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Alternative Transmission Media for Third-Generation Interface Standards

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PREFACE

This report is submitted as partial completion of a study being conducted for the National Communications System, Washington, DC, under Reimbursable Order Number RD 2-40167. The monitoring of this project is performed by the National Communications System Office of Technology and Standards, headed by Mr. Marshall L. Cain, with administrative monitoring by Mr. Dennis Bodson, of that office.

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LIST OF ACRONYMS AND ABBREVIATIONS

AlGaAs	aluminum gallium arsenide
ANSI	American National Standards Institute
APD	avalanche photodiode
BER	bit error rate
bis	Latin for 'additional' or 'second'
CCITT	International Telegraph and Telephone Consultative Committee
CPI	Common Physical Interface
DCE	data circuit-terminating equipment
DTE	data terminal equipment
EIA	Electronic Industries Association
EMI	electromagnetic interference
ILD	injection laser diode
ISDN	Integrated Services Digital Network
ISO	International Organization for Standardization
ITU	International Telecommunication Union
LED	light emitting diode
NA	numerical aperture (for an optical fiber waveguide)
NT	network termination equipment (for the ISDN)
OSI	Open Systems Interconnection (Reference Model)
R,S, and T reference points	optional points for physical interfaces (for the ISDN)
RT	pulse rise time for an optical fiber
SiO_2	silicon dioxide (fused silica)
SG	study group (of the CCITT)
ST	subscriber terminal (for the ISDN)
TE	terminal equipment (for the ISDN)
UPI	Universal Physical Interface (obsolete)
WDM	wavelength division (optical) multiplexing

LIST OF SYMBOLS

α	attenuation coefficient for a transmission line
$\delta\tau$	rms duration of an optical fiber's impulse response
a	for a coaxial cable, inner conductor radius - for an optical fiber, core radius
B	optical bandwidth (in units of energy - eV)
BW	base bandwidth (information bandwidth)
c	velocity of light in vacuum (2.9979×10^8m/s)
C	parallel capacitance per unit length of a metallic transmission line
Δ	optical fiber refractive index contrast (between core and cladding)
f	circular frequency
Fm	figure of merit for a transmission line
$F(\omega)$	output frequency spectrum for an optical fiber
g	a parameter that defines optical fiber profile shape
g(t)	impulse response of a metallic transmission line
G	parallel conductance per unit length of a metallic transmission line
h	Planck's constant (4.14×10^{-15} eV-s)
λ	optical wavelength
ℓ	cable length
L	series inductance per unit length of a metallic transmission line
μ	permeability of a metallic conductor
μm	micrometer
n	refractive index
n_1	refractive index of optical fiber core
n_2	refractive index of optical fiber cladding
n(r)	refractive index as a function of optical fiber radius
P	pulse rate
PO	optical power level at optical fiber's exit end
R	series resistance per unit length of a metallic transmission line
RT	pulse rise time for an optical fiber
σ	for a metallic conductor, the conductivity - for an optical fiber, rms impulse response per unit length
τ	a time interval
tc	a time constant characteristic of an optical receiver
T	duration of a square wave pulse
u	transmission line constant

γ	propagation constant for a metallic or dielectric transmission line
Z_o	(metallic) transmission line characteristic impedance

ALTERNATIVE TRANSMISSION MEDIA FOR THIRD-GENERATION INTERFACE STANDARDS

J. A. Hull, A. G. Hanson, and L. R. Bloom*

A review of EIA and CCITT data interface standards identifies three generations, namely: first (1960's), second (1970's), and third (1980's and beyond). The User/Network physical interface for the pending Integrated Services Digital Network is an example of third-generation standards. Wideband channel requirements under discussion by the CCITT will be limited by transmission media in the implementation of future interchange circuits. Conventional wire pairs and coaxial cables used in such interchange circuits are limited in the transmission rate and distance combinations by pulse distortion.

A figure of merit applicable to coaxial cable, wire pairs, and optical fiber waveguides is derived, based on physical and geometric properties. The distortion-limiting performance characterization of representative examples of the different media is presented. A recent survey of U.S. manufacturers' off-the-shelf optical fiber digital links is summarized to show evidence of viabiliy for high-bit-rate, medium-distance interchange circuits.

Key words: ANSI, CCITT, coaxial cable, Common Physical Interface, digital transmission lines, DTE/DCE interface, EIA, fiber optics, impulse response, Integrated Services Digital Network, ISDN User/Network Interface, optical fiber waveguide, telecommunication standards, twisted-wire pair

1. INTRODUCTION

The National Communications System Office of Technology and Standards (NCS/TS) leads the Federal Telecommunications Standards Program, which is intended to remove technical impediments to interoperability among the Federal interagency-developed networks. The rapid evolution and explosive growth of distributed (customer-premise) digital communication equipment has kept pace with the implementation of high-performance digital networks, both public and private. The large data-processing and network-supplier community is working very actively in the development of a new generation of standards in which improved data interchange circuits are needed, i.e., fewer interchange circuits with higher capacity and higher quality. These interchange circuits,

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between Data Terminal Equipment (DTE) and Data Circuit-Terminating Equipment (DCE), have been subject to standardization since the early 1960's. The first-generation DTE/DCE standards were predicated on a central computer remotely accessed by peripheral equipment (terminals) that were typically simple, low-data-rate devices. The network for such remote access was the analog (voice) public switched network. The DCE was a modem used to translate the digital bit stream into a quasi-analog message compatible with the voice network. These standards are widely used and will continue to be used as long as human-operated terminals are needed with transmission requirements of only a few hundred to a few thousand bits per second.

In response to new interconnect requirements of the 1970's, a second-generation series of national and international standards was developed, notably EIA Recommended Standard RS-449 and CCITT Recommendation X.21. For readers interested in further detail on these existing specifications and their interrelationships, an Appendix has been prepared as a tutorial on their evolution and technological limitations.

A third generation of interface specifications is now under development to meet needs of the 1980's and beyond. It is of interest that a recent U.S. proposal (EIA, 1982) recommends that the DTE/DCE designations be changed to <u>Digital</u> Terminal Equipment and <u>Digital</u> Circuit-Terminating Equipment to reflect additional digital services to be considered in the new generation of interface specifications. (Because this proposal has not been adopted, the 'D' in this report refers to 'data'.) This report describes an analysis of the limitations imposed by transmission media on these standards.

Current distributed data systems are made up of a mix of complex, high-data-rate devices as well as a growing proliferation of customer-premise concentrators and multiplexers that generate aggregate bit streams from many low-speed devices. Such bit streams are formed not only from high-speed computer-to-computer data transfer between widely separated geographical locations (and the aggregate of low-speed devices), but also include the transport of digitized voice for access to proposed all-digital transmission networks. Projected tentative requirements for the terminal-to-network interface for future all-digital applications call for multimegabit-per-second information transfer rates (ANSI, 1981 CCITT, 1982a) and for path lengths to 1 km (CCITT, 1982b). These projected requirements exceed the terminal-to-network maximum-bit-rate x path-length product capabilities of existing interface standards and Recommendations.

As reflected in the sources cited in the references of this report (including proposals of several U.S. and international study groups), these projected aggregated requirements have not been considered. The DTE/DCE transmission medium historically has been wire pairs (twisted or flat pack) which impose fundamental limitations on bit-rate x path-length product far below the multimegabit/second x 1-kilometer path length requirements cited above.

This report considers viable alternative transmission media that will permit the implementation of future physical interface requirements. An analysis of limitations of the transmission media caused by pulse overlap is used to develop a means for selecting appropriate technology. The study is applicable to interchange circuits either between data terminal equipment and data circuit-terminating equipment (modems) in existing analog networks or between terminals (TE's) and network terminations (NT's) in forthcoming integrated services digital networks.

1.1 Purpose

The purpose of this report is to demonstrate a potential need for multimegabit digital transmission rates on terminal-to-network interchange circuits over distances of 1 kilometer or more through a review of relevant national and international standards documents, and to consider the technical limitations of alternative transmission media available for implementation of such interchange circuits.

1.2 Scope

The scope of this study is limited to the review of existing and planned physical interface standards for digital communications and analysis of the transmission media required for implementation. The 'cut-off points' for the transmission media are illustrated in the block diagram of a DTE/DCE interchange circuit shown in Figure 1. These points are external to all electrical circuitry that may be required for multiplexing data, control, and timing information. Engineering approximations obtained from the referenceable literature are used to compare the pulse distortion limited performance of the alternative transmission media. Since optical fiber waveguides have not been widely used in the implementation of such interchange circuits, a survey of representative U.S. manufacturers' off-the-shelf digital links is presented to demonstrate technology readiness.

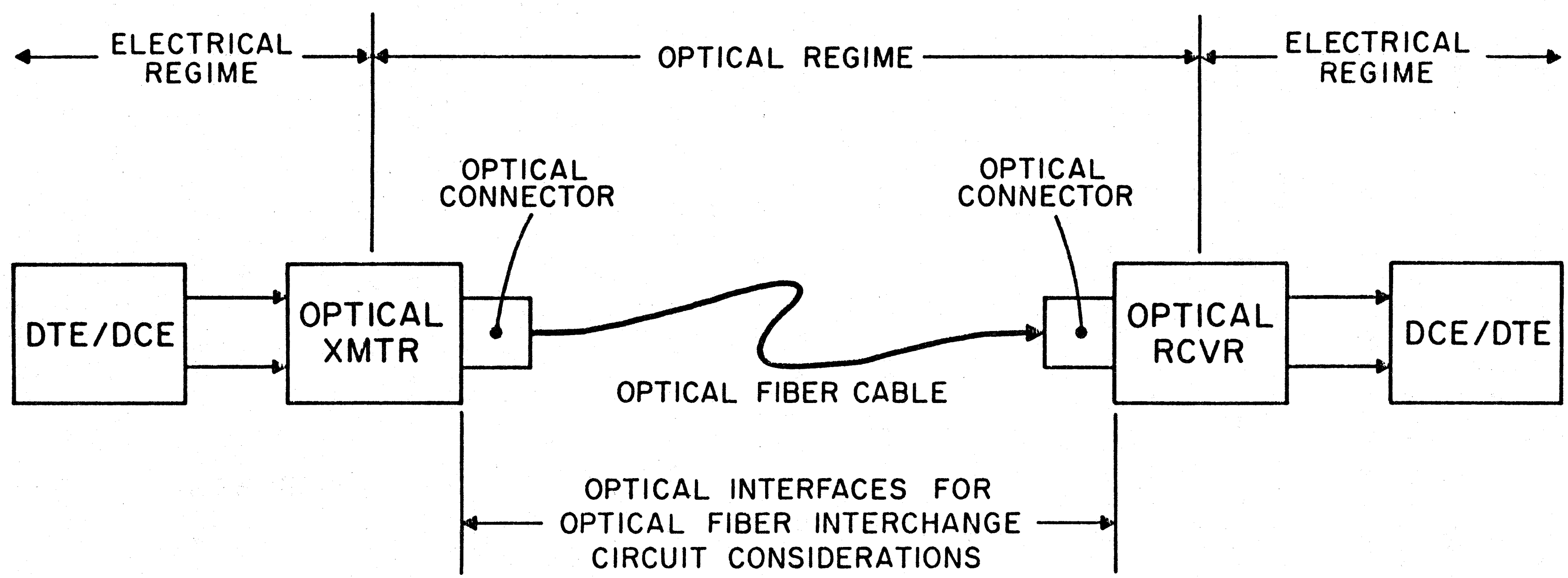


Figure 1. Optical transmission media application to DTE/DCE interchange circuits.

1.3 Organization of Report

The remainder of Section 1 presents background on recent and current standards work on development of next-generation interface specifications for the ISDN. Section 2 summarizes parameters of primary concern in development of these standards, and the parameters' influence upon type of transmission medium. In Section 3, the authors analyze digital transmission characteristics of metallic cables, and derive figures of merit to permit comparison of various configurations for desired maximum bit-rate x path-length product. Similar analysis of optical fiber waveguide cables is given in Section 4, and comparable figures of merit are derived. Section 5 presents results of a survey of U.S. commercially available optical fiber cables, optical transmitters, and optical receivers to indicate technology readiness for proposed applications of this study. Section 6 consists of report summary and conclusions. The Appendix gives historical background on development and evolution of DTE/DCE standards in the 1960's and 1970's.

1.4 Background: Third-Generation DTE/DCE Interface Standards and the ISDN

The development and adoption of next-generation interface specifications are closely associated with the international development of the proposed Integrated Services Digital Network (ISDN). A comprehensive description of ISDN is beyond the scope of this report. For detailed information on the ISDN and associated user access, the reader is directed to recent summary overviews (de Haas, 1982; Kennidi, 1981), in-depth reports (Cerni, 1982; Glen, 1982), and submissions of standards working groups (ANSI, 1982a; CCITT 1981a, 1982c, 1982d, 1982e, 1982f; and EIA, 1982).

Some background on the development of ISDN requirements and their potential impact on new DTE/DCE interface standards is presented as rationale for this report. A concern is expressed in a recent report on standards and the ISDN (Glen, 1982) that '...as the ISDN evolves, there is need to have <u>standard</u>, <u>simple</u>, <u>customer</u> <u>interfaces</u> within the network. A loss of flexibility would occur and higher costs would result, if a proliferation of interfaces occurs in the market place... . An example of existing conflict (proliferation) is the number of interface standards between Data Terminal Equipment (DTE) and Data Circuit-Terminating Equipment (DCE). These are the

EIA RS-232-C, EIA RS-449, CCITT Recommendation X.21, and more recently, the new EIA 'Mini-Interface,' and a Universal Physical Interface for ISDN....'

Issues involved in development of interface specifications are complex. Since this study is concerned with interchange circuit transmission media, discussion will be limited to transmission parameters defined in recent and current interface specification proposals. The 'Mini Interface' is described in the introduction to a June 1981 U.S. Contribution to CCITT Working Group XVII (1981b):

> A new standard for a DTE/DCE interface - referred to as the 'Mini Interface' - has been identified in the data communications industry and in international standards groups as being essential for maintaining long-term stable growth in the DTE/DCE product areas. The 'Mini Interface' must provide, in a connector of fifteen pins or less, the functional equivalents of existing interfaces such as RS-232/V.24, RS-449, and X.21, and must also anticipate the future requirements of a high-speed universal interface for applications such as the ISDN....

The Mini Interface proposal recommended a nine-pin connector for a symmetrical interface. This interface was to be implemented with two balanced metallic pairs in each direction for both data and control signals, plus one common return signal lead. Both data and control circuits were to be independently self-clocked, with the multiplexed control circuits supporting all interchange functions offered by existing DTE/DCE interfaces (e.g., RS-232-C/V.24, RS-449, and X.21). Interconnection with devices supporting existing standards was to be 'through active interface conversion units.' This preliminary document does not address bit rate or DTE/DCE cable path-length except by inference in use of the term 'high-speed/long-distance interface' when discussing propagation delay (op. cit., Section 7.2).

