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Considerations for Single-Mode Fiber Systems

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The intrinsic low-dispersion and low-attenuation properties of single-mode fibers between 1.3 and 1.6 μm make them attractive for use in high-capacity, long-haul digital systems. In this paper we discuss some fundamental performance limitations—such as attenuation, bandwidth, mode-partition noise, burst-type error, and receiver sensitivities—for systems with bit rates above 274 Mb/s. Also, we discuss the maximum capacity achievable by either using a single channel at the minimum-dispersion wavelength, or multiple wavelength-multiplexed channels with equal, but necessarily lower, bit rates. We conclude that the characteristics of present laser diodes limit repeater spacing to lengths far less than the potential capacity expected from single-mode fibers. For total capacity of bit rates less than 1 Gb/s, wavelength multiplexing is found to offer longer repeater spacings than single-wavelength systems.

I. INTRODUCTION

The intrinsic low-dispersion property of single-mode fibers makes them attractive for high-capacity, long-haul lightwave systems,[1,2] especially in the wavelength region between 1.1 and 1.7 μm, where low attenuation (less than 1 dB) has been demonstrated.[3] Minimum dispersion can be achieved over a range of wavelengths above 1.3 μm by controlling Ge-doping density and core size.[4–6] Low dispersion over a wide range of wavelengths can be achieved by introducing a certain amount of waveguide dispersion.[7,8] As in any communication system, there are three basic origins of system-performance limitations and degradations: (*i*) sources, (*ii*) media, and (*iii*) receivers. Some limitations, such as receiver sensitivity and source-output power, are determined by a single component. However, many other performance limitations and degradations are caused by the interaction of two components.

Laser diodes as sources have several characteristics that result in

Table I—Degradation factors of laser diodes

	Characteristics of Laser	Related Fiber Characteristics	Degradation Effects to System
Center wavelength	Manufacturing variation ±3 nm	Chromatic dispersion	Bandwidth (with fiber dispersion)
	Temperature variation 0.5 nm/°C		Bandwidth (with fiber dispersion)
	Mode skipping (jumps) 6 ~ 10 $\Delta\lambda$		Burst error
Spectrum (half-rms width)	Half rms width 2 ~ 4 nm		Bandwidth of fiber
	Spectrum broadening		
	Mode partition ($0 \leqq k \leqq 1$)		Mode-partition noise
Intrinsic noise	Quantum noise Transverse mode fluctuation	N.A. and Δ (coupling to fiber)	Noise Power fluctuation
Reflection	Spectrum noise Self-pulsing	Fiber end Pigtail length	Noise
Bandwidth	1 ~ 2 GHz		Bandwidth of transmitter

severe limitations on the performance of a single-mode fiber system. As indicated in Table I, these characteristics, such as spectral distribution,[6] longitudinal mode-partition effects,[9–11] and abrupt jumps[10,12] of the longitudinal or transverse lasing modes,[10] cause a degree of system degradation that depends on the characteristics of the fiber (chromatic dispersion). There are also fundamental performance limitations and degradation factors for single-mode fiber systems caused by fiber attenuation and bandwidth,[13,14] mode-partition noise,[9–11,15] and limited receiver sensitivity.[16–19]

Because of these limitations and their mutual interactions, it is a problem when designing a lightwave system with a given bit rate per fiber to decide whether to use a single high-speed digital signal or several lower-speed channels multiplexed on different wavelength lightwaves. This paper will discuss this problem and develop some general guidelines for solving it.

II. PERFORMANCE LIMITATIONS AND DEGRADATIONS

Table I shows detrimental aspects of laser diodes and Table II shows degradation factors caused by fibers. In this paper, we will focus on five fundamental factors that limit system performance: (*i*) fiber attenuation, (*ii*) fiber bandwidth, (*iii*) mode-partition noise, (*iv*) burst-type errors caused by mode jumps, and (*v*) receiver sensitivity.

