A Comparison of Lightwave, Microwave, and Coaxial Transmission Technologies

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Abstract—The relative performance, complexity, and cost for three digital transmission technologies—microwave, coaxial, and lightwave—are compared from the point of view of the lightwave technologist. It is found that lightwave systems are inherently noisier than the others. However, its bandwidth advantage can be exploited through bandwidth expansion techniques to overcome the noise disadvantage. It is further found that lightwave systems are potentially less complex than their radio and wireline counterparts given the advancements expected in the near future. Lastly, it is found that present-day lightwave systems can be less costly than the other technologies. Furthermore, it is found that anticipated near-term improvements to the technology will make lightwave systems even more attractive from the cost point of view. It is concluded that digital lightwave and microwave systems will continue to grow in usage—each has its own unique advantages relative to the other—and that digital coaxial systems will decline in usage.

I. Introduction

TELECOMMUNICATIONS transmission technology has steadily evolved from its beginnings with open-wire systems to the present. Along the way, several breakthroughs have occurred to allow giant leaps in both quality and quantity of transmission. Some of those breakthroughs have included the use of two-wire systems (initially open wire) to eliminate the single wire with ground return systems with their attendant noise problems, followed by shielded two-wire systems. Later came coaxial cable transmission, terrestrial microwave transmission, satellite transmission systems, and the latest breakthrough, guided optical waveguides. Interestingly enough, all of these transmission technologies are in use today, posing a myriad of choices to the engineer responsible for transmission system design. Of course, each system has its unique advantages and disadvantages relative to the other available transmission methods, further complicating the design choices.

The purpose of this paper is to discuss three of the most commonly used terrestrial transmission technologies—microwave transmission, coaxial cable transmission, and lightwave transmission—exploring their relative advantages and disadvantages with the intent of summarizing their future application. Because of the recent emergence of digital transmission technology, and because of its widespread use today, this paper will focus on that aspect of telecommunications transmission. Furthermore, the paper is written from the point of view of an optical fiber technologist—that is, the paper discusses the tradeoffs of lightwave transmission versus microwave and coaxial cable transmission from the point of view of understanding the relative strengths and weaknesses and future potential of lightwave transmission.

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The basis to be used in this paper for a comparison of the three technologies will be, first, a comparison of the noise and bandwidth characteristics of each transmission medium; second, a comparison of the relative complexity of each implementation; third, specific examples of each system type; and fourth, an economic comparison of each technology.

Before proceeding, however, it is appropriate to give a brief historical review of each transmission technology.

II. Historical Review

A. Wireline Systems

Early transmission systems [1] used a single voice circuit per wire pair on open-wire pairs. The first transcontinental transmission over such a system occurred in 1915. However, open-wire systems were costly and cumbersome, and furthermore were susceptible to weather effects. Therefore, it was desirable to use insulated wire pairs. Because of the high loss in the paired-wire transmission medium compared to open wires, the former were impractical for long-haul transmission. A breakthrough was required. The invention of the loading coils and the vacuum tube amplifiers made it possible to equalize and overcome the high losses of paired-wire cables, thus making transmission possible. This technology spread rapidly, and such systems were in widespread use by 1925.

The first multiplex system for open-wire pairs was called a *C*-carrier, and it transmitted three channels per pair. By the 1930's, requirements for higher capacity and lower cost led to the development and use of a 12-channel system which was made possible by the invention of the feedback amplifier by H. S. Black. Such carrier systems used both voice frequency (VF) cable and open wire as transmission media, and were in widespread use by the late 1930's.

Several inventions of the late 1920's and early 1930's led to the anticipated requirements for wide-band signal transmission, namely, video signal transmission. The considerations produced a flurry of significant breakthroughs that made modern transmission systems possible. Among these breakthroughs were the development of the first coaxial cable transmission

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systems, the initial work with microwave radio transmission, and early millimeter waveguide systems. Of course, the burgeoning requirement for voice transmission also benefitted from these developments.

Coaxial cable systems were the first to be put into use. A 3 MHz system capable of transmitting 300 VF channels or a single television channel was put into service in 1940. That system was known as *L*1. Further development in coaxial cable systems has resulted in the *L*5 system introduced in 1973 [4], which is capable of transmitting 10 800 voice circuits per coax tube.

Once again, burgeoning growth and economic considerations led to the development of digital transmission systems. These systems were primarily intended for intracity transmission where they proved economical in the early 1960's. The first such system [2], known as *T*1, followed the development of the transistor which was a necessary invention to allow economical digital encoding. The *T*1 system uses VF wire pairs to transmit 24 voice channels at a 1.544 Mbit/s rate. Digital wireline systems have continued to evolve, culminating in a 274 Mbit/s (*T*4) system using coaxial cable which was put into service in 1975 [3]. Other developments have included several digital systems in Europe; among them are a 140 Mbit/s coax system developed by Philips [5], 34 and 560 Mbits/s being developed by Siemens [6], and others at various transmission rates [7], [8].

B. Microwave Systems

Early radio transmission systems [1] were used primarily for overseas service. One of the first systems was a so-called long-wave system (50-60 kHz) which linked the U.S. and England in 1927. In 1929, England to Buenos Aires was linked by a short-wave (10-20 MHz) service. By the late 1930's, microwave systems with carrier frequencies above 1 GHz were being generated in the laboratory, and experimental systems were being tested. Of course, microwave propagation is much different from long-wave or short-wave propagation systems. Microwaves are not reflected by the ionosphere, and they are restricted to line-of-sight propagation. While these may seem like limitations, they actually were great advantages in the early development of microwave radio transmission systems because of the fact that line-of-sight transmission and directive antennas, coupled with the large microwave bands, meant that frequencies could be reused within relatively small geographic areas. Furthermore, such systems offered much wider transmission bandwidth than was available previously. As a result, a vast communications resource became available, and it was quickly exploited.

The first microwave system operating at 4 GHz was announced in 1944. It linked New York and Boston. Service was established over that link beginning in 1948. This initial system gave rise to what has become the workhorse of the Bell System's microwave radio network, the TD2 radio. This radio had a capacity of five two-way radio channels, each with 480 VF circuits. It operated in the 3.7-4.2 GHz band. A coast-to-coast TD2 route was installed, and was operational by late 1951. Even today, the bulk of the long-haul long-distance transmission is carried on TD2 radios. These, of course, have been modernized since their use in the 1950's. The latest TD2 radio was introduced in 1973, and is capable of 12 two-way radio channels, each with a capacity of 1800 voice circuits.

Microwave systems employing digital modulation techniques were first introduced in the 1930's for use in France [9]. These experiments occurred at about the same time as the initial work on PCM systems, and like this early work in PCM, there was a fairly long maturing period before the introduction of digital microwave systems occurred. Commercial digital radio systems were first introduced in the early 1970's. By the late 1970's, there was considerable activity, with several countries worldwide committed to long-haul digital networks involving digital radio systems. For example, in Canada, a commitment to an 8 GHz, all-digital, high-capacity system which would stretch from coast to coast has been made. In the U.S., there was activity with the FCC in approving various radio configuration types and frequency plans for use with digital transmission. Several modulation approaches have emerged as being viable for high-capacity digital microwave systems [10]; among them have been PSK-type (phase shift-keyed carrier) systems, QAM-type (amplitude and phase-modulated carrier) systems, and QPR-type (partial response) systems.