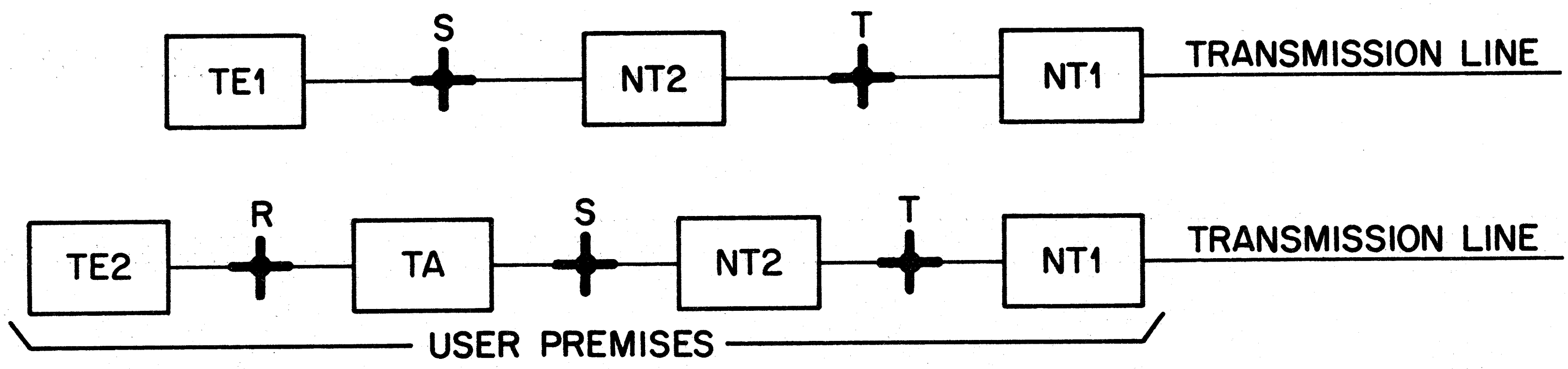
This Mini Interface document conceptually forms much of the basis of subsequent work, also by CCITT Study Group XVII, on the Universal Physical Interface (UPI) and its successor, the Common Physical Interface (CPI), directed toward interfacing customer-premise digital equipment with public data networks, public switched telephone networks, and the ISDN. This work has constituted primary inputs to CCITT Study Group XVIII in development of the ISDN User/Network Interface.

Primary efforts of national and international standards working groups on the ISDN User/Network Interface in mid- and late-1982 have been directed toward refinement of three May 1982 CCITT Draft Recommendations. These are:

- o Draft Recommendation I.xxx: ISDN User/Network Interfaces - Reference Configurations (CCITT, 1982a), which gives conceptual configurations for physical user access to the ISDN,
- o Draft Recommendation I.xxy: ISDN User/Network Interfaces - Channel Structures and Access Capabilities (CCITT, 1982e), which defines channel types, channel structures, and channel bit rates, and
- o Draft Recommendation I.xxw: General Aspects and Principles Relating to Recommendations on ISDN User/Network Interfaces (CCITT, 1982f), which gives conceptual principles for defining the ISDN.

The equivalent of the historical DTE/DCE interface is defined in the first of these Recommendations, as illustrated in Figure 2. Square blocks of Figure 2 portray ISDN 'functional groupings' of equipment. TE1 (previously designated T1) represents 'new' Terminal Equipment designed for ISDN interconnection through NT2, Network Termination equipment (such as terminal controllers, PABX's, or local area networks), and finally through NT1, Network Termination equipment 'intended to be associated with the proper physical and electrical termination of the network' (Draft Recommendation I.xxx). An option is direct interconnection of TE1 terminals to NT1 equipment. The ISDN equivalents of the DTE/DCE interface are at reference points S and T of Figure 2. The CCITT 'reference points' indicate optional points for physical interfaces, depending upon permissible, optional equipment configurations. For compatibility with 'older', existing terminal equipment (TE2 in Figure 2), a Terminal Adaptor (TA) is required to interface at the S reference point. For this configuration, TE2 and TA essentially replace the TE1 terminal, creating a new reference point, R, not a designated ISDN reference point, but which also constitutes a physical interface for 'non-ISDN' terminals. Thus, for proposed ISDN configurations, the DTE/DCE physical interface may be considered to be applicable to the R, S, and T reference points.

For purposes of this study, a parameter of primary concern is the reduction in number of physical interchange circuits (from the nine wires -- or 'connector of 15 pins or less' -- of the Mini Interface) proposed by the CCITT Draft Recommendations and subsequent working group submissions. Of similar concern is the emphasis upon both increased DTE/DCE transmission bit rate and path length. These questions are under continuing intensive study because of numerous tradeoffs involved. In the interest of brevity, the several proposals for number of interchange circuits are summarized in Table 1. A similar tabulation for proposed bit rates and path length is given in Table 2. As the result of the continuing interaction between Study Groups



LEGEND

TE1. Terminal Type 1: includes functions associated with ISDN Terminal Equipment complying with ISDN Interface Recommendations. Examples: DTE's, digital telephones, integrated services digital equipment. May also provide connection to other digital equipment.

TE2. Terminal Type 2: does not include all ISDN-required functions, but includes functions associated with terminal equipment complying with other interface Recommendations (e.g., X series).

NT1. Network Termination 1: includes functions belonging to OSI Reference Model Layer 1 (Physical).

NT2. Network Termination 2: may include functions belonging to OSI Layer 1 and higher layers such as Layer 2 (Data Link) and Layer 3 (Network). Equipment examples which provide NT2 functions: PABX's, LAN's, and terminal controllers.

TA. Terminal Adapter: includes interface and protocol adapting functions to allow connection of a TE2 terminal at the ISDN user/network interfaces (Converts TE2 to a TE1).

Reference Points: conceptual points, useful in separating functional groupings, which may, in certain physical configurations, correspond to physical interfaces.

-S and T: ISDN reference points.

-R: not an ISDN reference point; may be subject to other Interface Recommendations (e.g., X series).

Figure 2. Reference Configurations for the ISDN User/Network Interfaces (After CCITT Draft Recommendation I.xxx, Revised, Oct. 1982).

Table 1. Alternative DTE/DCE Interchange Circuits for the ISDN, Under Consideration by Standards Organizations

Total No. of DTE/DCE Interchange Ckts.	Technical Approach	Rationale/Tradeoffs	Proposal Source	Documentation (See Reference List)
"Minimum, preferably 2"	No specific discussion.	"For ISDN, it is not envisioned that separate control circuits will be required."	ANSI X3S3.7, contribution to CCITT S.G. XVIII	ANSI (1982c)
2 (4 wires, 1 pair in each direction)	Multiplexed "information and timing signals (i.e., with the possible exception of power) over the interface...." (Strong preference of most delegates.)	Emphasis on minimum number of circuits for cost efficiency.	CCITT meeting of experts on Question 1C/XVIII (Level 1 characteristics of the basic ISDN user/network interface).	CCITT (1982b)
3 (6-wire)	In addition to 2 basic circuits above, 3rd circuit for timing transfer to DTE in modem applications where modem provides clock, "as in present arrangements."	Consistent with digital network arrangements where clock is provided by network.	AT&T submission to EIA TR-30.2	EIA (1982)
4 (8-wire)	Use of phantom mode transformer-coupled control circuits for galvanic isolation with power-transmission capability.	Most economical approach where 2 DTE's or DCE's capable of providing power are interconnected.	EIA TR-30.2 ad hoc group	EIA (1982)
2 or 4 (4-wire or 8-wire)	Several 2-circuit approaches for symmetric/unidirectional, phantom/non-phantom powering, and one 4-circuit option. Agreement for primary focus on 2 circuits for information transfer.	Various tradeoffs among several approaches to combining power transfer and galvanic isolation.	CCITT ad hoc group on Question 1C/XVIII	CCITT (1982d)
3 (6-wire) (2-ckt. option for unidirectional power feed)	Symmetrical 3-circuit approach offers unrestricted interconnection, assures galvanic isolation; 2-circuit option proposed but not recommended.	Three circuits most cost-effective approach where remote power-feeding capability required in both directions; 2-circuit alternative not considered flexible or cost-effective.	CCITT S.G. XVIII	CCITT (1982c)
4 (8-wire)	In conjunction with 4-circuit approach (where 2 circuits transfer power), use 1 power circuit for DCE-DTE timing transfer.	Four-circuit approach for power + timing most flexible.	ANSI X3S3.7 contribution to CCITT S.G. XVII	ANSI (1982d)
2 (4-wire)	Phantom-circuit power transfer in only 1 direction.	Only 1 equipment type may supply power, and 2 such equipments must not be interconnected or damage will occur.	ANSI X3S3.7 contribution to CCITT S.G. XVII	ANSI (1982a)
or 3 (6-wire)	opt.(a) Two 2-wire transformer-coupled circuits + 2 wires for power transfer in both directions.	To preclude power source collision, different wires must be specified for DTE and DCE as power sources. For a given example, only DTE/DCE interconnection is possible.		
	opt.(b) Symmetric; 1/2 of each power circuit on 2 wires in phantom mode; other 1/2 on dedicated power circuit.	Achieves benefits of 8-wire symmetrical approach (below), but with no circuit for DCE-DTE timing transfer.		
or 4 (8-wire)	opt.(a) Asymmetric for DTE's and DCE's: 8-pin connector; uses 4 wires for ISDN applications, 8 wires for non-ISDN.	DTE-DCE power source collision not possible, but precludes DCE-DTE power transfer. Requires DTE modification. Limited interconnection of NT equipment.		
	opt.(b) Totally symmetric: phantom circuits for all power transfer; circuit available for DCE-DTE power transfer ("the historical approach").	Max. interconnect flexibility, with galvanic isolation, bidirectional power transfer, and historical approach to DCE-DTE power transfer. No equipment cost add-ons.		

Table 2. Alternative DTE/DCE Bit Rates and Path Lengths for the ISDN, Under Consideration by Standards Organizations

Max. DTE/DCE Bit Rate	Max. DTE/DCE Path Length	Rationale	Proposal Source	Documentation (See Reference List)
2.048 Mb/s (or higher)	--	For multiplexed channel structure, at ISDN reference point T, of 30 B + D (64 Kb/s for both B and D channels). Other, including higher-rate, channel structures designated for further study.	CCITT S.G. XVIII	CCITT (1982a) Draft Recommendation I.XXX
--	"At least" 300 m	For ISDN: "... where NT2 is a null and for some S interface applications."	ANSI X3S3.7, contribution to CCITT S.G. XVIII	ANSI (1982c)
--	1 km	Proposed in late contributions by both ITT and Sweden ("... based on the needs of the PABX line extension... considered to be essential for an early and wide penetration of the interface.")	CCITT meeting of experts on Question 1C/XVIII (Level 1 characteristics of basic ISDN user/network interface)	CCITT (1982b)
--	250 m or 1 km	"A strong preference was expressed for support of distances for L_S (star configurations) up to 1 km, especially for PBX terminal applications."	CCITT ad hoc group on Question 1C/XVIII	CCITT (1982d)
"... at least 200 Kb/s... max. desirable... at extended access rates of ISDN"	250 m as "reasonable compromise"	For interconnection of terminals with common equipment of a digital PABX, cable lengths "may even be much greater than 1600 m," but 10,000-interconnection survey suggests 98% are less than 60 m in length.	AT&T response to CCITT S.G. XVII Questionnaire on Isolating Interface	CCITT (1982d, Annex 5)
6.416 Mb/s (or higher)	--	Where several S interfaces are supported by NT2, the T interface may be required to support "n B64 + D16, where n is large (much larger than 24 or 30, probably in the 100's)."	ANSI X3S3.7	ANSI (1981)

XVII and XVIII, the tables reflect a mixture of contributions on the CPI and the ISDN User/Network Interface.

An interesting observation may be made relative to Table 2: although maximum values are proposed separately for bit rate and path length, none of the cited documents gives a proposed product for the two parameters. If they are indeed treated independently in final specifications, the user will be faced with limiting options and constraints similar to those of RS-232-C/V.24, as well as the second-generation RS-449/X.21 family of specifications. These later standards permit transmission either at a reasonably high bit rate or over a reasonably long path length, but not both simultaneously (see Appendix). For all present DTE/DCE interface standards, the transmission medium represents the ultimate limit to bit rate x path length product. The same comment will apply to third-generation physical interfaces, including the ISDN User/Network Interface unless user options are made available, within the specifications, to permit use of transmission media such as fiber optics or coaxial cable.

2. NEW DTE/DCE STANDARDS AND THE TRANSMISSION MEDIUM

As of December 1982, the status of third-generation DTE/DCE specification development may be described by the phrase 'requires further study.' Nevertheless, there appear to be some general agreements on the ISDN User/Network Interface characteristics: in particular, a strong preference exists for an interface with only two physical interchange circuits for information transfer. To achieve this, it is necessary to time-multiplex data, timing, and control information on a single interchange circuit. (Two circuits allow separate transmit and receive paths.) Study Group XVII of the CCITT, Data Communications over the Telephone Network, has submitted a contribution (CCITT, 1982c) to Study Groups VII, XI, and XVIII, which addresses the following interface characteristics for modem applications:

- low signaling power,
- high common mode rejection capability,
- possible power-feeding arrangements,
- possible galvanic isolation of interconnected equipment, and
- maximum distance of 300 meters.

The theme of this characterization is an emphasis on simplicity and improved performance. Improved performance must also be accompanied by reliability. The ISDN standardization work provides a major emphasis on the customer/network interface. As indicated in Figure 2, the TE1 and TE2 subscriber terminals are DTE equivalents. This designation should exist for a long time and should accommodate evolving technology. Long-term flexibility is equivalent to the accommodation of options and thus an implied 'technology independence.' If new technology options are not considered, then inherent limitations (e.g., those of transmission media) will remain and flexibility will not necessarily be assured. This thought is contained in a Study Group XVIII contribution (CCITT, 1982d) regarding a proposed six-wire S Interface: '...The door must be kept open in order to allow the future use of other couplers (e.g., opto couplers).' The desired interface characteristics are discussed further in the following subsections.

2.1 Low Signaling Power

One reason for the lack of acceptance of the RS-449 interface standard is the relatively high level of signaling power required at high bit rates. Terminals of the future will generally be designed to consume less and less power. This trend is exemplified by the availability of small devices like hand calculators which operate from photovoltaic sources. If there is sufficient light to use the device, there is adequate power to operate it. Low signaling power implies the need for immunity to electromagnetic interference (EMI) as well as decreased electromagnetic radiation to external equipment.

2.2 High Common Mode Rejection Capability

A balanced interchange circuit consists of a balanced generator connected by a balanced interconnecting wire pair to a balanced receiver. The impedances of the generator and receiver outlets with respect to ground are equal and the algebraic sum of the outlet voltages is constant. Such an interchange circuit is designed to cause minimum mutual interference with adjacent circuits and minimum susceptibility to EMI.

A balanced mode of operation reduces EMI vulnerability through common mode rejection of the unwanted signal. Twisted wire pairs are frequently used to reduce the pick-up of low frequency (power line) radiation. As requirements develop for lower BER, greater immunity to EMI and/or lower radiated EMI, shielding must be provided, or a different transmission medium not subject to EMI (e.g., fiber optics) must be adopted.

2.3 Power Feeding Arrangements

Power feeding across the ISDN User/Network Interface is the subject of much discussion in both national and international study groups. Two types of power feeding are under discussion: 1) emergency or wake-up power and 2) operating power for a wide variety of subscriber terminals. Emergency power would provide a nominal power level (approximately 400 mW) for assuring that at least one telephone terminal, for example, would be alive and active in the event of a customer-premise power failure. Other power feeding requirements include DTE to DTE as well as DCE/DTE and DCE/DCE full-power requirements. In this case a DTE might include a passive bus with up to 16 terminals. As in Section 2.1 above, the technology trend is toward low-power terminals and, ultimately, many terminals may be battery operated where the battery is kept charged locally or is designed to last for a year or more between replacements. The use of a 4-, 6- or 8-wire interface for the ISDN depends on the resolution of this powering problem. Emergency power as described above may well be supplied using a phantom mode over the proposed 4-wire circuit while maintaining the necessary galvanic isolation described below. If much higher power levels are required, then additional wires may be required to carry the necessary load(s).