Table II—Characteristics of fiber

	Loss	
Intrinsic loss	● Infrared absorption ● Ultraviolet absorption ● Rayleigh scattering	● Wavelength dependency
OH-absorption		● 1.24 μm ● 1.38 μm
Imperfection of waveguide	● Boundary of core and cladding ● Bubbles ● Core size variation	Refractive index Difference dependency
Microbending	● Coating ● Stress	● Core size and refractive index difference ● Wavelength dependency
Splicing loss		
	Dispersion	
Material dispersion	● Doping material	● Wavelength dependency
Waveguide dispersion	● Core size and refractive index difference	● Wavelength dependency

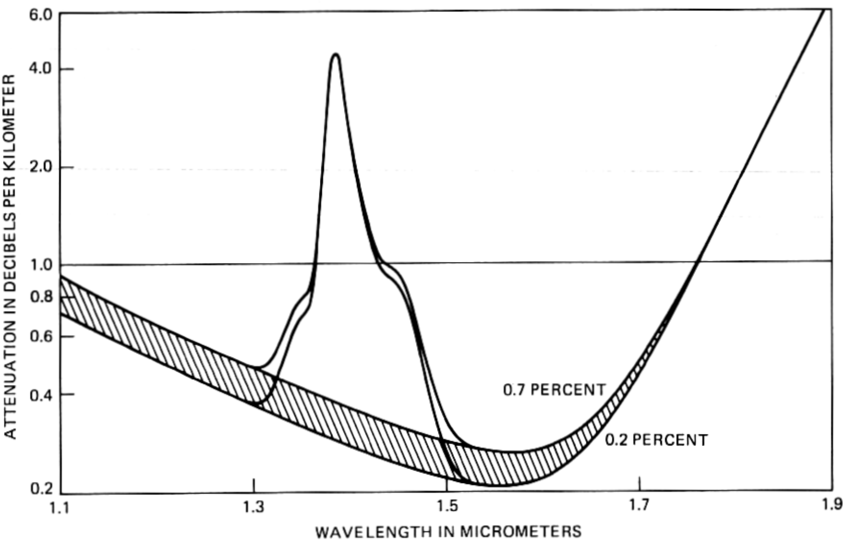

Fig. 1—Fiber attenuation spectrum of a Ge-doped core single-mode fiber.

2.1 Fiber attenuation

Figure 1 shows the theoretical attenuation of single-mode fiber (Ge-doped core) caused by Rayleigh scattering, infrared absorption, and ultraviolet absorption. The crosshatched area in Fig. 1 shows the theoretical limitation (refractive index difference $\Delta = 0.2$ to 0.7 percent) without the water absorption peaks at 1.38 and 1.24 μm. The water absorption peaks at 1.24 and 1.38 μm are expected to be eliminated eventually by improvement of the dehydration process. There are additional attenuation factors such as (*i*) imperfection losses of the waveguide,[20] (*ii*) microbending losses,[21] and (*iii*) splicing losses.[21,22] Considering these additional losses, probably 0.5 dB/km total fiber loss at 1.3 μm is the theoretical limit, and 1 dB/km can be assumed to be obtainable for practical fiber systems.

2.2 Bandwidth, mode-partition noise, and burst error by mode jumps

Bandwidth, mode-partition noise, and burst error caused by mode jumps are all generic functions of laser and fiber characteristics. If laser diodes are stabilized someday either by injection locking,[23] a new laser-cavity configuration,[24] or other methods (such as the use of an external modulator),[25] then these will not limit system performance so severely. However, at present these three factors are important considerations for single-mode systems.

2.2.1 Bandwidth limitations

The bandwidth of a system using a well-stabilized single-longitudinal-mode laser would be limited by the degenerate-polarized mode dispersion of the fiber,[26] not by the laser spectrum. Since most laser diodes show spectral broadening under direct-current modulation, the bandwidth is determined by the source spectrum and the chromatic dispersion of the fiber. Figure 2 shows the bandwidth of single-mode fibers. Two curves are shown for source rms half-widths of 1 nm and 2 nm. The wavelength of minimum dispersion is assumed to be 1.3 μm. The overall transmission bandwidth is determined by chromatic dispersion of the fiber and by the laser spectrum, as follows:[10,14]