C. Lightwave Systems

Telecommunications systems using light as a transmission medium are as old as wireline and radio systems. Evidence of this is Alexander Graham Bell's early experiments [11] in the 1870's with optical communications in the form of what he called the "Photo Phone." The theoretical basis for modern optical fiber systems had been laid in the 1920's by Hondros and Debye [12]. Further analysis and suggestions by Kao and Hockham [13] pointed out that systems with economic and performance benefits were within reach. However, it took some breakthroughs in glass material and semiconductor technology to make such systems practical. Efforts in the late 1960's were directed toward the development of low-loss glasses. These efforts culminated in the breakthrough in the early 1970's by scientists at Corning Glass Works which resulted in a fiber with less than 20 dB/km loss [14]. That development, coupled with the invention of room temperature, CW semiconductor lasers [15], also in the early 1970's, led to intensified research in the area of optical fiber transmission systems. By 1973, the analytical and device basis was laid so that practical systems could be developed [16]. The first major system trial occurred in 1976, when the Bell System operated an experimental DS3 (44.7 Mbit/s) system in Atlanta [17]. Since that time, many operating systems have been installed with rates ranging from DS1 (1.5 Mbits/s) [18] to DS4 (274 Mbits/s) [19].

New developments in optical fiber transmission technology make it even more attractive for future use. Considerable attention is being paid in various research laboratories around the world to making long wavelength, single mode, and wavelength division multiplex systems practical [20], [21]. Already such systems have been proposed or put into service [22]. Furthermore, research in the area of coherent optical systems [23], [24] is ongoing, with the promise of very long repeater spacings and high capacity.

III. General Performance Considerations

A. Noise and Bandwidth Comparisons

Analysis of the general communications channel involves characterization of the noise and bandwidth performance of that channel. Each of the three communications technologies considered in this paper has markedly different noise and bandwidth characteristics. In addition, the available signal power is an important variable in determining the performance of a given transmission medium. Analysis, considering in turn the signal-to-noise performance and bandwidth performance of each transmission medium, is given below in order to quantify the performance comparison.

1) Signal-to-Noise Ratio Comparison: Equation (1) gives a general expression for the signal-to-noise ratio in systems employing voltage or electron detection, such as microwave radio or wireline transmission systems [25]. Equation (2) gives a similar general expression for photon detection as is used in lightwave communications systems [26], [27].

$$\left(\frac{S}{N}\right)_v = \frac{P_{\text{sig}}}{N_{\text{thermal}} + N_{\text{shot}} + N_{\text{impulse}} + N_{\text{flicker}}} \tag{1}$$

where

P_{sig} = received signal power

N_{thermal} = thermal noise power
= kTB_n where k is Boltzmann's constant, T is absolute temperature, and B_n is the noise bandwidth

N_{shot} = shot noise power
= $2qIB_n$ where q is the electron charge and I is the direct current flowing through the detection device or circuitry

N_{impulse} = impulse noise due to switching transients or induced voltage surges

N_{flicker} = "$1/f$" noise caused by contact and surface irregularities in semiconductors.

Thermal noise results from the random motion of electrons within a conductor. It is the dominant noise source in voltage detection systems. Shot noise results whenever a direct current of value I flows in a device. It results from bias currents, leakage currents, etc., flowing in detectors or amplifier circuitry. Impulse noise and flicker noise are much less defined than thermal or shot noise in that general expressions for these terms do not exist. The magnitudes of these spurious noise sources are highly dependent on the specific circumstances in any given system. For example, impulse noise can be caused by switching transients which are random and not amenable to easy analysis. However, proper design techniques can minimize its effect.

$$\left(\frac{S}{N}\right)_p = \frac{i_s^2}{i_q^2 + i_{\text{dark}}^2 + i_{\text{preamp}}^2} \tag{2}$$

where

i_s = detected signal photocurrent
= rGP where r is the unity gain responsivity, G is the gain of the photodetector ($G = 1$ for a p-i-n photodiode), and P is the received signal power

i_q = rms value of the shot noise of the signal, known as the quantum noise
= $(2qG^{2+\alpha}rPB_n)^{1/2}$ where α is the excess noise factor of the detector

i_{dark} = rms value of the shot noise of the photodetector dark current
= $(2qG^{2+\alpha}I_bB_n + 2qI_sB_n)^{1/2}$ where I_b is the bulk (multiplied) leakage current and I_s is the surface (nonmultiplied) leakage current

i_{preamp} = input-referred rms noise current of the photodetector preamplifier.

The quantum noise is simply the shot noise of the signal photocurrent. It represents the fundamental noise limitation in optical communications systems. The dark current shot noise as shown above can be multiplied by the gain mechanism of the avalanche detector or not. In a unity gain, p-i-n detector, there is no multiplied noise current. In that case, a single leakage current term is given which accounts for both surface and bulk leakage effects. The preamp noise term represents a composite of several noise sources resulting from the photocurrent preamplifier. Depending on which type of input amplification device is used, this noise term results from base current shot noise, input-referred collector current shot noise, etc. (bipolar transistors), or input-referred channel noise, leakage current shot noise, etc. (FET's).

To facilitate comparison of the above two expressions, only the fundamental noise terms are considered. Equations (3) and (4) are the result.

$$\left(\frac{S}{N}\right)_v = \frac{P_{\text{sig}}}{kTB_n} \tag{3}$$

$$\left(\frac{S}{N}\right)_p = \frac{P^2}{2h\nu PB_n}. \tag{4}$$

In (4), the substitution $r = \eta q/h\nu$ where h = Planck's constant, ν = optical frequency, and η = detector quantum efficiency has been made. Further simplification of (4) has also resulted from assuming that $G = 1$ and $\eta = 1$. Note that the factor P is retained in the denominator in order to emphasize the fact that in the quantum noise limit, the noise power is dependent on the signal level. In that limit, the noise is, in fact, the shot noise of the signal photocurrent. In the strict sense, the noise floor in a quantum-noise-limited system is undefined: there is no noise in the absence of a signal. That represents a difficulty in the definition of "noise floor" in a quantum-noise-limited optical communications system. To avoid that difficulty, it has been the convention in optical communications technology to define the noise floor as that level that exists when the signal-to-noise ratio is equal to one.

The above equations present the fundamental limits of signal-to-noise performance for the two detection schemes considered. Specifically, the noise term in the optical equation is simply the shot noise of the signal current produced by a detecting photodiode, and it represents the fundamental noise limit in an optical communications system. The fundamental term in the voltage detection system represents the basic thermal noise limit, the well-known "−174 dBm" limit.

For a given noise bandwidth in each system, the noise floor can be determined. In the case of the optical system, the detected optical frequency determines the noise level. Similarly, in the voltage detection system, the noise level is determined by absolute temperature. As a result, the noise floor of each communications technology can be compared. Assuming a detected optical frequency of 350 THz (0.85 μm wavelength) and absolute temperature of 295°C, it is found that the optical communication noise power is 20.6 dB larger than the voltage detection system. With the addition of the heretofore neglected terms in each communications technology, the ratio will tend to become larger because the neglected terms in the photon detection scheme will tend to degrade the noise floor by at least 10 dB.

In general, then, it can be said that there is at least a 20 dB higher noise floor in optical communications systems compared to radio and wireline communications systems. Table I gives a comparison of noise floor for practical examples of each technology type. Note that in the practical case, the noise floor for optical systems is nearly 30 dB higher than coax cable or microwave radio systems. The values presented in Table I are calculated using: 1) the noise figures given in the references cited for the coax and microwave receivers, and 2) theoretical equations for signal-to-noise ratio for optical receivers, assuming that $S/N = 1$.

In comparing the signal power available in each communications technology, one finds a situation similar to the case above with the noise power comparison. Table II lists the output powers available for various types of devices in each communications system type. As can be seen from the table, guided optical communications systems are limited to maximum signal powers on the order of 1-10 mW. This is a result, largely, of device limitations. For example, in the case of semiconductor injection laser diodes, optical flux densities exceeding the nominal 10 mW output per facet can lead to facet damage with resultant low reliability [30]. A further limitation on signal power comes from the fact that the optical waveguide itself becomes nonlinear due to stimulated Brillouin scattering and stimulated Raman scattering phenomena [31]. The nonlinearities occur at power levels as low as 30 mW.

