performance is better than the NZDSF performance over most of the span, it can be said that the overall performance difference is small for 50 GHz carrier spacings.



(a) (b)

Figure 3. Minimum in-band Q vs. Distance. a) 50-GHz carrier spacings, b) 25-GHz carrier spacings

The performance difference between the standard SMF and NZDSF spans becomes much more pronounced when the channel spacings are reduced. Figure 3b shows the minimum Q values for the same standard SMF and NZDSF spans when the carrier spacing reduced to 25 GHz. The ideal launch power for the standard SMF span is 2.5 mW, but the NZDSF spans could tolerate no more than 0.6 mW, after which significant eye-closure penalties were encountered due to FWM. As can be seen, the lower NZDSF launch powers result in dramatically lower performance Q values for 25-GHz carrier spacings. Whereas the standard SMF span maintains Q values greater than 8 out to 950 km, the NZDSF span can maintain this Q no farther than 525 km.

The poor performance of the NZDSF fiber at 25-GHz carrier spacings is due mostly to FWM, since FWM susceptibility is inversely proportional to local, not average, dispersion. In WDM systems, it has been shown that FWM-induced crosstalk can be modeled as a noise superimposed on the optical signal [3]. The standard deviation of this noise is inversely proportional to local dispersion of the transmission fiber. The ratio between local dispersions of standard SMF (17 ps/nm/km) and NZDSF (2.5 ps/nm/km) is approximately 8 dB. In a signal-spontaneous beat noise limited optical receiver, this corresponds roughly to a 4-dB difference in the Q value if FWM is the dominant source of system performance degradation. Indeed our numerical simulation predicted a 3-dB difference in the receiver Q value when the WDM carrier spacing is 25 GHz. In the case of 50-GHz carrier spacing, Q difference between the two fiber types is smaller, since FWM is not a dominant degradation source of the system.

In WDM optical systems, cross-phase modulation and four-wave mixing are considered major sources of nonlinear crosstalk between channels. Although crosstalk induced by cross-phase modulation can be significantly reduced by proper dispersion compensation [1], four-wave mixing depends only on local the dispersion value of each fiber spool in the system [2]. The effect of FWM can usually be modeled as a coherent noise superimposed on the optical signal; the standard deviation of this noise, which indicates the crosstalk level, is proportional to the fiber nonlinear parameter, γ, and inversely proportional to the fiber local dispersion D where the nonlinear interactions take place [2]. In dispersion compensated WDM optical systems, if we consider FWM as the only source of nonlinear crosstalk, the FWM tolerance of the transmission optical fiber is simply $M = D \cdot A_{eff}$, where A_{eff} is the effective cross-sectional area of the fiber. This is FWM tolerance is a basic parameter that can be used to compare different types of fibers.

Competitive Assessment

Sprint has surveyed state-of-the-art 10-Gb/s system offerings across fiber types (all having PMD $\leq$ 0.05 ps/km$^{1/2}$) for 80-km spans consistent with our modeling effort. We compared these offerings in terms of both performance and cost across a number of fiber types from a given vendor. [To protect a vendor's information, Sprint has handled this material as innocuously as possible in making comparisons.] We are not comparing vendors, but merely addressing the underlying physics at play consistent with our modeling.

Very few vendors responded with a 40-Gb/s systems with 100-GHz carrier spacings (0.4b/s/Hz spectral efficiency). The performance and cost of these systems on NZDSF and standard SMF was similar, but not superior to a 10-Gb/s standard SMF reference modeled system.

All vendors surveyed offered 10-Gb/s systems with 50 GHz carrier spacings (0.2 b/s/Hz spectral efficiency), but only two leading vendors, referred to in this paper as vendors A and B, offered 10-Gb/s systems with 25-GHz carrier spacings (0.4 b/s/Hz spectral efficiency). Vendor A and B offerings are EDFA and Raman amplified (RA) systems, respectively. The relative performance and cost quotes for 50-GHz carrier spacing offerings across fiber type from vendors A and B are fairly representative of the larger vendor sampling and agree well with our modeling.