$$f_{6\mathrm{dB}} = \frac{187.3}{Z \cdot \sigma \cdot \left| \frac{d\tau}{d\lambda} \right|} [\mathrm{GHz}] \quad \text{off the wavelength of minimum dispersion}$$

$$f_{6\mathrm{dB}} = \frac{616.4}{Z \cdot \sigma^2 \cdot \left| \frac{d^2\tau}{d\lambda^2} \right|} [\mathrm{GHz}] \quad \text{at the wavelength of minimum dispersion,} \tag{1}$$

where $f_{6\mathrm{dB}}$[GHz] is the bandwidth of fiber (3-dB optical bandwidth), Z is its length, $\left| \frac{d\tau}{d\lambda} \right|$ [ps/nm·km] is the differential chromatic dispersion $\left| \frac{d^2}{d\lambda^2} \right|$ [ps/nm^2·km] is the third-order chromatic dispersion, and σ is the half-rms width of laser spectrum.

If we permit a 3-dB power penalty at an error rate of 10^{-9}, then the signal bit rate, B(b/s), and fiber bandwidth, $f_{6\mathrm{dB}}$, are related by[19]

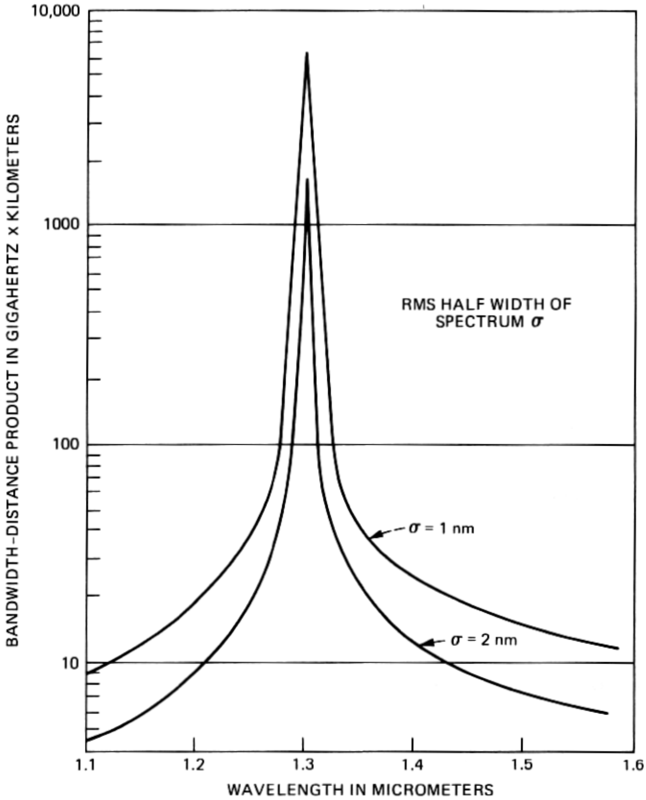

Fig. 2—Bandwidth of a single-mode fiber vs. wavelength.

$$f_{6dB} = 0.55B. \tag{2}$$

Combining equations (1) and (2), we obtain the performance limitation caused by bandwidth as a bit rate-distance product, $B \cdot Z$, as shown below.

$$B \cdot Z \leqq \frac{340.5}{\sigma \cdot \left| \frac{d\tau}{d\lambda} \right|} \text{[Gb/s·km]} \quad \text{off the wavelength of minimum dispersion}$$

$$B \cdot Z \leqq \frac{11207}{\sigma^2 \cdot \left| \frac{d^2\tau}{d\lambda^2} \right|} \text{[Gb/s·km]} \quad \text{at the wavelength of minimum dispersion.} \tag{3}$$