In the case of microwave systems, the use of very high power traveling-wave tube (TWT) amplifiers leads to output powers than can exceed 1 W. This is particularly true if modulation schemes that are not sensitive to distortion are used. In fact, there are available TWT's that are capable of greater than 10 W output power. For the case of wireline systems, output levels near 100 mW are possible.

Given noise floor and available power level for each transmission technology, one can construct estimates of system gain parameters where system gain is defined as the ratio of maximum transmit power to the allowable minimum received power. The allowable minimum received power is determined by the minimum signal-to-noise ratio required for a given performance level, i.e., bit error rate. Table III lists the system gain available for typical examples of digital systems for each transmission technology. This comparison is based on noise performance only. How this performance is modified by the bandwidth of each medium is discussed later. As can be seen from the table, both wireline and radio systems have available system gain that is at least 39 dB greater than lightwave systems.

2) Bandwidth Comparison: Each of the three transmission technologies considered herein has its own unique bandwidth characteristic. Wireline transmission systems are characterized by the well-known $\sqrt{f}$ bandwidth dependence caused by mutual capacitance and self-inductance in the transmission line. Microwave systems are characterized from a bandwidth point of view by the need to efficiently use the available radio frequency spectrum. Lightwave transmission systems also have unique bandwidth characteristics ranging from relatively narrow-band transmission systems using moderate quality graded-index fibers to very wide-band systems using monomode fibers.

TABLE I
NOISE FLOOR COMPARISON

RECEIVER TYPE	NOISE FLOOR Full Bandwidth	Per Hz of Bandwidth
3 MHz coax cable receiver[4]	-101 dBm	-165.5 dBm/Hz
60 MHz coax cable receiver[4]	- 91 dBm	-168.5 dBm/Hz
3.2 MHz microwave radio receiver[28]	-102.5 dBm	-167.5 dBm/Hz
23 MHz microwave radio receiver[28]	- 91.5 dBm	-165.1 dBm/Hz
23 MHz lightwave receiver[29]	- 66.5 dBm	-140.1 dBm/Hz
150 MHz lightwave receiver[29]	-55 dBm	-136.8 dBm/Hz

TABLE II
MAXIMUM AVAILABLE SIGNAL POWER

TRANSMITTER TYPE	TRANSMIT OUTPUT POWER LEVEL
6 GHz Analog Microwave Radio TWT Amplifier[32]	+40 dBm
6 GHz Digital Microwave Radio TWT Amplifier[32]	+30 to +33 dBm
Digital or Analog Coax[4,33]	+15 to +20 dBm
Digital or Analog Lightwave	
Laser Transmitter[16]	0 to +10 dBm
LED Transmitter[16]	-20 to -10 dBm

TABLE III
SYSTEM GAIN COMPARISON

System Type	Transmitter Output Power	Required Receiver Power for 10^{-9} BER	System Gain
Digital Microwave (45 Mb/s)	+33 dBm	-76 dBm	109 dB
Digital Coax (45 Mb/s)	+17 dBm	-73 dBm	90 dB
Digital Lightwave (45 Mb/s)	0 dBm	-51 dBm	51 dB

Fig. 1 shows a plot of loss versus frequency for a 4 mi section of 9.5 mm air dielectric coaxial cable. Equation (5) gives a mathematical expression for the loss as a function of frequency and various cable parameters [34].

$$\text{cable loss (dB/mi)} = \left[A\left(1 + \frac{0.0062}{\sqrt{f}}\right)\sqrt{f} + Cf\right] + \left[(T - T_0)D\sqrt{f}\right] \quad (5)$$

where

$A = 3.9$ dB/mi · MHz$^{1/2}$
$C = 0.0047$ dB/mi · MHz
$D = 0.0043$ dB/mi · MHz$^{1/2}$ · °F
$T_0 = 55°$F
f = frequency in MHz
T = cable temperature in °F.

As can be seen from the equation, the loss is dependent, in general, on the square root of frequency with some linear correction factors and a temperature dependence. It is also interesting to note from the figure that the loss at the relatively high frequency of 20 MHz is 72 dB.

The available bandwidths for available frequency bands used

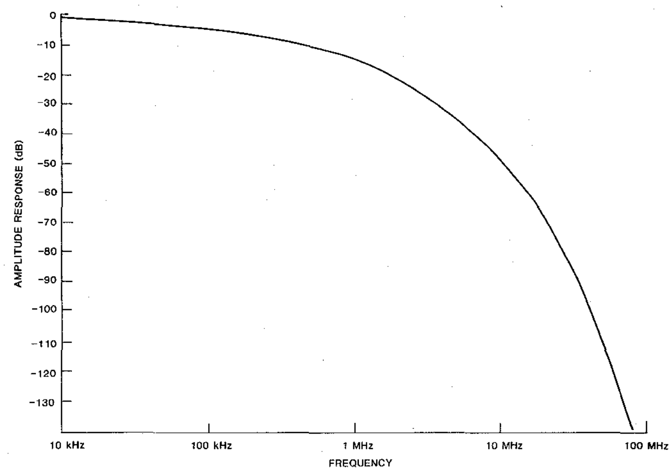

Fig. 1. Loss of a 4 mi section of 9.5 mm coax cable versus frequency.

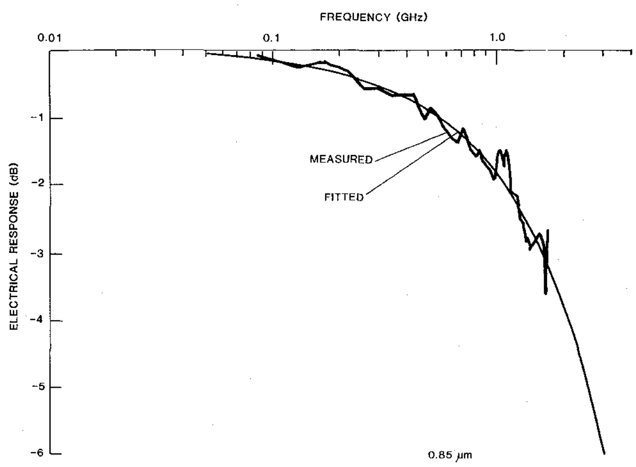

Fig. 2. Bandwidth characteristic of a high-performance graded-index fiber.

TABLE IV
AVAILABLE BANDWIDTHS IN VARIOUS MICROWAVE FREQUENCY BANDS

Frequency Band (GHz)	Available Bandwidth Per Channel (MHz)
2.11 to 2.13	3.5
2.16 to 2.18	3.5
5.925 to 6.425	30
10.7 to 11.7	40

for common carrier microwave transmission are summarized in Table IV [35]. These bandwidths are determined by the FCC in an attempt to fairly allocate the relatively scarce RF spectrum for use by various common carriers and industrial users. A further constraint is caused by the fact that the FCC requires certain minimum numbers of VF channels to be transmitted in the particular bands shown. As an example, in the 30 MHz bandwidth available at 6 GHz, a minimum channel transmission of 1152 VF channels [35] is required in order to obtain FCC approval for such a microwave transmission system. This, of course, leads to a requirement for fairly high spectral efficiency for any microwave radio transmission equipment.

While the bandwidth available is relatively flat, the requirement for large numbers of VF channels places a constraint that, in its way, is as severe as the restricted bandwidth characteristic of wireline systems described above. In addition, other factors such as atmospheric disturbances and multipath fading come into play to make this a relatively hostile environment for transmission systems.