2.4 Galvanic Isolation

The probable use of separate electrical power sources for DCE and DTE equipment creates an environment in which excessive ground loop currents can be generated if separately powered equipment items are not isolated from each other. Thus, there must not be a direct connection via shield braids or other common paths. Isolation transformers have been proposed to isolate the signal circuits and thus provide the galvanic isolation. Power can be transferred over the interconnected windings of these transformers provided the resultant currents do not saturate the cores of the transformers. Where additional power is required via separate leads, it is necessary to isolate the powered unit from local ground. Under normal operating conditions, voltage difference levels are of the order of 2 to 3 volts (can be very high currents). Fault conditions require designs to withstand levels of the order of 1200 volts.

2.5 Maximum Distance

The maximum distance to be supported by the ISDN User/Network Interface has not been defined at this writing. Surveys of current experience appear to develop numbers in the 250- to 300-meter range for some 90% to 95% of existing installations (CCITT, 1982d, Annex 5). Current practice of installing services for a campus of buildings connected to a PABX terminal requires distances more like 1 to 2 kilometers. Using twisted-wire pairs, this extended path length requires use of more expensive receivers with AGC capability. A submission to CCITT SG XVIII from the United States indicated that distances up to 300 meters were required and distances up to 1 to 2 kilometers were desired (CCITT, 1982d).

Equally important to the maximum distance is the bit-rate x distance product for future high-speed applications. The upper limit for twisted wire pair currently used in intrabuilding applications with good signal design and coding appears to be about 1.544 Mb/s for a 1-kilometer distance. No upper bit-rate levels are contained in current documentation, but it seems reasonable to assume for future large business installations that the ISDN user interface might have to support at least the T-2 level hierarchy (6.312 Mb/s in the United States and 8.448 Mb/s in Europe). Channel structure for the T interface of the ISDN is under continuing study.[1] For the case where NT2 supports multiple S interfaces, the T interface capacity requirements may be very high, e.g., '...n B64 + D16, where n is large (much larger than 24 or 30, probably in the hundreds)...' (ANSI, 1981). For n = 100 for the 64 kb/s B channels, the requirement would be 100 (64 kb/s) + 16 kb/s = 6.416 Mb/s.

2.6 DTE/DCE Transmission Media

The preponderance of network traffic for the foreseeable future will remain voice communications. The evolution of the ISDN will either require a TA or NT2 function which will perform the analog-to-digital and digital-to-analog transformations for the telephone terminal or a hybrid digital and analog interface will be supported, as indicated in CCITT Draft Recommendation I.xxy (CCITT, 1982e) cited in Section 1.4 of this report. Local telephone distribution plant in the United States has used twisted-wire pairs exclusively. Recent advances have included introduction of T-carrier systems

[1]Note: A contribution to to the SG XVIII meeting of experts (Kyoto), February 1983, proposes a high-speed (H) channel based on multiples of 384 kb/s. This is discussed in Temporary Document 49 - User Access, from this meeting.

at remote-support or pair-gain facilities, and the use of fiber optics is under evaluation.

Twisted-wire pairs or parallel ribbon wire assemblies are widely used in DTE/DCE interchange circuits. Current standards limit the length of such interconnections by allowing not more than 6-dB loss in voltage across the circuit. This is a loss in voltage amplitude. This wire pair, low-bit-rate interchange circuit is receiving current attention based on the above ISDN characteristics. The wire pair is clearly limited for future applications to either a modest bit rate or a short distance, as discussed in Section 3 of this report.

Coaxial cable is well established as a broadband analog transmission medium for use in cable television and in local area networks. It is a relatively well understood transmission medium which works very well under conditions where appropriate phase compensation can be introduced. Its use for multimegabit pulse transmission is less well-known. A method of characterizing coaxial cables from published manufacturers' data is needed to determine their usefulness in future DTE/DCE applications. One such characterization is developed in Section 3 of this report.

Optical fiber transmission media are clearly contenders for future DTE/DCE application. In addition to the pulse transmission properties discussed in Section 4 below, optical fiber provides total immunity to EMI, nearly total immunity to radiated EMI and crosstalk, and provides inherent galvanic isolation. Further study is required to evaluate potential methods of supplying power across an optical fiber interchange circuit.

3. PROPERTIES AND LIMITATIONS OF METALLIC CABLES

The use of metallic cables in DTE/DCE applications is almost universal. Such metallic cables are used to implement Interface Standards such as EIA RS-449. As the pulse repetition rate and the length of the interchange circuit increase, the performance of the resultant transmission system decreases and ultimately becomes unacceptable. The following material provides a review of the properties of metallic cables which affect their performance in a digital environment and develops a figure of merit which may be used in assessing the adequacy of commercially available cables. Since most manufacturers provide data on attenuation measured at a specific frequency, a means of converting this measured result to the figure of merit derived for digital performance is developed.

3.1 Coaxial Cables

Signal distortion in coaxial cable is analytically well-defined for digital signals that have spectral components up to several gigahertz (GHz). Primary references are: Wigington and Nahman (1957), Nahman (1962), Nahman and Holt (1972), Howard (1976), and Gallawa (1977). The principal source of signal distortion in coaxial cables results from the finite conductivity of the conductors. The dielectric losses in cables carrying signals with spectral components up to several gigahertz can be ignored.

Gallawa (1977) has treated the pulse dispersion produced by coaxial cables. Dispersion causes the characteristic broadening of pulses with consequent overlap for pulses with high repetition rates. This overlap of pulses causes an increase in the probability of error in detection circuits of a receiving system and this degrades the performance through an increased bit error rate (BER). At high frequencies, the series resistance of a wire is determined by the skin effect impedance. This impedance increases as the square root of frequency and algebraically with the length of the line. The key parameters of the line that characterize its response to digital signals are length and pulse rate. A figure of merit (Fm) that will characterize the performance (BER) of a given line should contain these two parameters. Both line length and pulse rate are usually specified in the definition of a transmission system and their values are normally not subject to change. Pulse dispersion, which results from the frequency-dependent skin effect impedance, should not be confused with signal diminution (attenuation), which increases exponentially with length.

Under pulse-dispersion limiting conditions defined by an acceptable BER, a maximum pulse rate, P, and a required cable length, ℓ, the relation between P and ℓ is:

$$P = Fm\,\ell^{-u} \tag{1}$$

where Fm = a figure of merit for the line, and

u = a constant dependent upon the generic line parameters (metallic or dielectric, etc.)

This relationship holds not only for metallic transmission lines but also for glass fibers. For metallic lines, $u = 2$ is a good approximation. The figure of merit can be increased by increasing the diameter of the conductors or by increasing the conductivity of the conductors (reducing the skin-effect impedance). A minimum figure of merit, for given line length and specified pulse rate for a desired BER, should be derivable both from the fundamental distributed parameters of the line and from measured data (attenuation at a specified frequency) in accordance with the expression:

$$Fm = P \ell^2. \quad (2)$$

The following section will derive figure of merit relationships based on 1) a limiting pulse rate equal to the reciprocal of the time required for the impulse response of the line to decay to 10 percent of its peak value, 2) a limiting pulse rate equal to the reciprocal of twice the 0 to 50 percent response time of the line when a step input voltage is applied, and 3) the measured attenuation at a specified frequency (near that characterizing the required pulse rate).

3.1.1 Analytical Description

An analysis of metallic cables is based on the lumped constants of resistance, inductance, conductance, and capacitance per unit length. The cable can then be considered as a four-terminal network where the desired characterization is the relation of output voltage to input voltage.

From the reference paper by Wigington and Nahman (1957), the transfer function of a line of length, ℓ, terminated in its characteristic impedance, Z_0, and with propagation constant, γ, is:

$$\frac{E_2}{E_1} = \exp -\gamma \ell \quad (3)$$

where: E_2 = output voltage,
E_1 = input voltage,

$\gamma = \sqrt{(R + pL)(G + pC)}$, and

$$Z_o = \sqrt{\frac{R + pL}{G + pC}}$$ where R, L, G, and C are the series resistance, series inductance, parallel conductance, and parallel capacitance per unit length of the transmission line, respectively.

$p = j\omega = j\,2\pi f$ (f = circular frequency).

For high frequencies (skin depth small with respect to conductor radius), the series resistance is equivalent to the skin-effect impedance. For a round wire, this is:

$$Z_s = R = K\sqrt{p}$$

where

$$K = \frac{1}{2\pi a}\sqrt{\frac{\mu}{\sigma}} \quad ,$$

a = conductor radius,

μ = permeability of wire ($4\pi x10^{-7}$henry/m), and

σ = conductivity of wire (copper = $0.58x10^{8}$ mho/m).

Dielectric leakage can be neglected: G = 0. Therefore equation (3) becomes:

$$\frac{E_2}{E_1} = \exp -\gamma\ell = \exp -\ell\sqrt{p^2 LC + p^{3/2} CK.} \tag{4}$$

Expanding the expression for γ by using a binomial expansion and keeping only the first two terms yields:

$$\frac{E_2}{E_1} = \exp -\ell\left[p\sqrt{LC} + \left(\frac{K}{2\sqrt{\frac{L}{C}}}\right)p^{1/2}\right]. \tag{5}$$

The $\exp(-\ell p\sqrt{LC})$ is a delay term so that the inverse transform of (5) is the inverse transform of $\exp -\ell\frac{Kp^{1/2}}{2\sqrt{\frac{L}{C}}}$ delayed an amount $\ell\sqrt{LC}$. This inverse transform is the impulse response of the line:

$$g(t) = \alpha x^{-3/2} \exp -\beta/x \qquad x \geq 0 \tag{6}$$
$$= 0 \qquad x < 0$$

where: $\alpha = \dfrac{\ell K}{4\sqrt{\dfrac{\pi L}{C}}}$

$$\beta = \left(\frac{\ell K}{4\sqrt{\frac{L}{C}}} \right)^2$$

$$x = t - \ell\sqrt{LC} \ .$$

The impulse response is:

$$g(t) = g(x + \ell\sqrt{LC}) = \sqrt{\frac{\beta}{\pi}} \ x^{-3/2} \exp -\beta/x. \tag{7}$$

This can be generalized so that β, the constant that determines a specific line, does not appear in the function but only in the scales to which the response is plotted, by choosing a change of variable $\rho = x/\beta$. This yields:

$$\sqrt{\pi} \ \beta \ g_o(\rho) = \rho^{-3/2} \exp -1/\rho \ . \tag{8}$$

This normalized impulse response is plotted in Figure 3 (after Gallawa, 1977). To apply this normalized impulse response to a particular case, the β is calculated using the physical data defined in (6) and the horizontal scale is multiplied by β and the vertical scale is divided by β to obtain the impulse response $g(t) = g(x + \ell\sqrt{LC})$.

3.1.2 Fm Based on Impulse Response

If one assumes that a pulse overlap of 10 percent of the peak amplitude will allow an acceptable BER, the maximum rate will be determined by the ρ corresponding to this amplitude. This occurs at $\rho = 7.715$ on the normalized plot. Converting this ρ to a particular case, one multiplies by β. Thus

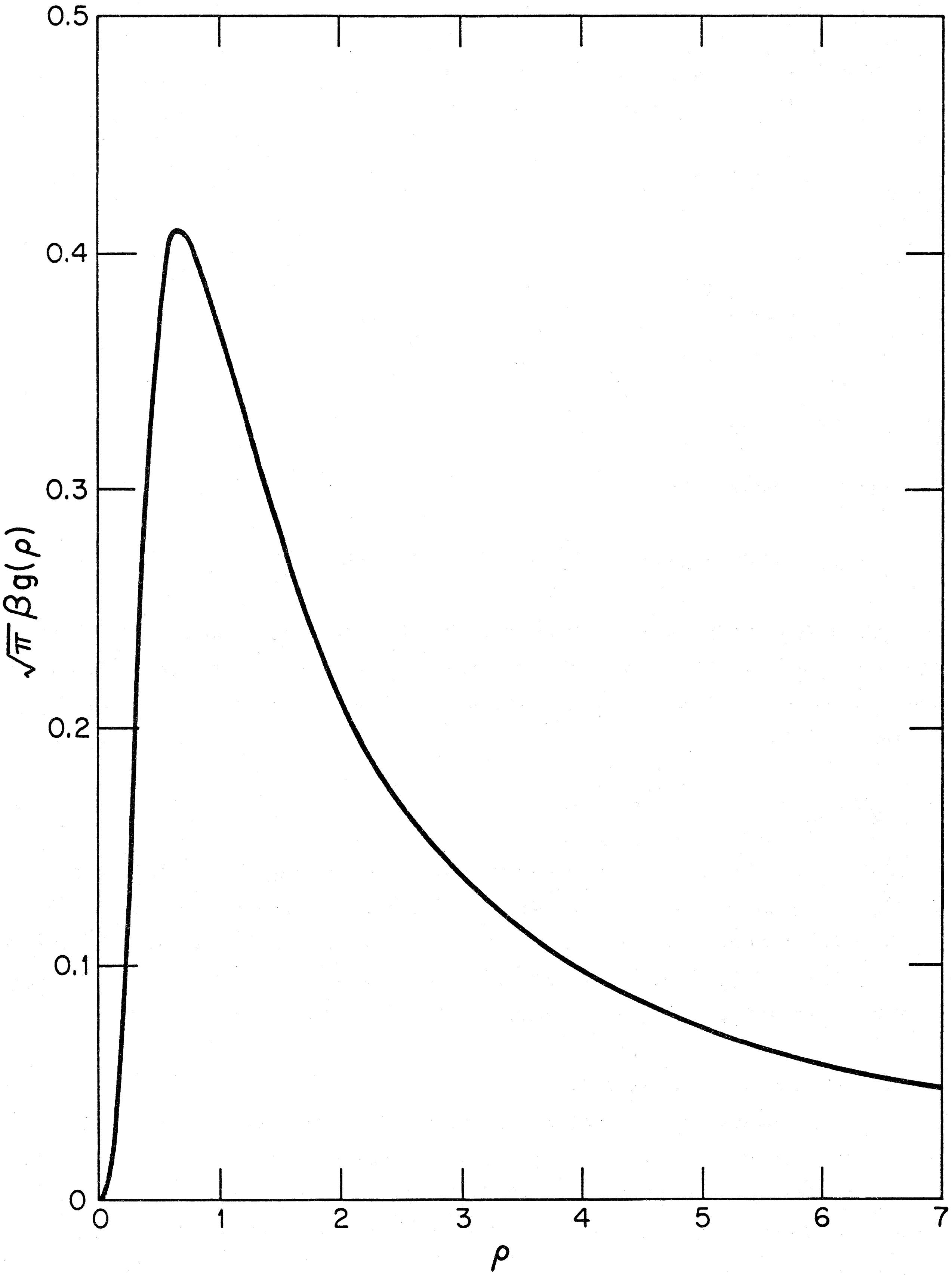


Figure 3. Normalized impulse response for coaxial cable.
(After Gallawa, 1977.)

$$P = \frac{1}{\rho\beta} = \frac{1}{7.715\left(\frac{\ell K}{4\sqrt{\frac{L}{C}}}\right)^2} \quad (9)$$

where $\sqrt{\frac{L}{C}} = Z_o$ = characteristic impedance.