2.2.2 *Mode-partition noise*

As discussed in Ref. 10, mode-partition noise can become a serious performance limitation. The bit-rate-distance product caused by this partition noise is expressed for the condition that the asymptotic error rate be 10^{-17} (or a power penalty or 1.5 dB at 10^{-9} error rate)

$$B \cdot Z \leqq \frac{130}{\sigma \cdot \left| \frac{d\tau}{d\lambda} \right| \sqrt{k}} \text{[Gb/s·km]} \quad \text{off the wavelength of minimum dispersion}$$

$$B \cdot Z \leqq \frac{1173}{\sigma^2 \cdot \left| \frac{d^2\tau}{d\lambda^2} \right| \sqrt{k}} \text{[Gb/s·km]} \quad \text{at the wavelength of minimum dispersion,} \tag{4}$$

where k is the mode-partition noise-suppression factor ($0 \leqq k \leqq 1$). Measured results indicate that k lies between 0.4 and 0.7 and a theoretical analysis of k shows that it cannot be zero and is about 0.1 even with dc operation. A comparison of eqs. (3) and (4) shows that the effect of partition noise is greater than that of bandwidth when k is greater than 0.1. Therefore, mode-partition noise is the dominant effect on the system. Figure 3 shows the bit-rate-distance product caused by the mode-partition noise in the worst case, which is $k = 1$. Two curves are shown for source rms half-widths of 1 nm and 2 nm. The wavelength of minimum dispersion is assumed to be 1.3 μm.

2.2.3 Burst error caused by mode jumps

Because of temperature variations or drive-current variations, some laser diodes show sudden jumps of the center wavelength. This causes a burst of errors until the retiming circuit locks into the shifted phase. This burst-type error will happen randomly at any repeater. To keep the system error rate within system requirements, there are two design approaches:

(*i*) Error-rate objective—worst short-term error rate must be under 10^{-9} when this burst error is a frequent random phenomenon.

(*ii*) Error-free-seconds objective—the error-free seconds must be at least 95 percent when burst errors occur occasionally.

If we assume that mode jumps at each repeater are rather frequent random phenomena, unlike fading or lightning, then a 6400-km terminal-to-terminal error-rate objective should be applied to this burst-type error caused by mode jumps. From Ref. 8, the bit-rate-distance product in the worst case is then given by the relation

$$B \cdot Z \leqq \frac{225}{\left| \frac{d\tau}{d\lambda} \right| \cdot \Delta\lambda} \text{[Gb/s·km]},$$

where $\Delta\lambda$[nm] is the center-wavelength shift for a typical jump.

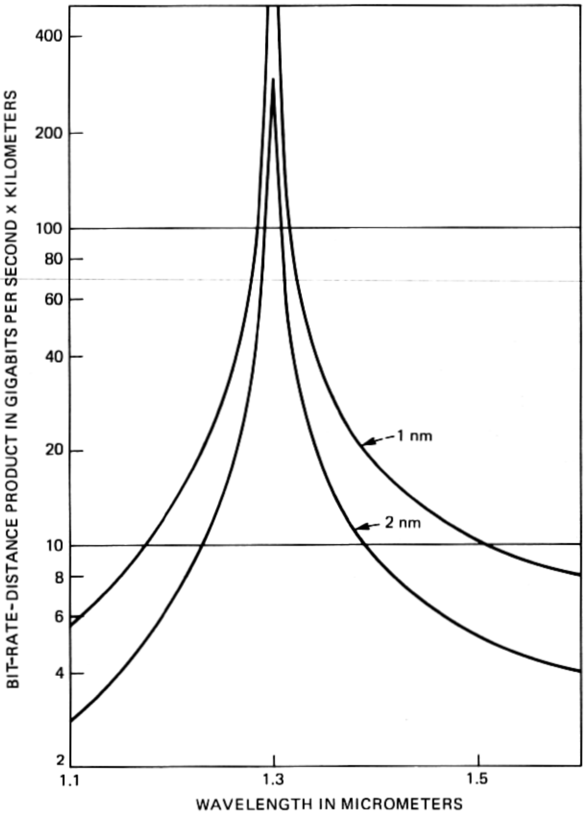

Fig. 3—Bit-rate-distance product caused by mode-partition noise vs. wavelength.