Fig. 2 shows the bandwidth characteristic of a 1 km section of high-performance graded-index optical fiber [36]. As can be seen from the figure, the 3 dB bandwidth extends to beyond 1 GHz. The rolloff beyond that point is at 6 dB/octave. This is a very encouraging bandwidth characteristic—one that would seem to be easily equalized. However, considerations discussed below point out that there are some drawbacks to the optical fiber transmission medium, even given this type of characteristic. Monomode fibers have even broader bandwidths, stretching to beyond 50 GHz in 1 km lengths [37], given the use of spectrally narrow-band sources.

While the bandwidth characteristics of individual 1 km lengths of graded-index fiber are very broad and flat, a problem arises because of the somewhat unpredictable way in which sections of 1 km lengths of fibers concatenate to form an end-to-end transmission system. It is this unpredictability of end-to-end bandwidth and loss characteristics that make optical fibers a somewhat hostile transmission medium. Much has been said in the literature about how the loss and bandwidth characteristics of individual lengths of optical fibers concatenate to form an end-to-end characteristic [38]. Fig. 3 shows a plot of the measured and predicted performance using an inverse length dependence (L^{-1}) in one case, and an inverse square root of length dependence ($L^{-1/2}$) in another, for long concatenated optical fiber cables [39]. As can be seen from the figure, bandwidth performance can vary widely depending on which length dependence is actually the case. Furthermore, it appears that some exponential dependence between linear and square root is the length dependence. However, even given long lengths as shown in the figure, end-to-end bandwidths are still very wide, allowing high-speed transmission over long distances.

Suffice it to say that while progress is being made in predicting the characteristics of long fiber lengths, such predictions can be rather inconsistent, leading the system designer to use costly, worst case design methods. In comparison, the coaxial cable transmission system designer and microwave transmission system designer both have a very well-characterized, although fairly hostile, transmission environment with which to work.

B. System Design Considerations

1) Design Tradeoffs Involving Noise and Bandwidth: When one takes into account the foregoing information on signal-to-noise characteristics and bandwidth, each transmission technology demands its own design approach. It is interesting and enlightening to compare the approaches required. The unique nature of each of the transmission media considered herein leads to unique system design considerations which are illustrated by the example below.

Fig. 4 shows a composite plot superimposing the noise floor as a function of frequency, the power output as a function of frequency, and the cable loss as a function of frequency for a 4 mi span of coaxial cable. Consider a binary digital system

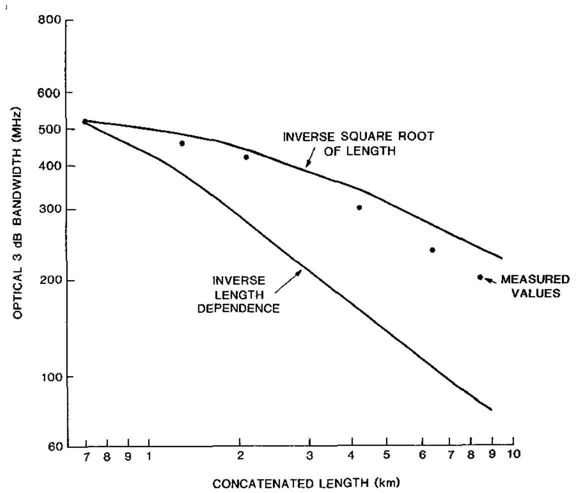

Fig. 3. Bandwidth of concatenated fiber sections.

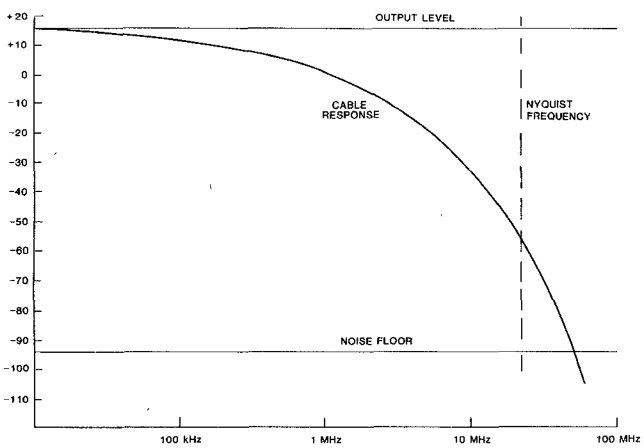

Fig. 4. Noise floor output level and cable response for coax cable system.

operating at 45 Mbits/s which is to be designed with the constraints illustrated in Fig. 4. For such a design, a Nyquist frequency of 22 MHz, as shown in the figure, is required.

Fig. 5 shows a similar plot for a 4 mi, 45 Mbit/s optical link. The frequency response of the cable in that case is for a typical graded-index fiber. Also shown on the plot is the response for a deliberately band-limited case similar to the coaxial cable system shown in the previous figure. The band-limited response profile shown is arbitrarily chosen to illustrate the effects of band limiting in noise-limited systems as discussed below.

As can be seen in the case of the coaxial cable system, the nearly 70 dB loss at the Nyquist frequency can be equalized without reaching the noise limit. In other words, an equalization circuit which compensates for the loss will not emphasize the noise to the point where the system becomes noise limited. This, of course, means that many more similar repeater spans can be tolerated in a system before a noise-limited system is seen.

In the case of the optical link, one can see that equalization in the general case is not required, but that the dynamic range (that is, the difference between the noise floor and available signal power) is considerably more restricted, as has been discussed previously. However, in the case where the optical

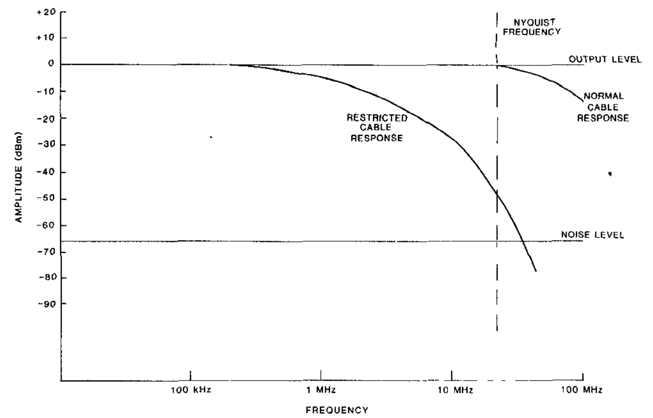

Fig. 5. Noise floor output level and cable response for lightwave system.

system is band limited, note that equalization of the cable rolloff leads very quickly to a noise-limited situation. In fact, in the early theoretical literature, Personick [26] pointed out that only a few decibels of equalization are possible in optical systems before the noise floor begins to be rolled up.

The conclusion of this comparison is that optical fiber transmission systems are inherently noise limited. Conversely, wireline and, similarly, microwave radio systems, are generally limited in performance by other phenomena, either bandwidth restrictions or distortion considerations.

To properly design an optical communications system, one must design with the transmission medium in mind: the lightwave transmission medium is one that is inherently noise limited, but has a flat, broad bandwidth. Hence, the designer should use as much bandwidth expansion as possible to overcome the noise limitation. Going further, one may conclude that baseband-type analog systems requiring a high signal-to-noise ratio will not be particularly successful in comparison to similar radio or wireline systems. They may, however, be implemented to exploit other advantages of optical fiber transmission, namely, immunity to interference or dielectric isolation. On the other hand, if bandwidth expansion is fully exploited—the ultimate case being pulse-code modulation—the optical fiber system offers distinct advantages, especially at higher bit rates.