From which:

$$P = \frac{2.07\ Z_o^2}{\ell^2\ K^2}\ . \quad (10)$$

Inserting the definition of K from (3)

$$P = \frac{6.50 \times 10^7 Z_o^2 \sigma\ a^2}{\ell^2}\ . \quad (11)$$

If the conductor is copper,

$$P = \frac{3.8 \times 10^{15} Z_o^2 a^2}{\ell^2}\ .$$

The figure of merit becomes:

$$Fm = P\ell^2 = 3.8 \times 10^{15}\ Z_o^2 a^2.$$

Let P be in megapulses/second, ℓ in km, and a in mm; this becomes

$$\boxed{Fm = 3.8 \times 10^{-3}\ Z_o^2 a^2}\ . \quad (12)$$

Choosing a line with characteristic impedance of 50 ohms, for a desired pulse rate of 10 Mb/s and length 1 km, requires a radius of the inner conductor, a,

$$a = 1.03 \text{ mm}.$$

The characteristic impedance of coaxial cables is given by (Ramo and Whinnery, 1948):

$$Z_o = \frac{\sqrt{\frac{\mu}{\varepsilon_1}}}{2\pi} \ \ell \log_e (b/a)$$

$$= \frac{60}{\sqrt{\varepsilon}} \ \ell \log_e (b/a)$$

For many dielectrics used in coaxial cables, $\varepsilon = 2.37$. Thus

$b = 3.64a$, and

$2b = 7.74$ mm (outer diameter of dielectric, exclusive of outer conductor and jacketing).

This derivation is based on an ideal impulse response of the line and requires pulses that are very short compared with the response time, β, of the line.

3.1.3 Fm Based on Response to a Step Function

The Wigington and Nahman (1957) paper derives the response to a step function input. The result is:

$$f(t) = f(x + \ell\sqrt{LC}) = C\text{erf} \sqrt{\frac{\beta}{x}}\ , \tag{13}$$

where Cerf(z) is the complementary error function of argument z, Cerf(z) = 1-erf(z), and erf(z) is the error function.

Gallawa (1977) shows that one can use tabulated rational approximations to calculate erf(z). See Abramowitz and Stegan (1968), Section 7.1.25, to determine a useful figure of merit from (13). Let

$$f(t) = 1-\text{erf} \sqrt{\frac{\beta}{x}}$$

and find β/x such that $f(t) = 0.5$. This corresponds to the 50 percent rise time for a step function input. Thus:

$$\text{erf} \sqrt{\frac{\beta}{x}} = 0.5.$$

This results in $\beta/x = 0.23$,

or

$$\frac{1}{x}\Big|_{50\%\ \text{point}} = \frac{3.7 Z_o^2}{\ell^2 K^2} \ .$$

Substituting from (3) for K yields

$$\frac{1}{x}\Big|_{50\%\ \text{point}} = \frac{11.6 \times 10^7 Z_o^2 a^2 \sigma}{\ell^2} \ .$$

Let

$$P = \frac{1}{2}\,\frac{1}{x}\Big|_{50\%\ \text{point}}.$$

This corresponds to a pulse duration which is two times the rise time (0 to 50%) for a step function input.

Let P be in megapulses/second, ℓ in km, a in mm, and σ = copper; the result is

$$\boxed{Fm = 3.4 \times 10^{-3}\ Z_o^2 a^2} \ . \qquad (14)$$

(Note: The choice of pulse duration on this derivation was quite arbitrary. It produces a constant of 3.4×10^{-3} vs 3.8×10^{-3} obtained by the derivation using the impulse response assumption.)

3.1.4 Fm Based on Measured Attenuation

From equation (5), the attenuation is caused by the real part of the exponent. Since $p = j\omega$,

$$\frac{K\sqrt{j\omega}}{2\sqrt{\frac{L}{C}}} = \frac{K(1+ j)}{2\sqrt{\frac{L}{C}}}\sqrt{\frac{\omega}{2}}$$

from which, the real part,

$$\alpha(\omega) = \frac{K}{2\sqrt{\frac{L}{C}}}\sqrt{\frac{\omega}{2}}$$

and

$$K = \frac{2\sqrt{\frac{L}{C}}\,\alpha(\omega)}{\sqrt{\frac{\omega}{2}}}.$$

From equation (6)

$$\beta = \left(\frac{\ell K}{4\sqrt{\frac{L}{C}}}\right)^2$$

$$= \frac{\ell^2\,\alpha^2(\omega)}{2\omega}$$

For the case of P = reciprocal of $\rho = 0.1\,\rho_{max}$, $\rho = 7.715$, and

$$P = \frac{1}{\rho\beta} = \frac{0.26}{\ell^2} \quad \frac{\bar{\bar{\omega}}}{\alpha^2(\omega)} \ .$$

From which

$$Fm = P\,\ell^2 = 0.26\left(\frac{\bar{\bar{\omega}}}{\alpha^2(\omega)}\right) = 1.63\left(\frac{\bar{\bar{f}}}{\alpha^2(\omega)}\right),$$

where $\alpha(\omega)$ is in nepers/km. A more often used unit is $\hat{\alpha}(\omega)$ in dB/km, where $\hat{\alpha}(\omega) = 8.686\,\alpha(\omega)$.

Then:

$$Fm = 123\left(\frac{\bar{\bar{f}}}{\hat{\alpha}^2(\omega)}\right) . \qquad (15)$$

The $(\bar{\bar{\ }})$ is used to emphasize that the attenuation must be measured at the corresponding frequency. This expression can be used to evaluate the potential digital performance of coaxial cables from published attenuation measurements. Coaxial cables, for which the attenuation constant $\alpha(\omega)$ is proportional to the square root of frequency, will have a straight line relation of slope 1/2 between the logarithm of the attenuation coefficient (dB/length) and the logarithm of frequency.

A similar figure of merit, based on the assumption that P is the reciprocal of 2 times the 0 to 50% response time with a step function input, can be derived. The result is:

$$\boxed{Fm = 109\left(\frac{\bar{\bar{f}}}{\hat{\alpha}^2(\omega)}\right)} \qquad (16)$$

In summary, the derivations outlined above are based on the transfer function of a line under the assumptions that the series resistance per unit length is determined by the skin-effect impedance and that dielectric loss per unit length can be neglected. Approximations are made by truncating the binomial expansion of γ in the transfer function. The reference paper (Wigington and Nahman, 1957) describes the error introduced by this truncation and for the purposes of this development, the error is negligible. The expressions for figure of merit, Fm, are arbitrarily based on pulse rate assumptions that appear to be reasonable and that provide results that are useful in assessing metallic cable transmission media.

To translate the manufacturer's coaxial cable measured attenuation coefficient (dB/km) at a specific frequency, equation (16) may be used to calculate Fm. If this Fm is greater than the required $Fm = P\ell^2$ needed for the installation, the cable should be satisfactory.

Howard (1976) treated the problem of pulse dispersion in a more general way and developed sets of universal curves for pulse rise time and pulse rate. His results are derived by computer analyses. He studied several representative wave shapes, including rectangular, raised cosine, and gaussian.

Howard concluded that the transfer function acts as a high frequency filter, so that pulse shapes with little high frequency content are less likely to cause decision errors in a receiver than pulses with higher frequency content.

3.2 Cable Evaluation

Performance parameters important to digital transmission were tabulated on both military-specified and commercial cables by Bloom, et al. (1977). The selection was based on the following:

(1) Pertinent MIL-specs and Handbooks were reviewed and cross-referenced to determine the most up-to-date list of RG/U cable types recommended for military applications.

(2) Numerous cable manufacturers were contacted for catalogs and additional available test data.

Some representative cables from the MIL-spec and commercial tabulations are shown in Tables 3 and 4, respectively. The manufacturer's attenuation at the specified frequency has been used to calculate an Fm in accordance with equation (16). If a cable is required to transmit 10 Mb/s over a distance of 1 km, the required minimum figure of merit is $Fm = P\ell^2 = 10$. An inspection of Table 3 shows that three of the RG cables exceed the required Fm. These cables exceed 2 cm in diameter. In Table 4 only two of the representative cables exceed the Fm. The diameters are 1.1 and 1.6 cm, respectively.

From the analysis of a limited survey of available coaxial cable, one can conclude that the desired performance at 10 Mb/s and 1 km distance requires a coaxial cable of the order of 1.0 cm in diameter. This means that considerable duct space per interchange circuit would be required. Such large coaxial cables are mechanically inflexible compared to twisted wire pairs and, if multiple interchange circuits are required, would require either multiple connectors or an especially designed, large, multiple connector. From these considerations, the use of coaxial cable to achieve the desired interchange circuit specification does not appear to be attractive.

3.3 Twisted Wire Pairs

The above derivation may be applied to noncoaxial lines (e.g., a twisted wire pair) where values for Z_o and Z_s are known in terms of lumped constants and geometric factors.

For the case of parallel-wire transmission line, Ramo and Whinnery (1948) show that

$$\beta = \left(\frac{\ell K}{4Z_o}\right)^2 ,$$

$$K = G_o \sqrt{\frac{\mu}{\sigma}} ,$$

$$G_o = R_{co}/R_s ,$$

$$R_{co} = \frac{2R_s}{\pi d} \frac{s/d}{\sqrt{(s/d)^2-1}} , \text{ and}$$

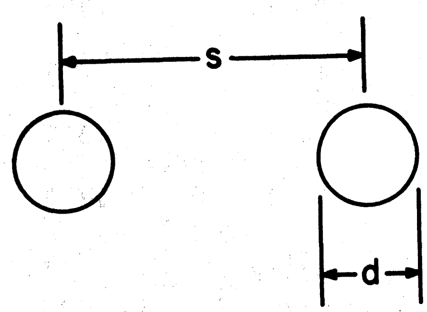


Table 3. Representative MIL-Spec Coaxial, Twinaxial, and Triaxial Cables

Cable	Largest Dimension (cm)	(dB/km) (at f MHz)	Fm(Mp/s-km^2)
CX-112301G	0.43	14.81 (2)	1.0
RG8A/U	0.7	66 (100)	2.5
RG200/U	2.3	23 (100)	20.6
RG11A/U	0.7	75 (100)	1.9
RG318/U	2.2	13 (100)	64.5
RG319/U	4.1	7.2 (100)	210.0
RG59/U Triaxial	0.8	85 (100)	1.5
Twinaxial	0.8	134 (100)	0.6

Table 4. Representative Commercial Coaxial Cables

Cable A	Diameter (cm)	(dB/km) (at 10 Mhz)	Characteristic Impedance Z_o(ohms)	Fm (Mp/s-km^2)
A	0.5	49.2	50	0.45
B	0.76	17.4	50	3.6
C	1.27	23.0	50	2.1
D	1.32	13.1	50	6.4
E	0.62	23.0	75	2.1
F	1.16	13.8	75	5.7
G	1.10	9.8	75	11.4
H	1.6	7.2	75	21.0

$$Z_o = \frac{377}{\pi} \cosh^{-1} \frac{s}{d}.$$

Thus,

$$\beta = \frac{\ell^2 \mu (s/d)^2}{4Z_o^2 \pi^2 d^2 \sigma[(s/d)^2-1]}$$

substituting values for μ and σ for copper,

$$\beta = \frac{0.5488\text{x}10^{-15} \ell^2 (s/d)^2}{Z_o^2 \, d^2 \, [(s/d)^2-1]}.$$

Let the maximum pulse rate be determined when $\rho = 0.1 \; \rho_{max} = 7.715$:

$$P = \frac{1}{\rho\beta} = 0.236\text{x}10^{15} \frac{Z_o^2 d^2 [(s/d)^2-1]}{\ell^2 \quad (s/d)^2}.$$

If P is in megapulses, d in mm, ℓ in km, then

$$P = 0.236\text{x}10^{-3} \quad \frac{Z_o^2 d^2 [(s/d)^2-1]}{\ell^2 \, (s/d)^2},$$

and

$$\boxed{Fm = P\ell^2 = 0.236\text{x}10^{-3} \frac{Z_o^2 d^2 [(s/d)^2-1]}{(s/d)^2}.} \qquad (17)$$

If one chooses d = 0.5 mm and s = 1 mm, this yields

$Z_o = 158 \; \Omega$

and Fm = 1.10.

This indicates that a twisted-wire pair of about 24 gauge copper wire will transmit about 1 Mb/s over a distance of 1 km under the condition that pulse dispersion is the limiting factor. Transmission rates up to 1.544 Mb/s are achievable with appropriate compensation. (Note: The twisted-wire pair is equivalent to the parallel-wire transmission line where the period of twist is much greater than the wavelength. The twists reduce 60-Hz pickup and tend to reduce crosstalk between pairs.)

4. PROPERTIES AND LIMITATIONS OF OPTICAL FIBER WAVEGUIDES

Optical fiber waveguide technology was one of the glamour technologies of the 1970's, during which time it matured from the experimental laboratory to commercial implementation in virtually all types of guided-wave transmission applications. The largest volume applications have been in long-haul and interexchange trunking by telephone common carriers. Careful attention to assure cost competitiveness has been exercised in these installations. Growing use of optical cable for customer local loops and local area networks (or equivalents) is reported (Schweiger and Middel, 1982), largely outside the United States. Numerous manufacturers, in the United States and elsewhere, offer optical links typically designed for RS-232-C or V.24 transparency. Similarly, there are commercially available optical links designed to be compatible with T-carrier hierarchies up to T-3 (44.5 Mb/s). These links do not offer optical compatibility among various manufacturers since standards necessary for such compatibility do not as yet exist.

The growing use of optical fibers may be attributed to advantages resulting from one or more of several inherent characteristics, such as:

- low attenuation,
- high bandwidth,
- low distortion,
- small size,
- immunity to electromagnetic interference, (and elimination of radiated spurious emissions),
- commercial availability of many alternative fiber and cable configurations,
- decreasing cost,
- savings in cost of installation, shipping, and storage,
- compatibility with digital signals.

This section provides a discussion of these inherent characteristics, and an analysis of optical cable application for ISDN User/Network Interface interchange circuits.

4.1 Optical Fiber Waveguide Parameters

Optical fibers are dielectric waveguide structures that are used to confine and guide light. Optical fibers essentially consist of an inner dielectric material called core, surrounded by another dielectric with lower refractive index, referred to as cladding. The geometry is circular in cross section. Other geometries are possible, but the circular symmetry results in ease of fabrication and handling and allows simpler theoretical treatment.

The most important parameters for specifying multimode optical fiber properties are: attenuation coefficient; core radius, a; the numerical aperture, NA = $\sqrt{n_1^2 - n_2^2}$ (where n_1 = core refractive index, n_2 = cladding refractive index); and a characteristic parameter called $V = (2\pi a/\lambda)\sqrt{n_1^2 - n_2^2}$ (where λ is the light wavelength in vacuum). The NA parameter is related to the maximum acceptance angle for rays entering the fiber.

Two important structural and operational characteristics of optical fiber waveguides need to be considered, namely: step index vs graded index and multimode vs single mode. The step index fiber consists of a uniform core of refractive index n_1 surrounded by a cladding of index n_2, with $n_2 < n_1$. Such a step index structure will support, generally, many propagating modes, their number being approximately equal to $V^2/2$ and therefore proportional to a^2 and to $(NA)^2$. Each mode traverses a different path in the guide and consequently arrives at the end of the guide at a slightly different time. This results in signal distortion and therefore limits the bandwidth of the waveguide. This is a drawback of the step index fiber in the context of long-haul, wideband telecommunication systems. Practical fibers for such systems exhibit limited NA (typically NA $\simeq$ 0.2).