2.3 Receiver sensitivity

There are two basic design approaches used to obtain highly sensitive receivers: (*i*) InGaAs-pin photodiode[27,28] with an ultra-low noise amplifier, and (*ii*) Ge[29] or InGaAs avalanche photodiode[30] with a low-noise amplifier. For the first approach, there are several device technologies that provide ultra-low noise amplifiers above 274 Mb/s: (*i*) Si-microwave bipolar transistors,[31] (*ii*) GaAs-MESFETS,[32] and (*iii*) Si short-channel MOSFETS.[18,33] Although Si bipolar transistors will deliver better noise characteristics than FETS above 300 Mb/s, theoretically FETS are still useful for high bit-rate amplifiers because the cut-off frequency (~4 GHz) of practical bipolar transistors is lower than that of FETS (10 ~ 25 GHz). An avalanche photodiode APD receiver delivers much higher sensitivities, theoretically, even with its intrinsic excess noise factor. However, the sensitivity achieved using a practical

GeAPD is comparable to InGaAs pin with a ultra-low noise amplifier. In general, the practical value of sensitivity can be expressed as

$$\bar{P} = -34 + 10 \log B[\text{dBm}],$$

where B is [Gb/s].

III. REPEATER SPAN

The achievable repeater spacing at different bit rates above 274 Mb/s can now be found assuming 0 dBm of average output power from laser diodes into the fiber. Figures 4 and 5 show two different cases: Fig. 4 shows that the half-rms width of laser spectrum is 2 nm and mode jumping $\Delta\lambda$ is less than 3 nm. Solid lines indicate performance limitations due to fiber attenuation (0.5 dB/km and 1.0 dB/km). The dot-dash lines are the fiber bandwidth of 1.3 μm and 1.275 μm. However, the mode-partition noise limitations indicated by the dashed

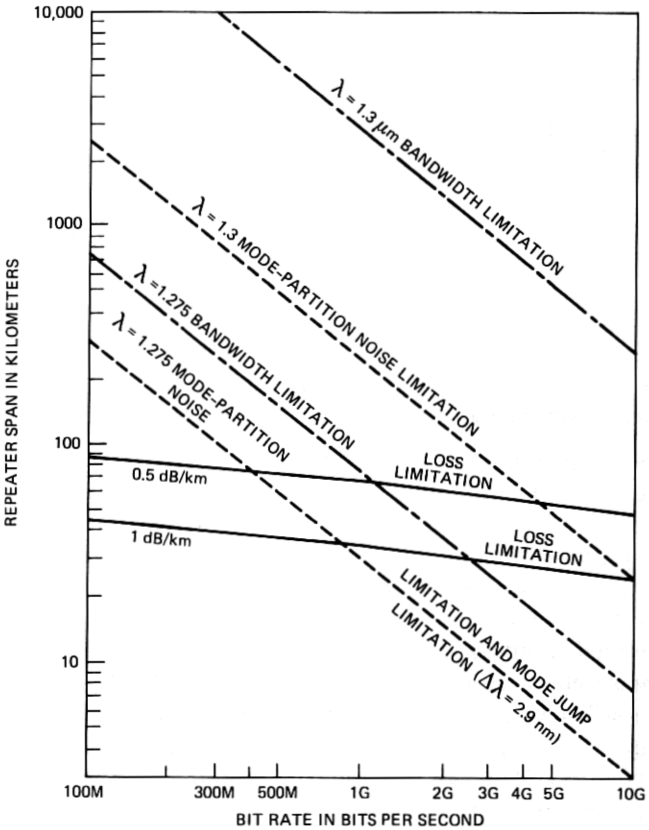

Fig. 4—Theoretical limits of repeater span due to the mode-partition noise limitation.