2) Modulation Techniques: Another interesting comparison of lightwave and other transmission technologies is found in the area of modulation techniques. The restricted bandwidths of wireline and microwave systems have led to the use of sophisticated modulation schemes. At the same time, lightwave systems generally use very simple modulation schemes.

In coaxial cable systems, unique line codes are chosen in order to minimize the bandwidth required in a given span to transmit the desired signal. Many recent digital coaxial cable systems have used variations of the ternary line codes to provide this function. Specifically, a recent 140 Mbit/s system developed by Philips [5] uses a 4B3T code. This is a code in which four binary digits are translated into three ternary symbols. The result of this coding is reduction in baud rate with a subsequent reduction in required bandwidth. Table V lists a comparison of several recent coax cable systems.

TABLE V
COMPARISON OF VARIOUS COAX CABLE SYSTEMS

System Rate	Manufacturer	Code	Baud Rate	Loss at Half Baud (9.5 mm Coax)	Repeater Spacing	Ref.
34 Mb/s	Siemens	4B/3T	25.2 MBd	77.8 dB	9.3 km	33
140 Mb/s	Siemens	6B/4T	92.8 MBd	77 dB	4.65 km	33
140 Mb/s	STC	6B/4T	92.8 MBd	79.2 dB	4.7 km	8
140 Mb/s	Philips	4B/3T	105 MBd	84 dB (4.4 mm coax)	2.1 km	5
274 Mb/s	ATT	NRZ	274 MBd	56 dB	1.6 km	3
560 Mb/s	Philips	4B/3T	420 MBd	51 dB	1.5 km	7
565 Mb/s	Siemens	AMI	565 MBd	62 dB	1.5 km	33

Given in the table are the rate at which the system operates, the manufacturer, the line code used, and the subsequent baud rate. Also included in the table is the loss in decibels at the half-baud rate (i.e., the Nyquist frequency) and the subsequent repeater spacing allowed for a given sized coaxial cable.

Similarly, in microwave digital radio systems, bandwidth restrictions imposed by the FCC have led to the use of sophisticated, higher order modulation schemes. Two that are in common use today [10] are the 8-state PSK technique and the 16-state QAM technique. In 8-PSK modulation, the microwave carrier is modulated at eight different phase angles. This is a relatively efficient modulation scheme resulting in a theoretical efficiency of 3 bits/Hz. Fig. 6 shows a signal constellation for 8-PSK.

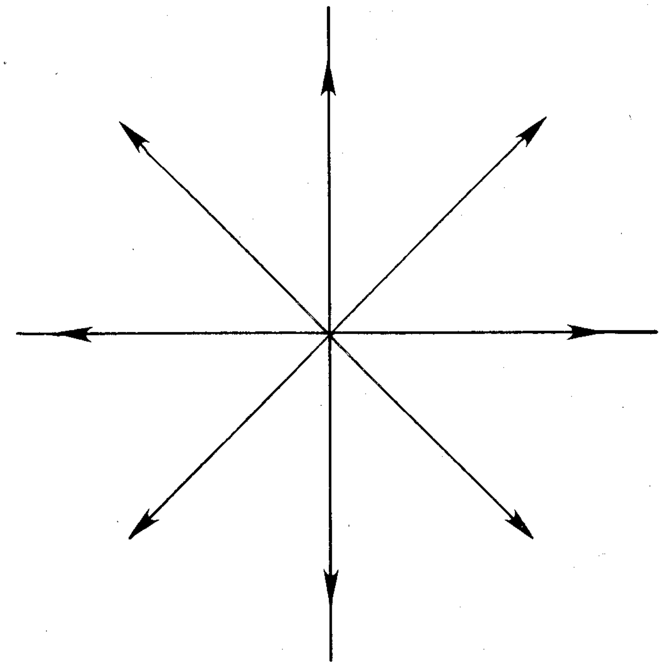

Fig. 6. Location of 8-PSK waveform in amplitude-phase space.

In the 16-QAM technique, both phase and amplitude of the microwave carrier are modulated to transmit the digital signal. Fig. 7 shows a signal constellation for 16-QAM. As can be seen from the figure, in each quadrant there are four different states available which represent three different amplitudes and three different phases. 16-QAM has a higher theoretical bandwidth efficiency than 8-PSK, the value being 4 bits/Hz. There are other higher order modulation schemes such as 64-QAM and 32-PSK which achieve even higher spectral efficiencies. However, these modulation schemes are presently in the development stages and are not currently being produced.

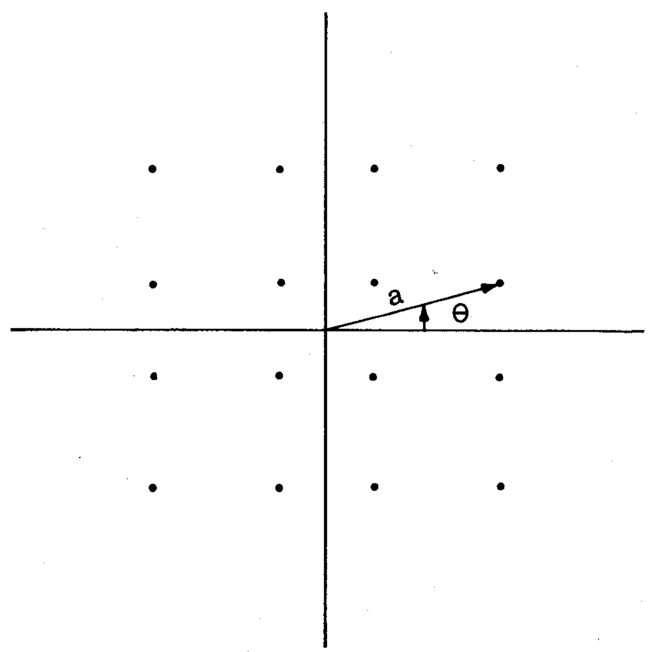

Fig. 7. Location of 16-QAM waveform in amplitude-phase space.

In contrast, lightwave transmission systems do not use such sophisticated modulation schemes. In general, very simple on-off keyed (OOK) modulation is used. This is primarily because of the available bandwidth in the transmission medium. OOK modulation is spectrally inefficient, but is simple to implement. Other factors which have influenced the simple OOK modulation scheme include nonlinearities of the available optical sources and available power output.

Specifically, multilevel block codes such as those used in coaxial transmission systems are not used in optical fiber systems because of the wide bandwidth available in the latter. The higher order modulation schemes are not used for lightwave systems because of the nonlinearities of the optical source, and because such bandwidth efficient schemes are not required. There have, however, been exceptions [40]. The future, however, may bring more bandwidth-efficient schemes to the lightwave medium, as capacity requirements increase in existing routes.

While present-day lightwave systems use direct power detection of an intensity-modulated optical carrier, future systems now being conceptualized and developed in the laboratory will use coherent techniques [23], [24], [41]. A coherent optical fiber transmission system has much in common with current microwave transmission systems. That is, in a coherent optical fiber system, the amplitude, frequency, and phase of the optical carrier are modulated in the same way that the RF carrier in a microwave system is modulated. The main difference in these two systems is the fact that the optical carrier is at a much higher frequency. The systems being considered in the laboratory at present have frequencies in the range of 200–400 THz (1.6–0.8 μm).

Coherent optical fiber systems have several distinct advantages over their intensity-modulated direct-detected counterparts, the main advantage being that receiver sensitivities are much improved in coherent systems. In fact, they are improved over present systems on the order of 20 dB at a given bit rate. Fig. 8 shows a comparison of receiver sensitivities for intensity-modulated direct-detection systems and various coherent-type systems [24]. The use of this improved sensitivity, when combined with low-loss single mode fiber technology, can result in repeater spacings that can exceed 200 km. This performance surpasses the equivalent microwave radio performance in which repeater spacings are generally limited to 60 km or less. Furthermore, the transmission medium in the coherent optical system can be less hostile than the microwave radio transmission medium.