The fiber core radius, a, may be reduced for a given λ so that a single mode is propagated. The condition for single mode propagation occurs when $V \leq 2.4$. Single mode fibers achieve the ultimate limit of bandwidth achievable in dielectric waveguides, since only material dispersion (discussed below) contributes to distortion. The impairing effect of differential mode delay on bandwidth described above for multimode step index waveguides can be greatly reduced by suitably varying the refractive index in the fiber cross section so as to develop a nearly parabolic index profile as a function of radius, with a maximum on the fiber axis. This provides a variable velocity for off-axis modes such that all modes have the same group velocity and arrive at the end of the waveguide at the same time. This graded index minimizes the time dispersion caused by the multiple modes and improves the resultant bandwidth over the step index waveguide.

4.2 Analytical Description

The theoretical analysis of dielectric waveguides may be carried out using either of two approaches, namely geometric or modal (electromagnetic). Geometric analysis produces well-approximated results particularly useful for providing physical interpretation of results in multimode fibers. The electromagnetic approach is necessary for single- or few-mode fibers and is necessary for certain phenomena such as coherence or interference. In either case, the theory is complex and beyond the scope of this study. Only qualitative discussions will be presented here. For a summary of the theoretical approaches based on a recent survey of the literature, the reader is referred to a recent book (Technical Staff of CSELT, 1980) where the theoretical, measurement, and system characteristics are described in detail.

4.3 Attenuation Characteristic

Attenuation in an optical waveguide is caused by absorption, scattering, and leaky modes. Absorption and scattering are primarily functions of the purity of the core and cladding material. The ultimate lower limit of these losses is determined by Rayleigh scattering which is proportional to λ^{-4}, where λ is, again, the optical wavelength. In multimode guides, attenuation may be different for different modes (differential mode attenuation). In this case the attenuation coefficient (generally expressed in dB/km) is not a constant function of distance. Recent advances in materials and manufacturing techniques have greatly reduced the absorption losses in high-quality optical fiber waveguides. Figure 4 shows a plot of attenuation vs wavelength of a typical communications-type fiber with low absorption loss. The attenuation at $\lambda \simeq 1400$ nm results from hydroxyl ion (OH) absorption, which can be almost totally removed, but at increased production costs.

Extensive work is underway to compare the accuracy and reproducibility of measurements of attenuation and other characteristics (Danielson, et al., 1982) and to develop standards for the measurement techniques (e.g., EIA P. 6.6 committee). From the perspective of systems design, the attenuation coefficient as measured by the manufacturer is sufficient for calculating system power margin, if the measurements are made under carefully standardized and recognized procedures.

For moderate-bit-rate systems, the attenuation ultimately reduces the energy transmitted in a pulse to a level that is not distinguishable from the noise of the receiver. This condition may determine the maximum length of

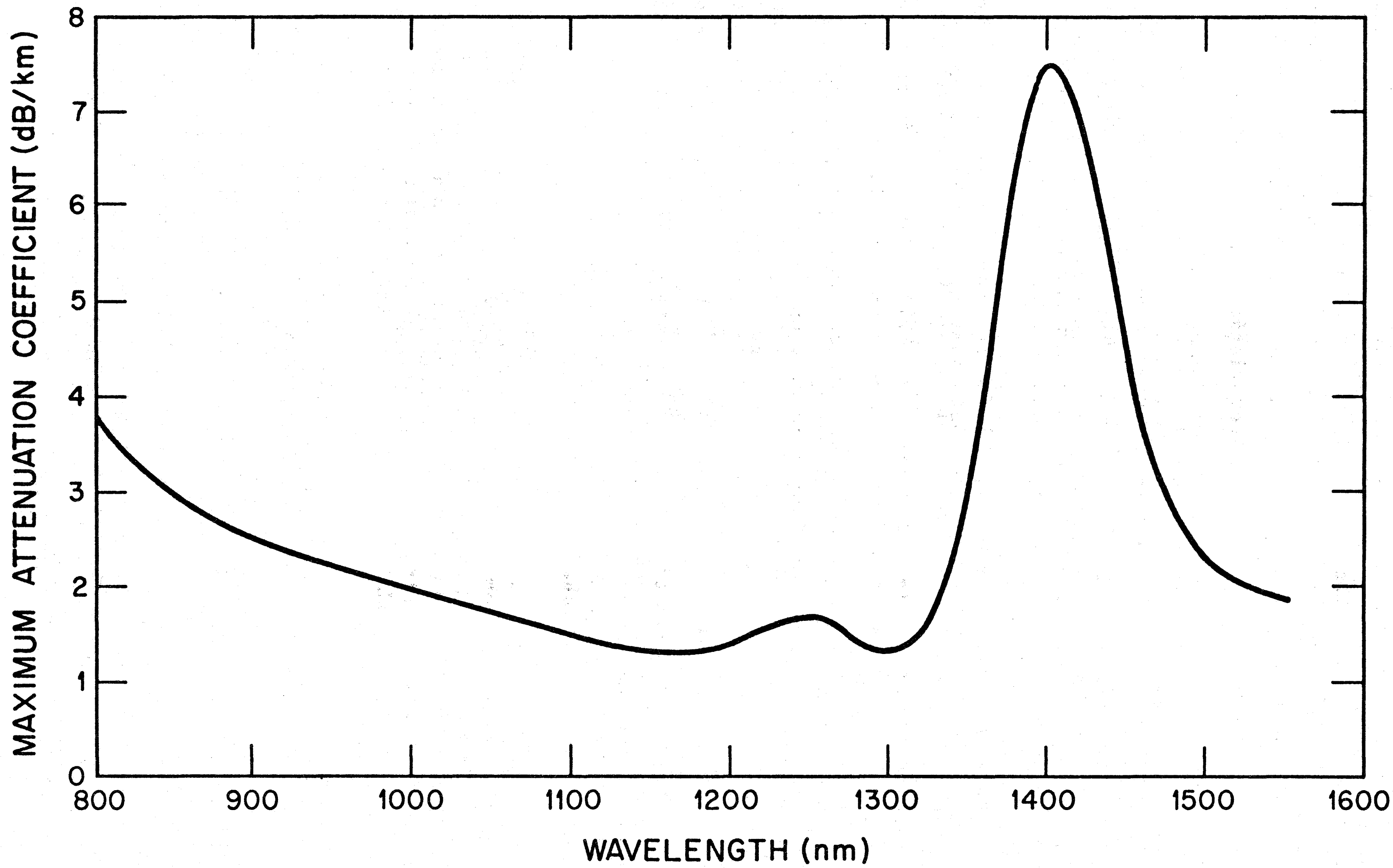


Figure 4. Attenuation vs wavelength for typical, low loss, silica-core optical fiber.

waveguide that can be used without repeaters or other amplification. Attenuation of optical fiber must be carefully considered, along with other losses such as splices, connectors, and coupling in system design, in order to assure adequate system margin.

4.4 Bandwidth Characteristic

When distortion of the received signal, rather than its amplitude (power), limits performance of a digital transmission, the system is said to be operating in the distortion-limited regime. This applies equally to the optical fiber waveguide and to the metallic transmission lines discussed in Section 3 above.

For the purpose of this report, it is desirable to look at those parameters of the optical fiber waveguide that cause the pulse distortion, and to develop appropriate rationale for a figure of merit suitable for comparing various optical fiber cables.

Optical pulses traveling in a multimode optical waveguide are subject to four primary mechanisms that cause pulse distortion, namely: (1) multimode distortion (often erroneously referred to as multimode 'dispersion'), (2) material dispersion, (3) waveguide dispersion, and (4) profile dispersion. These primary mechanisms and other terms have been defined (Hanson et al., 1982) by a North American committee.[2]

The definitions of the mechanisms are:

Multimode distortion: in a multimode optical waveguide, that distortion resulting from differential mode delay. Differential mode delay is defined as the variation in propagation delay that occurs because of the different group velocities of the various modes. (Note that multimode distortion is a time-dependent parameter as opposed to the wavelength-dependence of the following three dispersion parameters.)

Material dispersion: that dispersion attributable to the wavelength dependence of the refractive index of material used to form the waveguide. (Note that this mechanism is independent of waveguide geometry and is therefore common to both multimode and single mode fiber waveguides.)

[2]The resultant handbook has been adopted by standards committees of EIA, IEEE, and several international working groups.

Waveguide dispersion: for each mode in an optical waveguide, the process by which an electromagnetic signal is distorted by virtue of the dependence of the phase and group velocities on wavelength, as a consequence of geometric properties of the waveguide. In particular, for circular waveguides, the dependence is the ratio (a/λ).

Profile dispersion: in an optical waveguide, that dispersion attributable to the variation of refractive index contrast with wavelength, where contrast refers to the difference between the maximum refractive index in the core and the refractive index of the homogeneous cladding. Profile dispersion is usually defined by the profile dispersion parameter, which is that dispersion attributable to the variation of refractive index profile with wavelength. The profile variation has two contributors: (a) variation in refractive index contrast, and (b) variation in profile parameters.

The profile parameter, g, applies to a class of graded index profiles characterized by the following equations:

$$n(r) = n_1\ [1-2\Delta(r/a)^g]^{1/2} \qquad r \leq a \tag{18}$$

$$n(r) = n_1(1-2\Delta)^{1/2} \qquad r \geq a$$

$$\text{where } \Delta = \frac{n_1^{\,2}-n_2^{\,2}}{2n_1^{\,2}}$$

and $n(r)$ is the refractive index as a function of radius, n_1 is the refractive index on axis, n_2 is the refractive index of the homogeneous cladding, a is the core radius, and g is a parameter that defines the shape of the profile.

Measuring the impulse response of the dielectric waveguide will account for all of the above delays. This can be accomplished by sending a very short optical pulse (short in comparison to the total pulse broadening) into the fiber and observing the output pulse after it has traversed the fiber length, ℓ. Such a measurement, generally, requires a sophisticated and expensive light source and high-resolution receiving equipment. If the input pulse is not short compared with the total pulse broadening, the output pulse is the convolution of the input pulse and the impulse response of the line. If the input pulse shape is accurately known, it is possible to deconvolve the input from the output response and thus obtain the impulse response.

4.4.1 Multimode Distortion

Multimode distortion occurs in both step index and graded index waveguides. Higher-order modes have longer paths in traversing the waveguide than do lower-order modes, therefore requiring longer transit times. This results in broadening of the received pulse duration. For engineering approximations, the maximum value for this differential mode delay and consequent pulse broadening in step index waveguides is the difference between transit time for the highest-order mode, limited by the waveguide's critical angle, and the lowest-order mode, corresponding to an axial ray. Measured values tend to be lower than calculated values because of the relatively higher attenuation of high-order modes. Multimode distortion is generally the dominant cause of pulse distortion for the step index fiber.

4.4.1.1 Step index waveguides

There are a number of measures of performance that describe the degradation caused by the distortion effects produced by the fiber on the transmitted signal. The engineering parameter most often measured is the 3-dB bandwidth. The 3-dB bandwidth is the frequency of modulation at which the optical power at the output of the waveguide falls to one-half of the output power measured at zero frequency. Note that this loss in power is independent of and in addition to the attenuation due to scattering and absorption mechanisms discussed above. Another measure is the rms impulse response time of the fiber. This requires a very short duration input pulse. The rms impulse response is a characteristic that can be calculated. Some engineering approaches to system design require the distortion characteristic of the fiber to be expressed in terms of a rise time response of the fiber. Finally, the differential delay between the transit time of high-order modes and low-order (axial) modes transmitted by the fiber may also be used as a measure of the multimode distortion. The relationship of these several measures for the determination of a maximum bit rate x length product is desired here to develop a figure of merit useful in comparing the performance of different fiber waveguides.

A general description of the radial variation of refractive index that characterizes optical fiber waveguides is given by equation (18). Step index fibers are defined by equation (18) when $g=\infty$. Quantitative expressions for the impulse response of waveguides that conform to the index variations described by equation (18) have been derived (Olshansky and Keck, 1976). Neglecting some higher order terms, the result of this derivation is given by

$$\sigma = \frac{n_1 \Delta}{2c} \frac{g}{g+1} \left(\frac{g+2}{3g+2}\right)^{1/2} \frac{g-2}{g+2} . \tag{19}$$

For a step index fiber ($g=\infty$), the rms impulse response per unit length is

$$\sigma \simeq \frac{n_1 \Delta}{2c\sqrt{3}} = \frac{0.289 n_1 \Delta}{c} \text{ s/m.} \tag{20}$$

To obtain the rms impulse width for a length ℓ, the expression (20) must be multiplied by ℓ. If ℓ is in km, the result is

$$\delta\tau = \sigma \, \ell_{km} = 960 \, n_1 \, \Delta \, \ell_{km} \text{ ns/km.} \tag{21}$$

Thus for step index fiber with $n_1 = 1.4586$ (SiO_2), $\Delta = 0.01$, $\delta\tau = 14$ ns/km.

The shape of the received pulse influences the intersymbol interference effect at large pulse overlap and requires a higher input power to the receiver to achieve a given bit error rate (BER) performance. Personick (1973) has investigated this power penalty for various signal waveform shapes. His results demonstrate that for about 1 dB penalty in the received power requirements, one can specify an allowable bit rate x length (regardless of pulse shape) of

$$P_{max} = \frac{1}{T} = \frac{1}{4\delta\tau} \text{ megabits - km/s.} \tag{22}$$

Thus, for the step index fiber described above,

$$P_{max} = \frac{1}{4x14} = 18 \text{ megabits - km/s.}$$

4.4.1.2 Graded index waveguides

The general expression describing the radial variation of refractive index given in equation (18) describes the graded index fiber where g is the parameter that defines the shape of the profile. Note that the impulse response defined by equation (19) indicates no modal dispersion where $g = 2$, the parabolic profile. This is not quite true, and the more precise analysis contained in the reference (Olshansky and Keck, 1976) leads to an expression for an 'ideal' round-fiber impulse response:

$$\sigma_i = 0.037 \frac{n_1}{c} \Delta^2$$

$$\approx \frac{n_1 \Delta^2}{c\ 20\sqrt{3}}. \quad (23)$$

If Δ is of order 0.01, this indicates a decrease in multimode impulse response width of about 1000. A set of normalized rms width of impulse response for several index distributions (Miller et al., 1973) is given in Table 5. This table indicates that in practice, improvements of the order of 50:1 may be achievable. Using the value corresponding to the practical parabolic fiber, and assuming $n_1 = 1.4586$, $\Delta = 0.01$. The resultant $\delta\tau$ for graded index is

$$\delta\tau_{gi} = 0.3 \text{ ns/km}. \quad (24)$$

This corresponds to a maximum bit rate x length product,

$$P_{max} = 833 \text{ Mb-km/s}. \quad (25)$$

This number serves mainly to indicate that material dispersion discussed below will likely dominate in well-designed graded index fibers.

In practice, the contributions of both multimode distortion and material dipersion must be considered.

4.4.2 Material Dispersion

Material dispersion occurs in all fibers because the index of refraction varies with wavelength. It becomes more important when a source of wide spectral bandwidth such as a light emitting diode (LED) is used as a source. A reference paper (DiDomenico, 1972) treats the effect of material dispersion and its relationship to information bandwidth of the fiber. An expression is derived for group delay in terms of known parameters of the glass used for the waveguide. This derivation appears to provide approximations which are useful for engineering practice and are complementary to the above intermodal approximations derived by Gloge (1971).