Figure 4 shows the relative capacity-distance products for system offerings from vendor A, normalized to the product obtained for standard SMF fiber with 80-km hut spacing and 50-GHz spacings. The fiber types include SMF-28, LEAF, True-Wave-Reduced Slope (TW-RS), True-Wave-Classic (TW-C), SMF-LS, and Dispersion Shifted Fiber (DSF). (The dispersion, dispersion slope, and effective core areas of these fibers are summarized in Table 1.) A value of 2, for example, would be interpreted as having twice the capacity-distance product of a reference modeled system obtained for standard SMF with 50-GHz spacings. The fiber types on the horizontal axis of Figure 4 have been arranged according to their FWM 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 spacings. More importantly, the slope of this trend is more pronounced for the tighter carrier spacings, which agrees well with our numerical simulations. Clearly, the best dense DWDM performances are obtained on SMF-28 fiber.

Table 1. 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
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

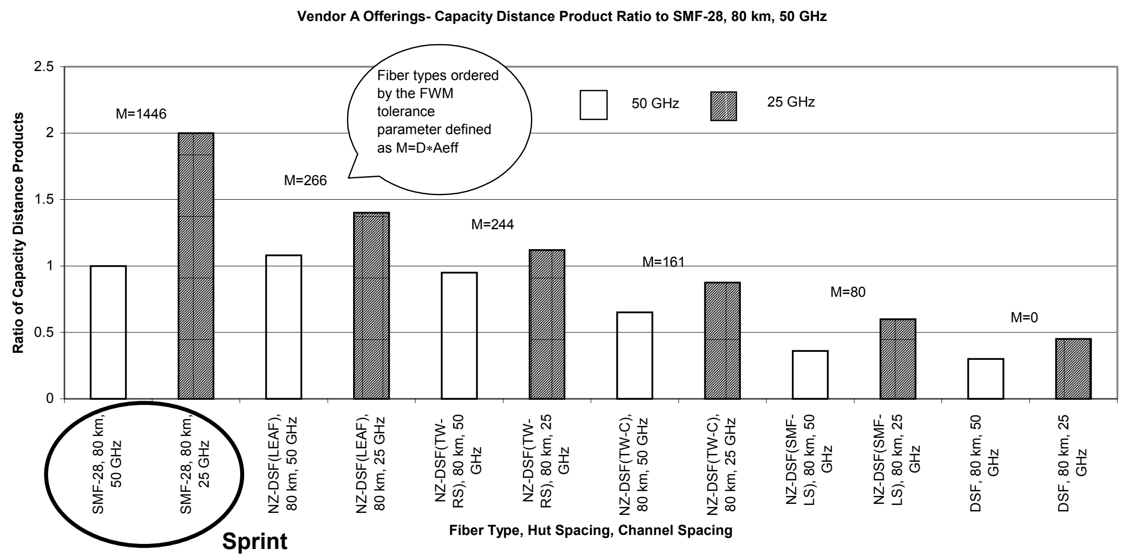


Figure 4. Vendor "A" capacity-distance comparison across fiber types- courtesy of vendor A. This figure shows the relative capacity-distance products for system offerings from vendor A, normalized to the product obtained for SMF-28 fiber with 80-km hut spacing and 50-GHz carrier spacings.

We also compared vendor offerings with respect to cost, measured in \$/DS3/mile. These values are shown in Figure 5 for the same vendor cited in Figure 4. Here, the costs are normalized according to the cost for an SMF-28 fiber plant with 50-GHz spacings. 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 spacings.