For such optical systems to become a reality, however, there are several breakthroughs in the technology that are required. First of all, the optical source must be stabilized with respect to its frequency much more than present optical sources. For present semiconductor lasers, frequency fluctuations on the order of 100 MHz occur. This, of course, is intolerable in a coherent system. External means of stabilization such as a Fabry–Perot resonator are required. With such external control, frequency stabilities on the order of 10 MHz can be achieved [24]. Even at that stability level, performance is impaired. Stabilities on the order of 10 kHz are required to approach ideal performance. Another requirement for coherent systems is a single mode fiber that preserves polarization. The output polarization of the fiber must coincide with that of the local oscillator. Otherwise, loss of signal occurs and performance is impaired. Present techniques include polarization adjustors at the output of the fiber length which match the transmitted wave's polarization to the local oscillator's polarization. Another desirable breakthrough involves the development of all-optical repeaters. Such repeaters would not demodulate the optical signal, but would amplify it as is, using laser techniques. Integrated optics technology would be utilized for such repeaters.

Some of the above "breakthroughs" have been demonstrated in primitive form in the laboratory [41], leading one to conclude that coherent optical systems can be developed and will be practical in the future. Such systems will likely find application in high-capacity, transoceanic routes. The possibility of spanning hundreds of kilometers with no repeaters or thousands of kilometers with repeater spacings on the order of 50 km is very attractive [24].

IV. System Complexity Comparisons

Obviously, each transmission technology requires a somewhat different implementation from a device and circuit point of view. Figs. 9-11 show block diagrams of a typical digital microwave radio, digital coax cable, and digital lightwave system, respectively. Each subsystem required to fully exploit the transmission medium involved is shown in the block diagrams. An explanation of each system follows.

The digital microwave system (Fig. 9) consists of the following modules: at each line interface there is a line receiver which converts the line code to logic levels used in the subsequent digital circuits. As an example, for a DS3 interface (44.7 Mbits/s), the line code is a bipolar code with three zero

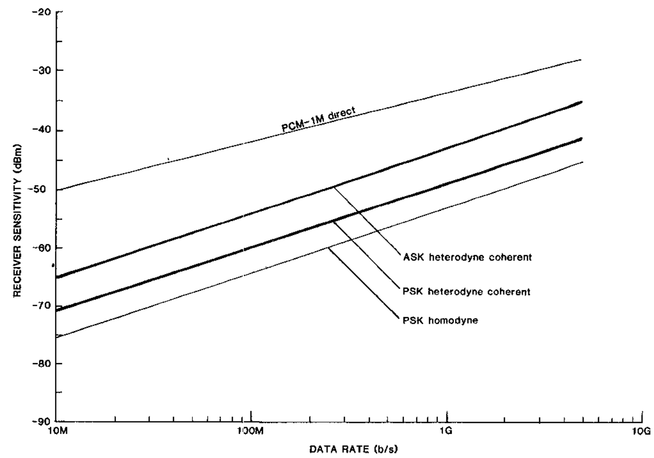

Fig. 8. Comparison of receiver sensitivity versus bit rate for intensity-modulated and coherent optical systems.

substitution (B3ZS). Since this code must be converted to logic level signals for signal processing in other modules, the line receiver provides that function. The next functional block (timing unit) consists of logic and timing circuits which find framing signals in the original digital signal and insert additional overhead as required. The output of the timing unit is then fed to the modulator. This unit converts the logic level pulses into a modulated 70 MHz carrier as required by the modulation scheme used in the particular system (16-QAM, 8-PSK, etc.). This output is routed to a predistorter unit which, in some systems [42], is required to add out-of-phase nonlinearities which cancel nonlinearities added by downstream elements, particularly the RF power amplifier. From the predistorter unit, the 70 MHz signal is up converted to the transmitted RF carrier by means of a mixer and local oscillator. That signal is amplified to the desired power output level and transmitted over the RF path. As shown in the figure, there is a variety of filters used at IF and at RF frequencies to filter the transmitted signal so that it meets the desired frequency characteristics as imposed by the FCC.

On the receive side, the received RF signal is amplified by an RF preamplifier, down converted to a 70 MHz IF signal, brought to constant level through various gain control stages, and filtered in order to remove extraneous out-of-band signals. That signal is routed through a static equalizer which compensates for various filtering elements in the signal path. Then the signal is routed to an adaptive equalizer which is used to compensate for any path distortions which occur. These distortions can take the form of constant slope across the IF band or a variety of notches within the IF bandwidth [42]. If this function is not provided, multipath fading and other signal distortions in the RF path can cause signal outages [43]. The output of the adaptive equalizer is passed to a demodulator which demodulates the 70 MHz carrier, as modulated on the transmit side, into logic level signals. Those signals are passed to a bit synchronizing function which extracts clock and retimes the data. Then the resulting digital signal is monitored for error rate, using overhead bits that were added to the data stream by the transmit timing unit or by using existing embedded parity bits [44]. This function, shown as the BER monitor in the block diagram, is required in order to detect

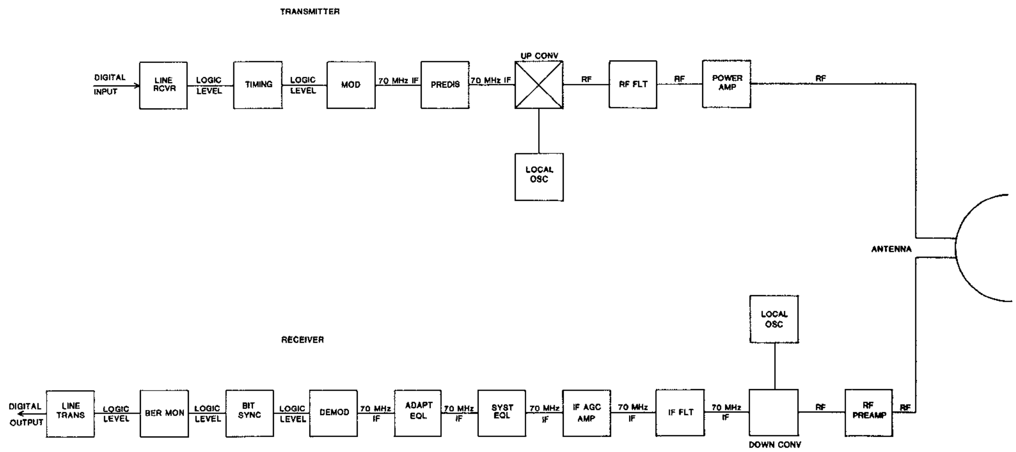

Fig. 9. Digital microwave radio system block diagram.

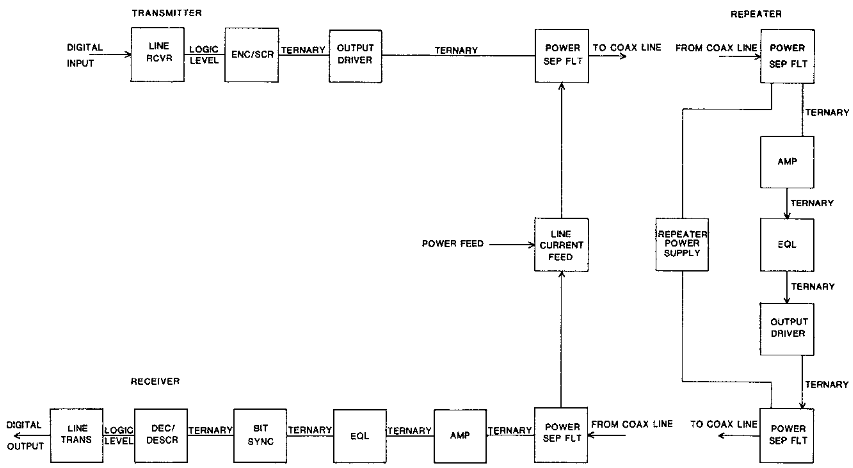

Fig. 10. Digital coaxial cable system block diagram.