Table 5

Normalized Root-Mean-Square Width of Impulse Response for Several Index Distributions

Index Distribution	$\frac{\sigma c}{n_1 \Delta}$
Step index ($g=\infty$)	$\frac{1}{2\sqrt{3}} = 0.289$
Pure eighth order ($g=8$)	0.165
Pure fourth order ($g=4$)	0.0873
Pure second order ($g=2$)	0.15Δ
'Ideal' near parabolic (round fiber)	0.037Δ
Practical (5% error) parabolic	0.00591

The reader is referred to the DiDominico paper for details. The results of interest here are the delay spread per unit length caused by the material dispersion.

If a gaussian pulse of width τ is transmitted through a dispersive medium of length ℓ, the output pulse width, τ_o, is

$$\tau_o{}^2 = \tau^2 + s^2 \ell^2 \tag{26}$$

where s = differential group delay per unit length of the medium.

In the region of transparency of the glass, the material contribution to the waveguide time dispersion is

$$s = 3B\, E_d\, E/cn\, E_o{}^3, \tag{27}$$

where B = optical bandwidth (expressed in units of energy - eV),

E_d = dispersion energy parameter,

E_o = oscillator energy parameter,

Note: E_d and E_o - provided in a table for representative glasses used in optical waveguides,

E = photon energy of the optical carrier,

c = velocity of light (2.9979×10^8 m/s), and

n = index of refraction.

Equation (27) applies for a pulse whose spectral width is small compared to the emission spectrum of the source (i.e., $\delta\lambda << \lambda_o$) or for a bandwidth-limited gaussian pulse. In the first case, B is the spectral width of the source (expressed in units of energy) while in the second case (below), B is the reciprocal of the pulse width, i.e., $B=h/\tau$, where h is Planck's constant ($h = 4.14 \times 10^{-15}$ eV-s) and τ is the pulse width of the source in seconds.

For a broadband source (e.g., an LED), case 1 above, which transmits a wide pulse,

$$s \approx 3 \left(\frac{B}{E}\right) E_d E^2/cn E_o^3 \tag{28}$$

and for SiO_2, this becomes

$$s \approx 170 \frac{\delta\lambda}{\lambda_o} \text{ (ns/km)}. \tag{29}$$

The desired delay spread is

$$s \ell_{km} = 170 \frac{\delta\lambda}{\lambda_o} \ell_{km} \text{ ns} . \tag{30}$$

For a bandwidth-limited pulse (i.e., $\tau \approx sL$) and $\delta\lambda$ very small compared to λ_o such as a mode-locked laser, case 2 above,

$$s \approx 3 \left(\frac{h}{\tau}\right) E_d E/cn E_o^3 \tag{31}$$

and for SiO_2

$$s \approx \frac{0.35}{\tau} \times 10^{-12} \text{ ns/km}, \tag{32}$$

where τ is expressed in seconds.

Substituting $\tau = s\ell_{km}$,

$$s = \left(\frac{0.35 \times 10^{-12}}{\ell_{km} \times 10^9}\right)^{1/2} . \tag{33}$$

The desired delay spread is

$$s\,\ell_{km} = 18\sqrt{\ell_{km}} \quad ps.$$

Note that for a bandwidth-limited pulse, the material dispersion increases as the square root of length.

An LED source might have a (B/E) ratio (source spectral width/source center wavelength) of 1 percent. The material dispersion would then be about 1.7 ns/km from equation (30). For very short laser pulses, pulse spread of a fiber is about 18 ps for a 1-km length for material dispersion.

In the discussion of multimode distortion, it was stated that the rms width of the impulse response is needed to calculate the information bandwidth of the fiber. Note that in the discussion above, the information bandwidth was taken to be the reciprocal of the pulse spread caused by material dispersion. An analysis (Miller et al., 1973) based on the impulse response of the fiber and assuming a gaussian spectral shape of the input pulse yields a value for the rms width of the impulse response for an AlGaAs LED and fused silica fiber of 1.75 ns/km, compared with the predicted value above of 1.7 ns/km. Using the relationship (Personick, 1973) between rms width and maximum bit rate, gives a pulse rate x length product of 142 Mb-km/s.

In multimode fibers, each mode experiences a different group delay but, to a good approximation, the same differential group delays. This group delay must be added to the multimode distortion to determine the envelope delay.

4.4.3 Relation of Bandwidth and Impulse Response

For any given impulse response shape, there is a constant such that:

$$f_{(3-dB)}\ \sigma_{rms} = \text{constant.}$$

If the impulse response shape of the fiber is gaussian, this relationship has been shown (Danielson, 1982) to be:

$$f_{(3-dB)}\ \sigma_{rms} = 190, \tag{34}$$

where $f_{(3-dB)}$ = lowest frequency at which the optical power is one-half the power at zero frequency (MHz/km),

and σ_{rms} = impulse response width of the fiber (ns).

Experimental measurements (Buckler, 1982) have shown that for several graded index optical fibers, the above constant is 169 $\pm$ 11. This would indicate that the shape of the impulse response is relatively uniform among the several fibers tested.

The maximum pulse rate x distance relation from equation (22) may be expressed in terms of the $f_{(3-dB)}$ response, assuming a gaussian impulse response shape, by combining equation (34) and (22):

$$P_{max} = 1.3\ f_{(3-dB)}\ \text{Mb-km/s}. \tag{35}$$

4.4.4 Rise Time (RT) Approximation

The detection circuitry of an optical receiver is often modeled as a resistance-capacitance (RC) single-pole filter having a time constant tc. The output waveform, for a square wave of amplitude A_m and duration T, is given by:

$$f(t) = A_m\ [1-\exp(-t/tc)],\ 0 \leq t \leq T \tag{36}$$

$$= A'_m\ \exp\ (-t-T)/tc,\ T \leq t,$$

where $A'_m = [1-\exp\ (-T/tc)]$, and

tc = a time constant characteristic of the receiver.

From this expression, a rise time, RT, defined as the time for the f(t) to change from 10 percent to 90 percent of A_m can be determined, namely

$$RT = 2.2\ tc. \tag{37}$$

The frequency spectrum of the output pulse can be obtained via the transformation

$$F(\omega) = \int_{-\infty}^{\infty} f(t)\ \exp\ (-j\omega t)\ dt.$$

The result is

$$F(\omega) = A_m\ T\ \exp\ (-j\ \frac{\omega T}{2})\ \frac{\sin \frac{\omega T}{2}}{\frac{\omega T}{2}}\ \frac{1}{1+j\omega tc}. \tag{38}$$

The last term of this equation determines the amplitude effect of the resultant low-pass filter. The frequency at which the power response is down by 3 dB can be determined as:

$$\frac{1}{\sqrt{1 + (2\pi \, f_{(3-dB)} tc)^2}} = \frac{1}{\sqrt{2}}$$

$$f_{(3-dB)} = BW_{(3-dB)} = \frac{1}{2\pi tc}. \tag{39}$$

Combining equations (37) and (39), one obtains:

$$RT = \frac{0.35}{f_{(3-dB)}}. \tag{40}$$

Equation (40) is sometimes used to relate the rise time of a fiber to its $f_{(3-dB)}$ bandwidth:

$$RT\ (ns\text{-}km) = \frac{350}{f_{(3-dB)}\ (MHz\text{-}km)}. \tag{41}$$

This is properly the characterization of a single pole RC filter and may not characterize the optical fiber response.

4.5 Summary and Conclusions

A complete analysis of the optical fiber waveguide using either the Maxwell field-equation approach or the somewhat more approximate geometric optic approach is quite complex. A search has been made of referenceable literature for approximate equations that provide a basis for relating the key parameters published by manufacturers to the fundamental performance characteristics of step index and graded index optical fibers. Single mode fibers have been mentioned in the context of material dispersion limitations, but no attempt has been made to characterize the limiting performance of this promising waveguide. This is because the extremely high bandwidth obtainable with single mode waveguides is not required for applications considered here, and economical sources such as LED's are not practical for use with these fibers, because of the LED's inherent near-Lambertian emission.

The properties of the multimode optical fiber waveguide that affect its limiting performance as a transmission medium are attenuation and bandwidth. The attenuation is ultimately limited by Rayleigh scattering from very small discontinuities in the core material and absorption losses caused by trace impurities in the material. The Rayleigh scattering is proportional to λ^{-4} and is therefore less at longer wavelengths (i.e., 1300 and 1500 nm). Bandwidth is dominated generally by intermodal distortion in step index fibers and by material dispersion in single mode fibers. Graded index fibers can provide a bandwidth increase of about 50 times that of step index fibers under practical conditions.

Measurement procedures are receiving much attention by standards committees, and methods should be accepted in the near future to provide both precise and well-defined parameters for use in engineering design. Procedures for measuring attenuation are now being compared by leading laboratories (Danielson et al., 1982) with good results. The greatest uncertainty in making bandwidth measurements on multimode fibers is the lack of standardized launching conditions.

In section 3, a figure of merit was defined [equation (1)] as $Fm = P \ell^u$. The P in this equation is the maximum pulse rate for acceptable overlap of successive pulses. The exponent, u, identifies the relation of pulse distortion to length. In multimode fibers, the impulse response is proportional to length [equation (21)], therefore

$$Fm = P_{max} \ell_{km} \tag{42}$$

For a typical step index fiber, Fm = 18 [equation (22)]. For a practical optimum graded index fiber, Fm = 833 [equation(25)]. For a transmission requirement of 10 Mb/s and 1-km length, the required $Fm = P\ell = 10$. Thus, the step index exceeds the requirement. The graded index fiber exceeds the requirement by nearly a factor of 100--a major overkill!

For the special case of a bandwidth-limited pulse, the material dispersion is proportional to $\sqrt{\ell}$. In this case (e.g., mode-locked laser source),

$$Fm = P_{max} \sqrt{\ell_{km}}. \tag{43}$$

Thus, the figure of merit [equation(1)] applies to optical fiber waveguides as well as to metallic cables. For multimode fibers, u = 1, and for single mode fibers with an optimum input pulse, u = 1/2.

The approximations presented here are useful in comparing the performance of different optical waveguides and in computing a figure of merit for a particular application. A corresponding figure of merit for available waveguides can be computed from manufacturers' specifications to determine the acceptability as a transmission medium for the particular application. These aproximations indicate that, for multimode distortion, the critical parameter values needed for comparing performance are the core index and a steady state NA. For strongly overmoded guides, the distortion is dominated by the NA of the guide. It is therefore important to know what effective NA was used in any measured bandwidth specified by the manufacturer.

5. TECHNOLOGY READINESS OF SUBSYSTEM COMPONENTS FOR OPTICAL FIBER INTERCHANGE CIRCUITS

Preceding sections of this report have dealt with analysis of optical fiber waveguide capabilities for meeting technical requirements for next-generation DTE/DCE interchange circuits. This section presents examples of commercial subsystem components that, based on manufacturer's specifications, fulfill these technical requirements.

Specific subsystem components addressed are optical fiber cables, optical transmitter modules, and optical receiver modules. Technical analyses of this report are specifically limited to the transmission medium which, for the optical regime, consists of the cabled optical fiber(s) and associated connectors. However, to characterize the optical fiber realistically, it is necessary to consider characteristics of commercial electro-optic transducers that constitute system interfaces to the optical cable. The transmitter and receiver modules consist of these transducers and the minimal electrical circuitry required for electrical interfacing to the DTE and DCE.

Performance data tabulated below for commercial hardware are taken directly from manufacturers' product data sheets. To ensure broad coverage of suppliers, a commercial survey of fiber optics manufacturers and vendors (Laser Focus, 1982) was used. A total of 72 suppliers was identified as marketing potentially applicable hardware; all were contacted for technical data. Many products represented by the above survey were not pertinent to interchange circuit application. The majority of those found pertinent did meet (and usually exceeded) the maximum requirements identified by this study.

These data were supplemented by contacting other vendors through trade journal advertisements and by contacts at major trade shows through spring 1982. Because the technical information obtained from foreign suppliers was inadequate for representing a broad cross section of foreign products, the tabulations contain performance data on only U.S.-manufactured cables and devices.

5.1 Optical Interchange Circuit Design Considerations

The transmission performance requirements of 10 Mb/s x 1 km for BER $\leq 10^{-9}$, chosen earlier in this report for analytic characterization of metallic and optical fiber interchange circuits, were used for evaluation of commercial optical hardware. These minimum performance limits have been based on current CCITT deliberations for ISDN User/Network Interface requirements (see Section 1.4). Both the preceding technical feasibilty analysis and the following survey of technology readiness indicate that communications-grade optical fibers can and do measurably exceed these selected values for the performance parameters. This frees the designer and user to select from various manufacturers and among numerous fiber configuration options, all of which offer the optical fiber's fundamental advantages of galvanic isolation and EMI isolation.

5.2 Commercial Optical Fiber Cables

The commercial optical fiber cables whose characteristics are shown in Table 6 were selected based on the following minimum requirements: 10 Mb/s transmission over 1 km with attenuation coefficient not to exceed 10 dB/km for the 800-900 nm spectral window. The minimum bit error rate specified for this study was omitted, because BER -- a specification for the electrical signal -- is not applicable to the optical transmission medium per se. (Bit error rate is addressed as a parameter for the optical subsystem, including transmitter and receiver, in the following section.)

All values shown in Table 6 are from (U.S.) manufacturers' published data sheets. Values are shown for bandwidth (MHz-km) rather than for bit rate (Mb/s), since the BW designation is employed by fiber and cable manufacturers, who typically use a sinusoidal waveform for measurement of optical pulse spreading to specify throughput bandwidth. Using the derivation of Section 4.4 of this report, maximum bit rate = 1.3 (3-dB BW).

Table 6. Representative, Commercial Optical Cable Characteristics

Mfgr./ Supplier (a)	Maximum Attenuation Coefficient α (b)	Core Diameter 2a	Minimum NA	Minimum BW (b)	Fiber Material (c)	Index Profile (d)
	(dB/km)	(μm)		(MHz-km)		
1	6	200	0.17	45	S	
2	4	50	0.20	100	S	G
11	4/850 nm 3/1300 nm	50	0.2	225	S	G
3	8	50	0.20	200	S	G
3	10	100	0.30	20	S	SG
11	5	50	0.2	400	S	G
4	4	50	0.2	200	S	G
4	7	100	0.3	20	S	SG
11	5/850 nm 4/1300 nm	50	0.20	500	S	G
8	10	200	0.3	20	PCS	SG
11	6/850 nm 5/1300 nm	100	0.28	100	S	G
8	6	200	0.4	20	PCS	SG
8	7	50	0.2	200	S	G
3	8	200	0.27	25	PCS	SP
9	6	80	0.30	200		SG
5	7	100	0.22	200	S	SG
7	8	200	0.33	10		
3	8	300	0.27	20	PCS	SP
8	10	100	0.3	20	S	PG
6	6	200	0.21	200	PCS	SP
10	6	100	0.20	100		

Notes:

a Codes for manufacturers/supplies are assigned randomly.

b Attenuation and BW for 850 nm unless otherwise specified in table.

c Fiber-material designation: S = all silica, PCS = plastic-clad silica.

d Index profile designators: G = graded index, SG = semigraded (partially graded) index, SP = step index.

The selection of a maximum value of 10 dB/km for attenuation coefficient is arbitrary. There is no standardization of values for 'high' or 'low' attenuation for cabled fibers, but there is a growing tendency in the literature to classify those with attenuation coefficients above 6 dB/km (for the 800-900 nm spectral range) as high-loss fibers (Hume, 1982). Most such categorization is in terms of long-haul trunking requirements, where maximum attenuation of approximately 3.5 dB/km (at 800 nm) for concatenated paths is highly desirable (op. cit.) to reduce repeater spacing. As indicated in the following section, simple, commercial transmitters and receivers are capable of operation with 10 dB/km (and even higher) fiber attenuation for 1-km paths. Thus, consideration of fibers with the higher attenuation permits broader user options for cost tradeoffs.