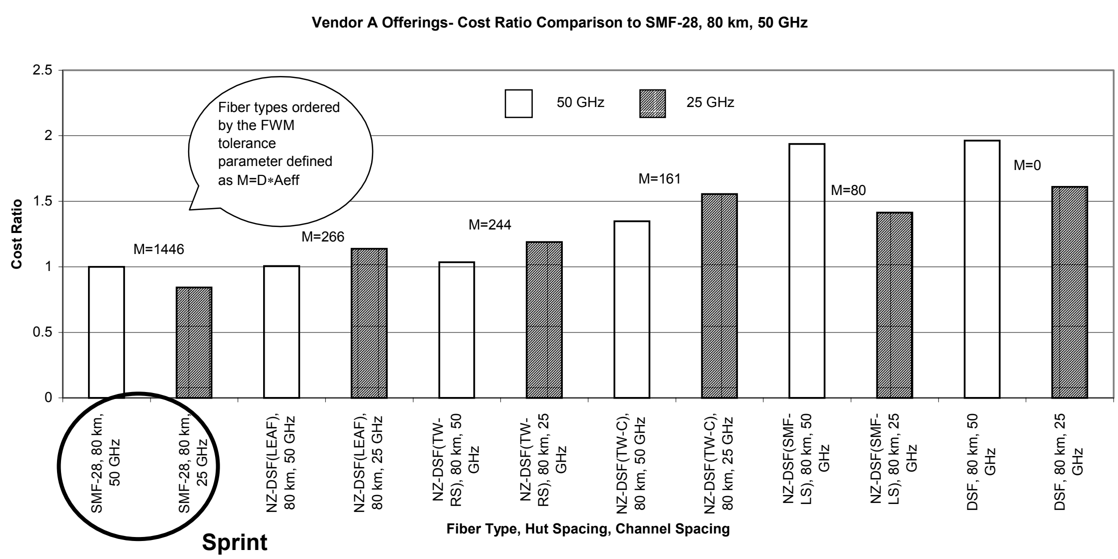


Figure 5. Vendor "A" cost comparison across fiber types- courtesy of vendor A. The costs (\$/DS3/mile) are normalized according to the cost obtained for an SMF-28 fiber plant with 80-km hut spacing and 50-GHz carrier spacings.

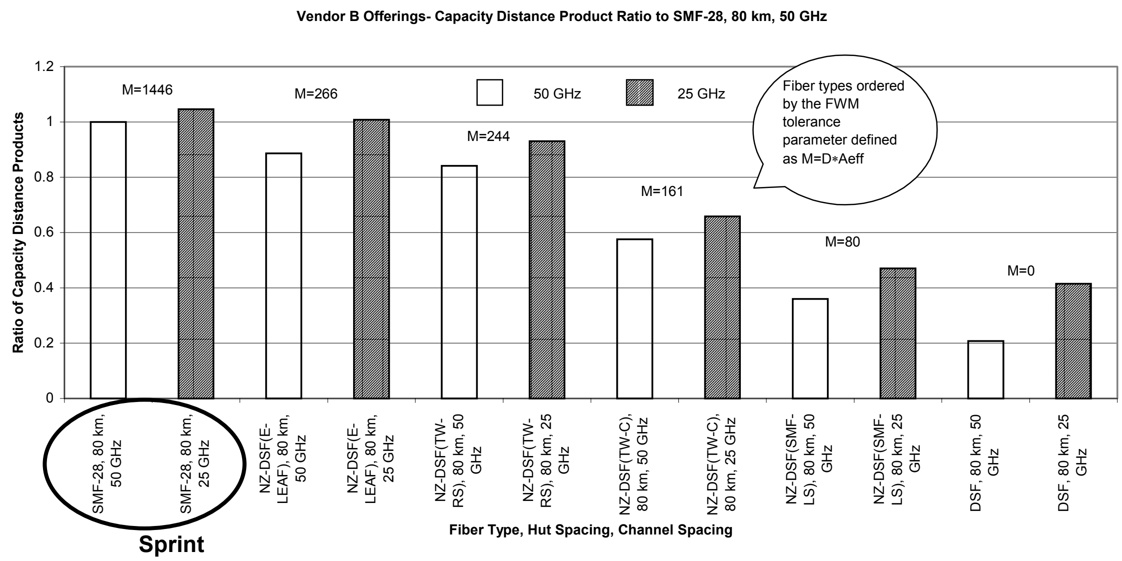


Figure 6. Vendor "B" capacity-distance comparison across fiber types- courtesy of vendor B. This figure shows the relative capacity-distance products for system offerings from vendor B, normalized to the product obtained for SMF-28 fiber with80-km hut spacing and 50-GHz carrier spacings.

Similar capacity-distance and cost comparisons are shown for vendor B in Figures 6 and 7, respectively. Vendor B's offering is a Raman-amplified system and not the EDFA system modeled in our academic study. Performances were once again ordered according to our FWM tolerance, M. Here, the performance benefit on transitioning from a 50 GHz to 25 GHz carrier spacing seems marginal as if trading-off distance for capacity for all fiber types.