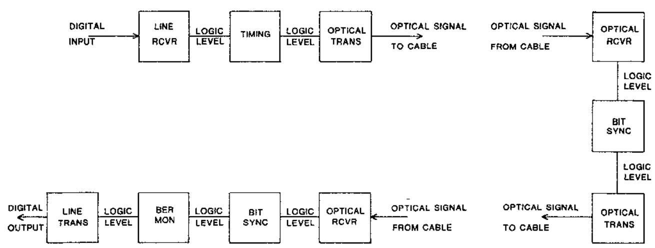

Fig. 11. Digital lightwave system block diagram.

any failures, either in the signal path or in the equipment. The BER monitor function is used as the basis for a protection system which allows switching to an unused channel in the event of high BER. The output of the BER monitor is then passed to a line transmitter which encodes the data back to their original line interface format. In the example given previously, this function would encode the logic level signals into a B3ZS signal for transmission to a DSX3 cross-connect.

Fig. 10 shows the transmit and receive functions as well as an intermediate repeater function for a digital coaxial cable system. The digital coaxial cable system also has a line receiver function which converts the line code to logic level signals. That function is followed by the block code encoder which adds overhead for supervisory signals, scrambles the signals, and then converts blocks of binary bits into equivalent blocks of ternary bits. The resulting signal is transmitted over the cable via the line output driver. Digital coaxial cable systems require frequent line repeaters [3] (see Table V). To power these repeaters, a dc current is fed to the repeater via the center conductor of the cable [45]. A power separation filter, as shown in the figure, is used to combine the transmitted signal with the dc power feed for transmission down the same coax tube.

The repeater consists of a power separation filter which separates the dc power feed from the transmitted signal. This dc signal is used to power the repeater and is passed on down the line to the next repeater. The transmitted signal is first amplified and then passed to an equalization stage which adaptively equalizes the cable loss and compensates for changes in loss due to temperature or other effects. The signal is then transmitted down the line, after once again going through a power separation filter.

In the general case, purely analog repeaters such as the one shown in the figure are used in repeater sites. Digital repeaters which retime the signals are used in selected sites as required. Because of the nature of the transmission medium (refer to Fig. 5), noise accumulation is such that complete regeneration is required only occasionally [46]. The signal can be amplitude-regenerated at most sites, without sacrificing performance, provided occasional retiming repeaters are used.

At the receive terminal, the signal first goes through the power separation filter. From there it goes to an amplifier and equalizer similar to the one used in the repeater. Following that, the signal is routed through a bit synchronizer which extracts clock and retimes the signal. The bit sync output routed to the block code decoder which converts the ternary bits into binary bits extracts error rate information and monitors error rate performance. One of the advantages of block coding is the fact that the redundancy in the code leads to very simple error-rate monitoring schemes [8]. Thus, the BER monitoring function can be combined with the decoder, and a separate unit is not required. The signal is descrambled and routed to the line transmitter which reencodes the signal to the original received format.

Fig. 11 shows a block diagram of a digital lightwave transmission system. Terminal functions and a repeater function are shown. As was the case with the previous two technologies, the signal is routed to a line receiver which decodes the line code, converting it to logic levels. That signal is routed to a timing unit similar to the one used in a digital radio application where overhead is inserted as required. The output of the timing unit is sent to an optical transmitter unit which contains the optical source and any thermal or age-stabilization circuitry for the source, as is used generally in the case of laser transmitters. The optical output is routed through the cable to a repeater which consists of a low-noise optical receiver which converts the optical signal to an electrical signal and amplifies it. The signal is then routed through a bit synchronizer which extracts timing, regenerates, and retimes the digital signal. The output of the bit synchronizer goes to an optical transmitter for transmission on the optical fiber. Digital repeaters such as this are required in optical fiber systems because of the noise-limited nature of the transmission medium. Analog repeaters such as those used in digital coax systems, in general, cannot be used.

The optical signal at the receive terminal is routed through an optical receiver, which converts it to an electrical signal which is amplified. That signal is then routed to a bit synchronizer for retiming. The signal is then monitored by a BER monitor function similar to the one in the digital radio case, and then routed to a line transmitter and reencoded to the appropriate line code.

In comparing the three system approaches, it can be seen that the optical fiber system is the least complex from the point of view of the number of functional blocks required to implement a system. However, the optical communications technology requires sophisticated devices in the optical transmitter and receiver functions, namely, the laser diode and avalanche photodiode. While these devices are complicated from a material technology point of view, they are relatively simple from an input/output point of view. That is, they are simple to use in interfacing to the circuits which utilize their electrical inputs and outputs. As a result, they are easily used in spite of their complexity and cost.

The digital radio system is the most complex. Of course, the terminals are spaced at further distances than the other two technologies, somewhat offsetting the additional complexity of each site. Sophisticated devices and functions are also required for radio systems. Predistortion and adaptive equalization are required in high performance systems to compensate for anomalies in the output stages and transmission path. In addition, the requirements for high spectral efficiency also require additional complexity in the way of filtering and equalization. The complexities are in addition to the sophistication of those functions that are required to implement the higher order modulation schemes.

The nature of the coaxial transmission medium—its high loss at a given frequency—requires relatively sophisticated equalization circuitry to compensate for fluctuations in this high loss as a function of temperature and other parameters. The multilevel coding schemes require well-controlled bandwidth characteristics. The optical fiber system requires no such equalization because of its flat bandwidth characteristic. However, because the optical system is basically noise limited, digital repeaters are required, whereas in the coaxial cable system (which is not noise limited), analog repeaters can be used.

In general, then, it can be said that the lightwave system is the least complex of the three considered.

V. Specific System Comparison

A. Link Length Comparison

To further highlight and explain the comparison among the three technologies considered, a specific system design is presented. The system design parameters for a 45 Mbit/s digital microwave radio system, digital coax cable system, and digital lightwave system are given. The particulars of the system implementation are contained in the previously given block diagrams (Figs. 9–11). The important design parameters are summarized for each system in Table VI. The main parameter used for comparison is the link length or repeater span possible in each technology. The implementation approach assumed for each example is that of a presently available state-of-the-art type of system. A short wavelength lightwave system is considered in this example in spite of the fact that long wavelength technology is becoming available at the present time because the comparison considered herein is intended to illustrate the performance of today's available, installed equipment. The effect of new technology such as long wavelength transmission on this comparison is considered below.

As can be seen from the table, the repeater spacing of the digital microwave system far outstrips that of the lightwave and coaxial cable systems. This is done at a somewhat higher complexity level, as discussed above. The lightwave system

TABLE VI
SYSTEM PARAMETER COMPARISON, 45 Mbit/s SYSTEMS

System Type	Modulation Format	Channel Bandwidth	Available System Gain	Margin	Link Length
Digital Microwave (11 GHz)	16-QAM	20 MHz	109 dB	40 dB (required as fade protection)	48 km to 60 km
Digital Coaxial Cable (9.5 mm coax)	4B3T	17 MHz (baud rate of 33.5 MBd)	90 dB	6 dB	7 km max.
Digital Lightwave (0.85 μm)	NRZ	22 MHz	51 dB	6 dB	12 km

has the second longest span; the coaxial cable system has the shortest span of the three.