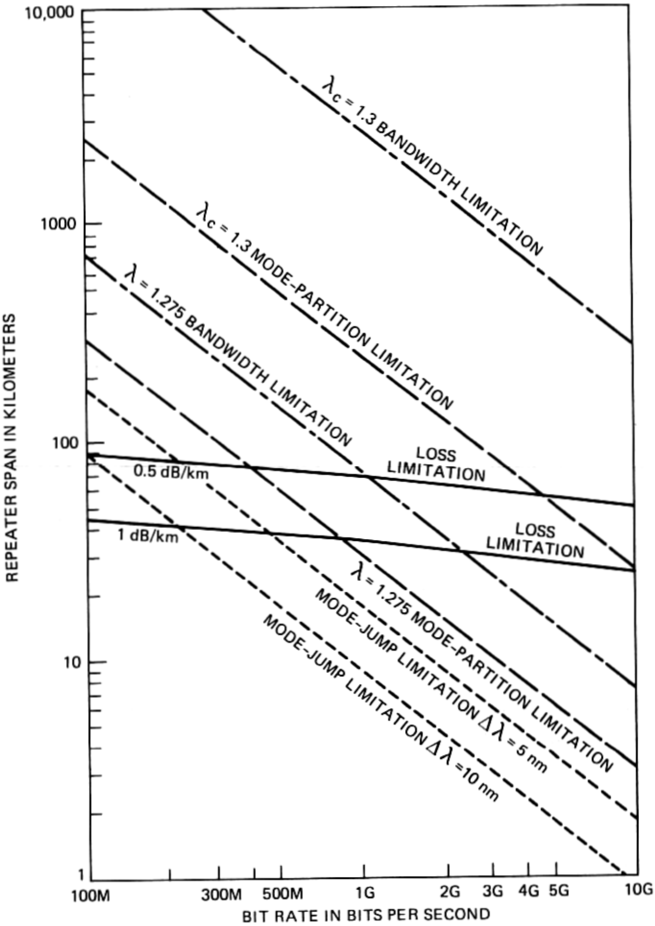

Fig. 5—Theoretical limits of repeater span due to the burst-error limitation.

lines are much more severe than the fiber bandwidth limitations. Also, when the center wavelength shift caused by a mode jump is 2.9 nm, the burst-error limitation is the same as the mode-partition noise limitation for 1.275 μm. Figure 5 shows that the half-rms width of laser spectrum is 2 nm and mode jumping $\Delta\lambda$ is 5 to 10 nm. When the center wavelength shift due to a mode jump becomes large (5 nm to 10 nm), the system performance is limited by the burst errors caused by mode jumps. Two dotted lines indicate the performance limitation caused by mode jumps. For both figures, two solid lines indicate the fiber attenuation limitations; one is 0.5 dB/km and the other is 1 dB/km. The dashed lines indicate the performance limitations caused by the mode-partition noise when the mode-partition factor, k, is 1; the dotted line is the performance limitation of the burst-errors caused by mode jumps. The chain line indicates the bandwidth limitations caused by laser spectral width. As we see in Figs. 4 and 5, the fiber bandwidth limitation is no longer dominant in comparison with mode-partition noise or mode-jump penalties. The difference between Figs. 4 and 5 is due to the effect of mode jumps. This shows that when we use laser diodes with narrow spectra, the mode jumps become the dominant effect.

IV. MAXIMUM TRANSMISSION CAPACITY

Laser diodes have about 1- to 2-GHz modulation bandwidth. The following criteria are used to maximize transmission capacity by either increasing signal speed or using wavelength multiplexing.

(*i*) Total data rates are to be $n \times 274$ Mb/s ($n = 1, 2, 4$).

(*ii*) For wavelength multiplexing, the separation of wavelengths is 25 nm. Since InGaAsP/InP laser diodes have a wavelength temperature dependency of 0.5 nm/°C,[2] we assume stabilization of the temperature is within ±10°C. We also assume that the initial variation of laser wavelength is within ±2.5 nm, and that the separation band required to suppress the interference from a neighboring channel is 10 nm. Therefore, a total value of 25 nm becomes the separation of neighboring wavelengths.

(*iii*) The transmission distance and bit rate for each wavelength-multiplexed channel is the same.

(*iv*) The laser spectrum half-width is 2 nm and mode jumps are less than 3 nm.

(*v*) We ignore the insertion losses of the wavelength multiplexing and demultiplexing devices.

(*vi*) We also ignore the mode-partition noise caused by the optical filter of wavelength multiplexer, which must be carefully designed to minimize that noise.