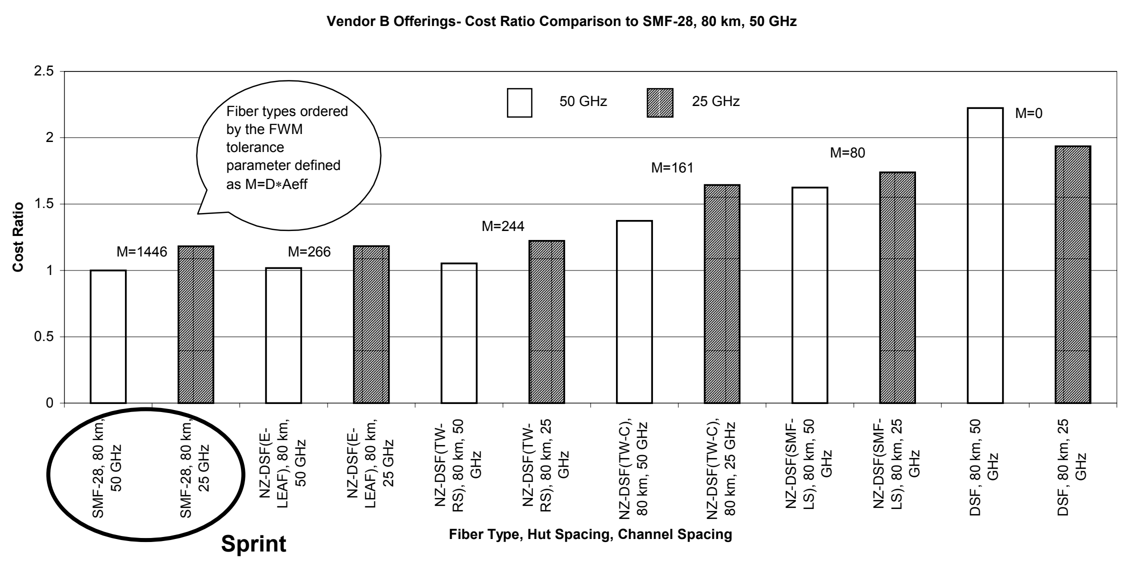


Figure 7. Vendor "B" cost comparison across fiber types- courtesy of vendor B. The costs ($/DS3/mile) are normalized according to the cost obtained for an SMF-28 fiber plant with 80-km hut spacing and 50-GHz carrier spacings.

Sprint actually conducted a more extensive competitive assessment, surveying performance and cost across representative fiber plants, including 40, 80, & 90 km spans. Raman-amplified systems were particularly interesting. The ordering of performance across fiber types for a given hut spacing was consistent with our FWM tolerance, M. The underlying physics at play appeals to our notion of an RA system and its application. Performances for 40 km spans tower over greater hut spacings.

Summary

In keeping with its proven strategy of paced technology introduction, the Sprint long-haul network should opt for cost effective proven 10-Gb/s technology and look toward 40-Gb/s systems after they mature in 2-3 years. Currently, this means 10-Gb/s systems offering 50-GHz carrier spacings with 25-GHz carrier spacings on the horizon as an in-service upgrade. With this strategy, high up-front capital exposure is avoided, thus valuing pay as grow. Based on numerical simulations, we have shown that standard SMF has a definite advantage over alternative fiber types due to its inherently high chromatic dispersion and relatively large effective core area. Furthermore, from data provided by vendors, it is apparent that long-haul standard SMF networks offer efficiencies and reach not possible with other fiber types. This fiber-type evolution shown in Figure 1seems to be a testimony the admitted capabilities of standard SMF and that the future is not unfolding as investor's in NZDSF would have hoped.

Many future 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, such as vestigial optical side-band (VSB), differential optical phase shift key (DPSK), sub-carrier optical multiplexing (SCM) and so on. No matter what modulation format is used, increasing optical bandwidth efficiency implies a tighter WDM carriers 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 systems. In addition, the effect of FWM is accumulative, and for longer non-repeated transmission distance, the FWM effect intensifies and it cannot be reduced by a dispersion compensation.

In terms of an ultra-dense scenario, the Sprint network appears very competitive. From a strategic planning perspective, we have great confidence that Sprint's standard SMF plant will continue to support state-of-the-art networking into the foreseeable future.

Acknowledgment

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