Among the product offerings of U.S. manufacturers, many optical fiber cables were identified that met the above broad requirements. In fact, only a few did not fulfill these requirements. The representative cables shown in Table 6 were selected, to minimize the size of the tabulation, using the following criteria:

(1) conformity with the minimum 10 Mb/s x 1 km, maximum 10 dB/km requirements,

(2) for each manufacturer, elimination of special-purpose cable options (e.g., armoring) for identical fiber configurations (all cables in the table are all-dielectric construction), and

(3) for each fiber configuration produced by a given manufacturer, selection of the lowest cost option. This often, but not always, resulted in fibers of higher attenuation.

Since all of the fiber cables in Table 6 -- and most of those surveyed -- meet or exceed requirements of this study, the user has many acceptable options among fibers with widely varying physical dimensions, numerical aperture, and attenuation coefficients. Most manufacturers represented in the table offer off-the-shelf cables with numbers of individual fibers compatible with various proposals for numbers of interchange circuits for the ISDN User/Network Interface.

The primary requirements for long-haul trunking -- appreciably higher bit rate x path length products and lower attenuations than required for this application -- have resulted in de facto preliminary standardization of graded index, 50 μm-core, low-attenuation fibers with an NA of approximately 0.2. These parameter values are useful also for the DTE/DCE interface, but are far from optimum for this short-haul application in terms of optical power acceptance (light-gathering) efficiency. Little attention has been given in the literature to characterizing fiber efficiency for short-haul links. An approach is presented here for comparison of fibers with various physical configurations. To make such comparisons, it is essential to have previously ascertained that all fibers under consideration are not bandwidth limited for the proposed application. The primary parameters of concern are:

- core radius, a relative measure of power acceptance efficiency that is proportional to fiber cross section, or radius squared,
- NA, the angular measure of acceptance efficiency, also a squared dependency, and
- attenuation coefficient, the measure of throughput efficiency.

To compare two different fibers characterized in terms of these three parameters, the term relative power throughput, PO, is used for the optical power level at the fiber's exit end:

$$\frac{PO_n}{PO_r} = 10 \log \left[\frac{(NA_n)^2 \ (a_n)^2 \ (10^{-\alpha \ell/10})_n}{(NA_r)^2 \ (a_r)^2 \ (10^{-\alpha \ell/10})_r} \right]$$

where PO_r = the optical power available at output end of the fiber of the last row in Table 7, normalized to 0 dB to permit presentation of values in dimensionless units,

PO_n = power at output end of any other fiber,

NA = fiber numerical aperture,

a = fiber core radius in μm,

α = fiber attenuation coefficient in dB/km,

ℓ = path length in km,

subscript_r = arbitrary reference fiber, and

subscript_n = any other fiber, for comparison purposes.

The above expression is empirical, but it does serve to form a basis for comparison among dissimilar fibers. The power throughput value for cable No. 19 of Table 7 was arbitrarily normalized to 0 dB to permit presentation in that table of relative values in dimensionless units.

Table 7. Relative Power Throughput for Representative, Commercial Optical Cables

	Mfgr./ Supplier	NA (Low Wavelength Window)	Core Diameter 2a	Attenuation Coefficient α	Relative Power Throughput (See Text)
			(μm)	(dB/km)	(dB)
1	8	0.4	200	6	20
2	3	0.27	300	8	18.2
3	6	0.3	200	6	17.6
4	7	0.33	200	8	16.4
5	3	0.27	200	8	14.6
6	8	0.3	200	10	13.6
7	1	0.17	200	6	12.6
8	11	0.28	100	6	10.9
9	4	0.3	100	7	10.5
10	9	0.3	80	6	9.6
11	10	0.2	100	6	8.0
12	5	0.22	100	7	7.8
13	3	0.3	100	10	7.5
14	8	0.3	100	10	7.5
15	2	0.2	50	4	4.0
16	4	0.2	50	4	4.0
17	11	0.2	50	5	3.0
18	8	0.2	50	7	1.0
19	3	0.2	50	8	0 (Arbitrary Reference)

Note:
Above cables are from Table 6. In all cases, manufacturers' published bandwidth exceeds requirements for this study.

This reference fiber, with 50-μm core and NA of 0.2, represents a typical design for high-bit-rate, long-haul trunking applications, even though the attenuation of 8 dB/km is relatively high. It is seen from row 2 of Table 7 that a fiber of 300-μm core, the same attenuation coefficient, and similar NA yields an 18.2 dB increase in power throughput efficiency -- almost exclusively due to the increase in core size. The 200-μm-core fiber of row 1 offers 20 dB relative efficiency improvement with its very large NA of 0.4 and attenuation of 6 dB/km.

Numerous similar tradeoffs are possible for the various fiber design configurations of Table 7. Transmission at 10 Mb/s for a 1-km path is a modest requirement for optical fibers, permitting use of large cores and NA's, thus relaxing attenuation requirements. Costly, premium-grade fibers with ultra-low losses are not required for interchange circuit applications. The high relative throughput efficiency of large-core, large-NA fibers of moderate loss is of paramount importance in establishing optical power values for the interfaces between the transmission line and optical source and detector. Use of high-efficiency fibers will permit cost tradeoffs involving optical transmitters of reduced power output and receivers of modest sensitivity as compared to that required for coupling to fibers designed for long-haul trunking.

Caution must be exercised, however, in making such comparisons, to ensure that the manufacturer's stated value for NA is for measured, steady-state NA -- not a value calculated from core and cladding indices. This is especially important for large NA's, where radiation losses and mode mixing of higher-order modes typically result in considerable -- often drastic -- decrease in steady-state values, as compared to calculated (acceptance) values. For example, manufacturers' data for some fibers with a calculated NA of 0.4 indicate a steady-state value of 0.27, measured at 0.5 km.

For Table 7, manufacturers' values for NA have been used, assuming measured data. Analysis of bandwidth capabilities of those fibers indicates that, in some cases, the assumption may have been incorrect. This emphasizes the need for standardized measurement conditions to provide the user with adequate information for comparability among various fiber designs as well as among various manufacturers' products.

One factor that has been ignored in the approximations of the above comparisons is the difference in collection efficiency between otherwise-similar step index and graded index fibers. For the same NA and core diameter, the step index design accepts approximately 3 dB more optical power than does the graded index fiber (which offers approximately an order of magnitude higher bandwidth). (Collection efficiency of the semigraded fiber lies between that of the graded and step index designs.) Thus step index fibers, which tend to be less expensive, are viable alternatives for the proposed 10 Mb/s x 1 km application.

This study has not addressed fiber-to-fiber coupling (connectors, bidirectional couplers, or splices), primarily because it has assumed an uninterrupted, point-to-point transmission link. Such a line, however, will be end-connected, quite probably to optical source and detector fiber-pigtails. And, realistically, the user must not be prohibited from using intermediate connections with other fiber cables. In addition to mechanical considerations (e.g., fiber-to-fiber alignment, core and cladding dimensions), index profile is an important intrinsic coupling-loss parameter for all such connections.

To minimize coupling losses resulting from mating fibers having non-identical index profiles, one must assure, in some way, that profiles of the mating fibers are similar. For the step index design, this should prove to be relatively straightforward, such as specification of $\pm$ deviations in index over a stated percentage of fiber core diameter. For the graded index design, index specification is more complex. As an alternative approach, one might consider specification of fiber bandwidth to a (high) level such that a nominally parabolic profile would be required. This will result in minimizing coupling losses (private communication, G. Day).

For the proposed requirements of this study, the step index profile offers adequate bit rate x path length product, provides improved collection efficiency over the graded index design, and is more amenable to coupling standardization which should yield minimal and predictable throughput coupling losses.

5.3 Commercial Optical Transmitter/Receiver Modules

To ascertain technology readiness of optical fiber hardware for DTE/DCE interchange circuits, it was necessary to investigate commercial availability of transmitters and receivers for interfacing to the optical cable. Commercial U.S. products were identified by the process described above for optical cables.

Two broad types of hardware were identified on the U.S. market as of spring 1982:

(1) Optical links, consisting of relatively sophisticated transmitter and receiver packages including multiplexers/demultiplexers designed to time-multiplex various numbers of electrical channels over a single optical fiber in each direction, usually for a 1-km path. Electrical compatibility is typically for RS-232-C, with V.24 as an option. Specified optical cables and connectors constitute a part of the system's packaging.

(2) Relatively simple transmitter and receiver modules, consisting of electo-optical transducers and the minimal electrical circuitry required for TTL electrical interfacing compatibility. Package size is as small as 43.4 mm x 16.5 mm x 7.9 mm. Matched transmitter and receiver (and one transceiver model) modules are specified for mating to fibers of one or more geometries, and are available with or without the optical cable.

Commercial availability of the former, more sophisticated RS-232-C/V.24 links for DTE/DCE interconnection shows technology readiness of optical fiber subsystems. Specifications of the latter more simple transmit/receive modules, however, are more amenable to a subsystem analysis to indicate how fiber geometry variables affect power throughput.

Values for performance parameters of concern to this study are given for commercial transmit/receive modules (type 2 above) in Table 8. All data are from published manufacturers' data sheets. Those few models which did not meet minimum requirements of 10 Mb/s transmission over a 1-km path at BER $\leq 10^{-9}$ have been deleted from the tabulation. All transmitters employ LED optical sources and all receivers use PIN photodiodes, operating in the 800-900 nm spectral range. These transducers are far less expensive than the higher power injection laser diode (ILD) sources and higher sensitivity avalanche photodiode (APD) detectors. Since manufacturers' specifications for the LED/PIN modules prove adequate for 1-km interchange circuits, for a broad spectrum of commercial optical cables, modules using ILD/APD combinations have not been considered for this application. The best-case receiver sensitivity (Table 7) of -40 dBm may be compared to the ideal theoretical sensitivity of -51 dBm for a PIN photodiode operating at 10 Mb/s for BER = 10^{-9} (Personick, 1973).

Table 8 (Sheet 1 of 4). Digital XMTR/RCVR Modules for Optical Transmission (dc to Min 10 Mb/s) Over One Kilometer at BER $\leq 10^{-9}$

Module Type	Bit Rate or BW	Optical Power: XMTR: Max. Output dBm (μW)	Optical Power: XMTR: At Specified Fiber-Coupling Parameters	Optical Power: RCVR: Threshold for BER $\leq 10^{-9}$ dBm (μW)	Reference Code: Mfgr./Model
XMTR	0-25 MHz Manchester	-7 (200) Output NA 0.48	Typ. 200 μm-core fiber		I
RCVR	0-25 MHz			-31 (0.9)	I
XMTR	dc-20 Mb/s NRZ	-11 (79)	Into 200 μm-core fiber		J
RCVR	dc-20 Mb/s NRZ			-27 (2)	J
XMTR	dc-55 Mb/s NRZ	-4.9 (320) -6.5 (220) -14 (40)	Into 300 μm-core, NA = 0.22 (SI) Into 200 μm-core, NA = 0.36 (SI) Into 100 μm-core, NA = 0.22 (GR)		A
RCVR	dc-42 Mb/s NRZ			-28.2 (1.5) at 0-20 Mb/s, NRZ	A
Transceiver	dc-20 Mb/s NRZ	-17 (20)	Into 50 μm-core, NA = 0.20		L
	dc-50 Mb/s NRZ			-35 (0.32)	L

Table 8 (Sheet 2) continued

Module Type	Bit Rate or BW	Optical Power: XMTR: Max. Output dBm (μW)	Optical Power: XMTR: At Specified Fiber-Coupling Parameters	Optical Power: RCVR: Threshold for BER $\leq 10^{-9}$ dBm (μW)	Reference Code: Mfgr./Model
XMTR	dc-50 Mb/s NRZ	-7 (200)	Into 200 μm-core, NA = 0.36		H
RCVR	dc-50 Mb/s NRZ			-23 (5)	H
XMTR	dc-20 Mb/s NRZ	-4 (400)	Into 200 μm-core, NA = 0.3		P
RCVR	dc-20 Mb/s NRZ			-27 (2)	P
XMTR	0-32 Mb/s NRZ	0.75 W/ steradian/ cm^2 for 300 μm source (microlensed)	19 dB link budget for 200 μm-core, NA = 0.3, including input coupling losses		B
RCVR	0-32 Mb/s NRZ			-31 (0.75)	B
XMTR	dc-25 Mb/s NRZ	-8 (160)	Into 100 μm-core, NA = 0.3		C
RCVR	dc-25 Mb/s NRZ			-24 (4)	C

Table 8 (Sheet 3) continued

Module Type	Bit Rate or BW	Optical Power			Reference Code: Mfgr./Model
		XMTR		RCVR	
		Max. Output	At Specified Fiber-Coupling Parameters	Threshold for BER $\leq 10^{-9}$	
		dBm (μW)		dBm (μW)	
XMTR	dc-20 Mb/s NRZ	-13 (50) pigtail output			F
RCVR	dc-20 Mb/s NRZ			-33 (0.5)	F
XMTR	dc-20 Mb/s NRZ	-16 (25) pigtail output			G
RCVR	dc-20 Mb/s NRZ			-33 (0.5)	G
XMTR	dc-50 Mb/s NRZ	-3.5 (450)	Into 200 μm-core, NA = 0.22		D
RCVR	dc-50 Mb/s NRZ			-20 (10)	D
XMTR	dc-10 Mbd NRZ	-10.7 (105) pigtail output 100 μm, NA = 0.3	Into 100 μm-core, NA = 0.3		M
RCVR	dc-10 Mbd NRZ			-40 (0.1)	M

Table 8 (Sheet 4) continued

Module Type	Bit Rate or BW	Optical Power			Reference Code: Mfgr./Model
		XMTR		RCVR	
		Max. Output	At Specified Fiber-Coupling Parameters	Threshold for BER $\leq 10^{-9}$	
		dBm (μW)		dBm (μW)	
XMTR	dc-20 Mb/s NRZ	-8 (160) pigtail -14 (40) pigtail	Into 100 μm-core, NA = 0.3 Into 50 μm-core, NA = 0.21		O
RCVR	dc-20 Mb/s NRZ			-27 (2)	O
XMTR	dc-20 Mb/s NRZ	-13 (50) pigtail -17 (20) pigtail	Into 100 μm-core, NA = 0.3 Into 50 μm-core, NA = 0.21		N
RCVR	dc 20 Mb/s NRZ			-27 (2)	N

Optical fiber specifications of Table 8 are quoted from module manufacturers' data. Availability of this type of data, giving optical power coupled into a specified fiber geometry, reflects the growing maturity of fiber optics hardware and consequent providing of information in a form that is readily meaningful to the user. The LED, in its simplest physical form, approximates Lambertian emission as an optical source, and its output is typically expressed in watts per steradian per square meter, the units for the radiometric term 'radiance'. Using such values to compute the amount of power that can be coupled into a fiber of specified core diameter and NA can be an interesting exercise. Recently, manufacturers have made available transmitter assemblies that employ various techniques for optimizing LED-source-to-fiber coupling, and now typically quote values for power coupled into a specified fiber, rather than leaving that problem to the systems designer/user.

The modules listed in Table 8 use various such coupling techniques, which include integral fiber pigtails (short fibers, usually proximity-butted to the LED), micro lenses, and custom-shaped emitting areas of the LED -- or combinations of these. This permits the specification of optical output in engineering terms of power coupled into a specific fiber geometry.