Figure 6 shows the total capacity and repeater spacing. There are two cases: one for 0.5 dB/km, and the other for 1-dB/km fiber loss. The solid line is for a basic transmission rate of 274 Mb/s. The small numbers on each dot are the orders of multiplexing. The dashed lines are the cases of 548 Mb/s. The chain lines are the cases of 1096 Mb/s. Each number (1 ··· 5) indicates the number of wavelength multiplexed channels. There are two dominant performance limitations: (*i*) loss limitation, and (*ii*) mode-partition noise limitation. In loss limitation, the wavelength multiplexing technique is advantageous to increase its capacity. In the mode-partition noise limitation, increasing the bit-rate of single channel is a more powerful way to increase capacity and repeater spacing.

Once fiber attenuation and repeater spacing are given, what bit rate

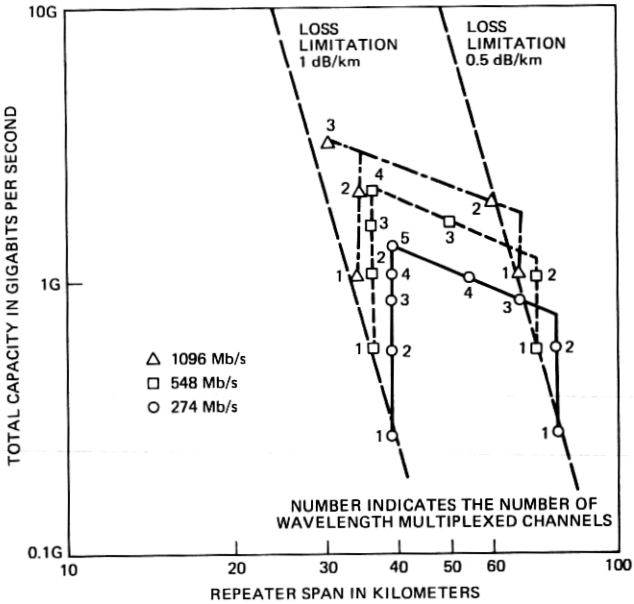

Fig. 6—Maximum capacity and repeater span.

is the best choice? Let us choose a fiber attenuation of 0.5 dB/km and the repeater spacing of about 60 km. A 274 Mb/s-multiplexed system can achieve its maximum capacity of 3 × 274 Mb/s with three-wavelength multiplexing. The 548 Mb/s system and the 1096 Mb/s system can achieve maximum capacities of 1096 Mb/s and 2192 Mb/s, respectively; further wavelength multiplexing reduces the repeater spacing to a much lower span than 60 km. Thus, the maximum capacity can be achieved by 1096 Mb/s systems using two-wavelength multiplexing. The choice of bit rate, 274 Mb/s or 1096 Mb/s, will be determined by availabilities of components and transmission capacity demands.

V. CONCLUSION

We have discussed performance limitations for single-mode fiber systems and introduced formulas for several performance limitations. Also, in Fig. 6, we have shown that wavelength multiplexing increases transmission capacity. We conclude that

(*i*) For more than 1 Gb/s capacity, system performance is limited by fiber dispersion, especially mode-partition noise. In this case a single high-bit-rate channel is the better choice to achieve the maximum capacity and longest repeater spacing.

(*ii*) For less than 1 Gb/s capacity, wavelength multiplexing becomes the most effective technique to increase total capacity, to achieve longer repeater spacing, and to lower the bit rate for each channel. The lower channel bit rate eases component requirements.

(*iii*) Mode-partition noise and burst errors caused by mode jumps severely limit performance.

Results of the bit-rate-distance product we discussed here are far less than the theoretical 400 to 3000 Gb/s·km that can be expected from single-mode fibers. To achieve such a high-capacity single-mode fiber system, further research effort is required, especially in the areas of: (*i*) fiber and cabling improvements, (*ii*) fabrication, stabilization, and mode behavior of laser diodes, (*iii*) high-sensitivity receiver design using low-noise components, (*iv*) a high-gain detector such as InGaAs-APD or InGaAs-photo-FETs, and (*v*) high-speed integrable components such as GaAs-MESFETs, and Si-MOSFETs.

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