B. Effect of Future Technology

The microwave and coaxial cable technologies are essentially developed as far as they will go from the point of view of repeater spacing. Improvements in both technologies will lead to increased capacities at a given length, but are not likely to improve the link distance possible. This is because these technologies are nearer their fundamental noise limits than is lightwave technology. Furthermore, radio and wireline systems use transmission media that are not likely to improve in performance.

On the other hand, optical fiber technology is on the verge of several breakthroughs which will not only increase capacity, but improve link distance. Specifically, long wavelength transmission and the use of single mode fibers will combine to extend repeater spacings by a large amount. For the 45 Mbit/s example considered, long wavelength transmission would allow a repeater spacing exceeding 30 km [47], compared to the present best case of 12 km for a short wavelength system. In addition, the use of coherent techniques will lead to a large performance increase.

To summarize the expected future performance of lightwave systems, Fig. 12 is given. The figure shows repeater spacing as a function of data rate for several lightwave systems. Specifically, it shows the performance for current state-of-the-art short wavelength systems, expected near-term long wavelength system performance; future long wavelength, single mode system performance; and last, performance that can be expected from coherent optical systems. It should be pointed out that this figure is intended to represent the performance of practical, installed systems. A recent experiment at Bell Laboratories [48] has demonstrated a 101 km, 274 Mbit/s, single-mode transmission system. That result represents better performance than is shown in the figure. However, the transoceanic system represented by this experiment is likely to have a 54 km maximum repeater spacing [21] when actually installed. That level of performance is shown by an "X" on the figure.

As can be seen from the figure, depending on the technology used, repeater spacing can range from nominally 10 km to over 200 km. This dramatically illustrates the future potential that lightwave systems offer.

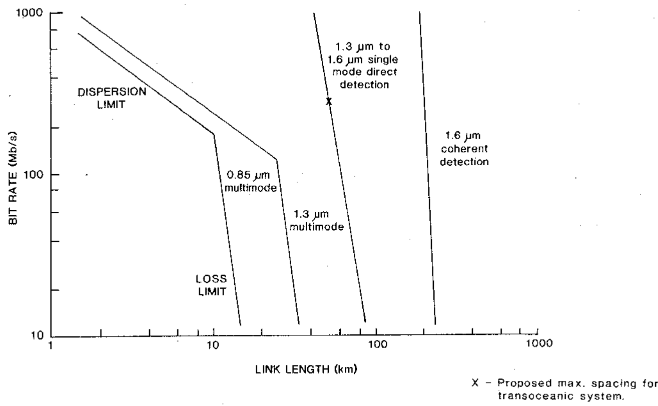

Fig. 12. Bit rate versus link length for various optical communication systems.

C. Cost Comparison

Another mechanism for comparing lightwave systems to other technologies is in the area of cost. Fig. 13 shows a simplistic cost comparison for the 45 Mbit/s systems considered in the preceding analysis. The cost comparison that is represented in the figure is not absolute in the sense that it covers all possible situations; it is derived for a specific type of comparison. As such, it has its limitations. However, it does provide a glimpse into the relative costs of each technology and the trends for the future.

Digital microwave, coax, and lightwave systems are shown in the figure. No unusual installation circumstances were assumed. Typical circumstances for microwave tower installation and cable duct installation were assumed. Each curve has some characteristics which need explanation, specifically, the stepped shape of the curves. In the case of the microwave system, the small steps represent incremental increases in cost due to the increasingly higher towers required for the resulting increases in repeater spacing. The large step represents incremental cost associated with the repeater required at that distance. In the case of coax cable and lightwave systems, the smaller steps are a result of the incremental cost of required repeaters. To show the potential effect that new technology in the lightwave area can have, a relative cost for a long wavelength system is shown. Table VII lists the cost parameters assumed in the above comparison.

The conclusions drawn from the above cost comparison are the following.

1) Digital coaxial cable systems are the most expensive of the three technologies. In the comparison presented, costs for new cable were included. However, if existing cable is used, then the cost picture could be radically different. Hence, for systems which would use in-place cables, digital coaxial transmission may be desirable. However, where new systems are planned, it is certainly the least desirable of the three alternatives.

2) The digital radio system is, in general, less costly than the lightwave short wavelength system. However, for the first 23 km, the lightwave system costs less. This points out that lightwave systems can be very cost effective on short routes.

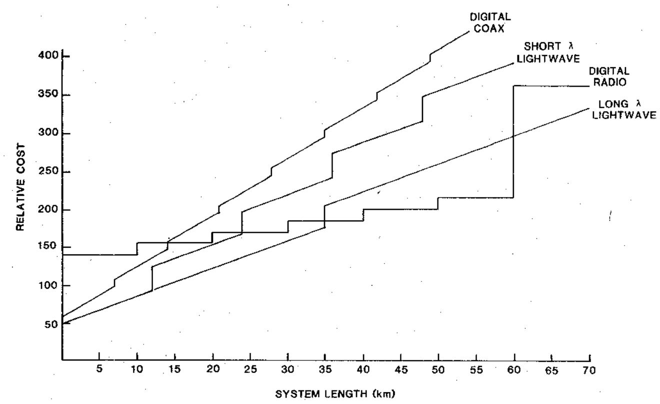

Fig. 13. Cost comparison.

TABLE VII
COST PARAMETER SUMMARY

Technology	Installed Terminal Costs (per site)	Installed Repeater Costs (per site)	Repeater Spacing	Cable Cost (per km)	Cable Installation Cost (per km)	Antenna Cost (per end)
	Assumed Costs					
Digital Microwave	$50K	$100K	60 km	-	-	$20K+$7K for each 10 km
Digital Coax	$30K	$ 10K	7 km	$2.5K	$3K	-
Digital Lightwave						
short λ	$25K	$ 30K	12 km	$2.7K	$1K	-
long λ	$25K	$ 30K	35 km	$2.7K	$1K	-

3) In the case of the long wavelength lightwave system, it is the least costly alternative for the first 35 km. It again becomes the least costly at the point where the radio repeater is required. This bodes well for the future of lightwave transmission technology as newer innovations such as long wavelength transmission are introduced.

It should be emphasized that the relative costs for any given technology will vary depending on the exact circumstances. For example, a cost study comparing wire pair, digital radio, and lightwave systems intended for use in rural Pennsylvania [49] showed lightwave to be the most expensive alternative. However, the growing acceptance of lightwave systems coupled with the results given herein point out that the future cost trends favor lightwave technology.

VI. SUMMARY

Three telecommunications transmission technologies have been compared from the point of view of the lightwave technologist. It is found that lightwave systems compare favorably to microwave and wireline systems, especially where digital transmission is concerned. On the basis of the comparisons made herein, it appears that digital lightwave and digital microwave systems will become the dominant means of signal transmission in the future, with the use of digital coax systems declining. Present trends in the market bear out this conclusion. Lightwave and microwave systems will likely continue to grow in usage with lightwave systems ultimately becoming dominant. The latter conclusion is reached on the basis of the lightwave system's simplicity and ultimate lower cost. Microwave systems will continue in relatively heavy use because of their unique advantage over cable-based systems: they do not require a right-of-way for cable placement. In addition, they can traverse spans that are hostile or even untenable from a cable placement point of view, e.g., mountain top to mountain top. This advantage will, of course, offset the concern of increased cost and complexity. In fact, lightwave and microwave systems can be complementary. If, for example, in the heart of the city there is sufficient frequency congestion that a particular transmission frequency is not available, a lightwave entrance link could be used to allow location of the radio in an area out of town where the desired frequency is available. That type of system exploits the advantages of both technologies.

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