5.4 Power Budget Examples for Commercial Fiber Optics Subsystem Components

The preceding sections have given characteristics of commercial optical fiber cables and transmit/receive modules whose specifications meet requirements of this study. Table 9 presents some examples of power throughput, using manufacturers' data, for several combinations of these modules and fibers. The table was compiled in the following manner:

- Each column gives data for a matched transmitter/receiver module pair by a common manufacturer. Values for transmitter output (row III) and receiver threshold sensitivity (row VIII) are from manufacturers' data sheets. All transmitters use LED's, and all receivers employ PIN photodiodes.

- Fiber geometry parameters (rows I and II) are those specified by module manufacturers for transmitter output coupling.

- Attenuation values for row IV are the lowest values for the above specified geometries, from Table 6 (<u>not</u> the lowest available).

- For row VI, the 2-dB coupling losses (including connectors and fiber-end Fresnel losses) and 3-dB long-term system degradation losses are arbitrary but reasonable.

Table 9. Optical Power Budgets for Commercial Digital XMTR/RCVR Pairs as Function of Commercial Optical Cable Parameters (Transmission Conditions: dc to Min. 10 Mb/s (NRZ) Over 1 Kilometer at BER ≤ $^{-9}$)

	Unit															
I Fiber Core Diameter	µm	50		100					200							300
II Fiber NA	--	0.20-0.22		0.30					0.21 -0.22	0.30			0.33-0.36		0.40	0.22
III Max. XMTR Optical Power Coupled into Fiber	dBm	-14	-17	-10.7	-14	-8	-13	-16	-3.5	-2	-11	-4	-6.5	-7	-5.5	-4.9
IV Cabled-Fiber Attenuation (for 1 Km)	dB	3		7					6	10					6	8
V Optical Power Out of 1-Kilometer Cable	dBm	-17	-20	-17.7	-21	-15	-20	-23	-9.5	-12	-21	-14	-16.5	-17	-11.5	-12.9
VI Coupling Losses (2 dB) & Degradation Budget (3 dB)	dB	5		5					5							5
VII Max. Optical Power Available at RCVR	dBm	-22	-25	-22.7	-26	-20	-25	-28	-14.5	-17	-26	-19	-21.5	-22	-16.5	-17.9
VIII RCVR Threshold	dBm	-28.2	-35	-40	-27	-24	-33	-33	-20	-31	-27	-27	-28.2	-23	-31	-28.2
IX Excess Power Margin for Above Configuration	dB	6.2	10	17.3	1	4	8	5	5.5	14	1	8	6.7	1	14.5	10.3
IX Matched XMTR/RCVR Mfgr.	--	A,O	L,N	M	J	C,O	F,N	G	D	B	J	P	A	H	I	A

- Subtraction of the above losses from transmitter output values of row III gives optical power available at output of the 1-km interchange circuit, in row VII. Comparison of these power levels with the receiver thresholds of row VIII yields the excess power values of row IX, which are seen to range from 1 to 17.3 dB above levels required for individual receivers.

It may be concluded from the data of Table 9 that there exist numerous combinations of commercially available optical fiber cables and relatively simple transmitter and receiver modules that meet proposed requirements for DTE/DCE interchange circuits. These requirements are modest for the tabulated subsystems. As seen from Table 9, all fiber/module combinations yield excess power margin, and use of lower-loss cables would permit increasing all of these values. With one exception, the transmitter/receiver pairs are rated for maximum channel capacities ranging between 16 Mb/s and 50 Mb/s, for bit error rates from 10^{-9} to 10^{-15} over 1 kilometer. For operation at 10 Mb/s, quality of performance of those devices will be proportionately better. Since interface standards do not yet exist, matched transmitters and receivers must be purchased from a common manufacturer.

5.5 Summary

The preceding discussion documents commercial availability of numerous options among optical fiber cables and optical transmitter/receiver modules whose performance meets or exceeds interchange circuit requirements compatible with proposals for the ISDN User/Network Interface. The data of Table 8 above do not constitute results of a system design study, but rather an indication of what can be accomplished with user-option combinations of off-the-shelf hardware. None of these combinations is recommended for the DTE/DCE application, but all should work, meeting or exceeding proposed minimum requirements. The optimum subsystem for this application has not been designed. Until standards are developed to specify both optical and electrical interfaces, the user must procure transmitters and receivers from the same manufacturer to ensure compatibility. The user must also procure optical cable that meets coupling geometry and attenuation specified by the transmitter/receiver manufacturer.

Sections 1 and 2 above indicate the strong CCITT preference for the two-interchange-circuit approach for the ISDN User/Network Interface, with time-multiplexed data, control, and timing signals. A two-fiber optical cable, one of the most common commercial configurations, meets this requirement, providing a single fiber for all information transfer in each direction. This approach is typically used in off-the-shelf optical fiber links offering serially multiplexed transmission of RS-232-C- and V.24-compatible channels. Various other multifiber cable configurations are available.

Optimum fiber-per-cable efficiency is achievable by using a single fiber for bidirectional transmission. This full duplex, one-interchange-circuit concept can be achieved using optical wavelength division multiplexing (WDM). In WDM, multiple optical signals are transmitted simultaneously and independently, at different optical wavelengths, over a single fiber. Improved attenuation of fibers at wavelengths out to $\lambda \simeq 1.5$ µm permits use of several low-loss optical 'windows' for WDM. The complexity of WDM results from requirements for optical multiplexing and demultiplexing, using reflective, dispersive, or refractive equivalents of optical beam splitters to insert and extract the distinct optical signals.

Considerable laboratory work has been devoted to advanced WDM technology (Campbell et al., 1980 Fitch et al., 1982; Nicia, 1981; Aoyama and Minowa, 1979; and Watanabe and Nosu, 1980). Some commercial WDM couplers, operating at multiple wavelength bands between 0.8 and 1.4 µm, are available. At present, the WDM concept is too complex and too costly to be viable in the tradeoff of one-fiber cable versus two-fiber cable for the DTE/DCE interchange circuit application. Continuing advances, possibly including highly efficient optical integrated circuits, may well prove WDM bidirectional interchange circuits to be feasible in the long term.

6. SUMMARY AND CONCLUSIONS

Attention is being focused by CCITT working groups on the development of a User/Network Interface (which specifies equivalents of the DTE/DCE interface) to be used as part of the international standards for the ISDN. This interface is to be simple, with a minimum number of circuits, and must be capable of supporting bit rates of nB+D where n is an integer for which all values are not yet defined. B is the 64,000 bit per second PCM voice channel sampling rate and D is a 16,000, 32,000, or 64,000 bit per second signaling and control channel. For the Basic ISDN User/Network Interface, n is to be 2. For the Primary Interface (DS-1 multiplexing level), n will be 23 for North America and 30 for Europe. Some documents indicate that n could be 100 or more for some applications. Other documents indicate that n may be a flexible number based on user needs.

Distances to be supported by the interface are yet not standardized but position papers indicate that although 250 to 300 meters may cover most applications, it is desirable to extend the coverage to 1 to 2 kilometers for applications in campus-type building complexes. Other important factors under consideration in this interface development include need for low signaling power, high common-mode rejection capability, possible power-feeding arrangements, galvanic isolation of interconnected equipment, and support of passive bus arrangements.

The high-bit-rate x long-distance requirement supportable by the interface is ultimately limited by the transmission medium in the absence of repeaters and/or specialized compensation. High-bit-rate performance of metallic transmission lines (coaxial cable and wire pairs) is limited by skin effect impedance. Pulse broadening is caused by the frequency dependence of this impedance. This pulse broadening causes overlap of successive pulses with consequent failure of the receiver to distinguish between the presence or absence of a pulse. This increases the bit error rate (BER) above an acceptable value. The resultant upper bit rate for a required BER is proportional to the square of the length of the transmission line. A useful performance requirement for a given application is the maximum bit rate x $(\text{length})^2$ product.

A figure of merit (constant) for metallic transmission lines is derived based on physical parameters or on measured attenuation coefficient at a known frequency. This figure of merit must exceed the performance requirement to assure satisfactory application of a specific transmission line. Representative commercial cables and twisted wire pairs are characterized in accordance with this figure of merit. The conclusion reached is that coaxial cable can support a bit rate of 10 Mb/s over a distance of 1 km only if it is approximately 1 cm or greater in diameter. Such cable is relatively costly, and its use for multiple interchange-circuit applications presents sometimes severe mechanical installation problems (e.g., in-duct pulling). Also, a nominal twisted wire pair will support about 1 Mb/s over 1 km (without special compensation). These performance limits can be extended by use of amplifiers with special frequency compensation.

High-bit-rate-performance in multimode optical fiber waveguides is limited by pulse broadening caused by differential mode delay (difference in transit time for arrival of different modes). The broadened pulses may overlap succeeding pulses with consequent degradation of receiver performance as in the case of metallic transmission lines. The upper bit rate limited by pulse broadening is proportional to the length of the waveguide.

Engineering approximations based on referenced publications are used to develop characteristic maximum bit rate (bandwidth) performance descriptors of step index and graded index optical fiber waveguides. The desired parameter for determining the maximum pulse rate for a particular fiber is the rms impulse response width. This maximum rate is relatively independent of the shape of the input pulse for properly designed receivers, provided the pulse rate is limited to the reciprocal of 4 times the impulse response width. An approximation for calculating the multimode impulse response width based on the index profile parameter, core refractive index, and the refractive index contrast is used to show the relative pulse rate limitations of step index and graded index fibers. Approximations for calculating material dispersion of representative fiber core material are used to show that, for relatively broad spectral sources, material dispersion is proportional to the length of the waveguide. For spectrally very narrow sources and for input pulse duration equal to the duration of the material dispersion, the resultant limiting pulse rate is proportional to the square root of the length of the waveguide.

A step index, quartz core fiber with a refractive index contrast ratio of 0.01 will permit a maximum pulse rate of ~ 18 Mb-km/s in accordance with the calulated impulse response width. This assumes operation in the 840 nm wavelength (LED) region. Practical increases up to a factor of 50 appear to be possible through proper control of the index profile (graded index fiber). In the future, longer wavelength (1300 or 1500 nm) single mode fibers will be available with suitable driver and receiver circuitry. The bandwidth of such fibers would be limited by the material dispersion properties. Such single mode waveguides will permit Gb-km/s capability and would generally not be needed for interchange circuits.

Manufacturers' specifications sheets frequently provide the frequency at which the optical power is reduced by a factor of 2 from zero frequency. This $f_{(3-dB)}$ bandwidth multiplied by the impulse response width is a constant for a given impulse response shape. This constant is obtained from the literature for gaussian shaped impulse response. A relationship between maximum pulse rate and $f_{(3-db)}$ optical bandwidth is derived for guides with gaussian shaped impulse response characteristics. An approximation is derived which relates

$f_{(3-db)}$ bandwidth to an equivalent rise time. This approximation is sometimes used to characterize fiber bandwidth in calculating overall system rise time.

A survey of commercially available hardware (U.S. manufacturers only) was made to assure the technology readiness of fiber optic transmission media -- including transmit and receive modules. A summary of this survey is presented. Multifiber optical cables with outside diameters as small as 0.05 cm, useful for implementing multiple interchange circuits, will facilitate mechanical installations.

Optical fiber waveguides represent an alternative transmission medium for multimegabit rates over 1-kilometer distances. This medium provides galvanic isolation and freedom from electromagnetic interference.

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APPENDIX: FIRST- AND SECOND-GENERATION DTE/DCE INTERFACE STANDARDS

A.1. Terminology and Definitions

This report is concerned with transmission media for physical interconnection of digital equipment at the interface between Data Terminal Equipment (DTE) and Data Circuit-Terminating Equipment (DCE) - the DTE/DCE interface. The term 'DTE', as historically used, includes digital computers and peripheral digital data processing equipment such as terminals and printers. In the evolution toward definition of requirements for all-digital transmission, within international standards organizations, 'DTE' essentially encompasses all user (customer-premise) equipment for services such as digital data, telephone, video, and facsimile, and information-providing services (e.g., Videotex and Teletext). As a result of this evolutionary process, 'DTE' is no longer limited to a description of a single module of user equipment (e.g., computer or terminal device), but may be an enhanced PABX or local area network.

Historically, 'DCE' meant the modulation/demodulation device (modem) employed to interface digital devices to analog transmission networks, modulating the digital bit stream into a quasi-analog signal format compatible with analog tranmission, and the inverse at the receiver end. This definition has also become more inclusive, now encompassing all devices designed for DTE/network access, e.g., multiplexers, concentrators, and front-end processors. Equipment providing digital-to-digital interconnection, as well as conventional digital-to-analog/analog-to-digital signal conversion, are included.

In early DTE/DCE standards, 'DCE' was used to mean Data <u>Communication</u> Equipment. This sometimes-ambiguous usage is now obsolete. A U.S. standards organization has recently proposed (EIA, 1982) that the present designation for DCE, Data <u>Circuit-Terminating</u> Equipment, be further modified to <u>Digital</u> Circuit-Terminating Equipment, and the DTE be designated <u>Digital</u> Terminal Equipment to reflect the evolution toward a future all-digital environment. This proposal has not as yet been approved.

The DTE/DCE interface applies to the physical interconnection of equipment in terms of requirements of the Physical Layer (Layer 1) of the Open Systems Interconnection (OSI) reference model (ISO, 1980) of the International Organization for Standardization (ISO). The term 'interchange circuit' refers to a physical transmission element between DTE and DCE. This physical element may be a single metallic conductor (for electrically unbalanced circuits, where the common return lead is considered a distinct interchange circuit), a metallic twisted-wire pair, coaxial cable, or an optical fiber waveguide. Since no ground is required in the optical regime, balanced/unbalanced transmission is not meaningful and, for example, a single optical fiber may replace a pair of metallic conductors.

For interfaces employing multiple, parallel interchange circuits (one transmission element -- e.g., one metallic conductor -- for each function), there exists a one-to-one relationship between the number of DTE/DCE functions and the total number of physical interchange circuits (for existing standards, as many as 37 plus an optional 9). This is no longer so for the evolving serial interfaces which will employ time division multiplexing to transmit many functions on a few physical interchange circuits. The actual number of interchange circuits to be employed for third-generation DTE/DCE interfaces is a current topic of intensive study by standards working groups (see discussion of Section 1.4). The minimum (and desired) number under consideration is a total of two interchange circuits -- one in each direction (CCITT 1982).

A.2. First-Generation DTE/DCE Interface Standards: 1960's

In the early 1960's, growth of distributed peripheral equipment (e.g., digital terminals) interconnected to centralized computer centers, over analog telephone networks, resulted in an environment that forced development of the first DTE/DCE interface standards. Technical Committee TR-30, Data Transmission (established in 1962), of the U.S. Electronic Industries Association (EIA), developed the first U.S. interface standard, EIA RS-232: 'Interface Between Data Terminal Equipment and Data Communication Equipment Employing Serial Binary Data Interchange.' The revision of this standard, RS-232-C, officially adopted in August 1969, has since been the dominant physical interface standard in the U.S. data communications industry. Despite limitations for today's requirements (see following discussion and Section 1.4) its use is expected to continue, where applicable, for a number of years because of its ubiquitous implementation in operational equipment.

The international equivalent of EIA RS-232-C was adopted in 1964 by the International Telegraph and Telephone Consultative Committee (CCITT) as Recommendation V.24 (amended in subsequent study periods). 'Equivalent' standards as shown in Table A-1 may vary in relatively minor detail. United

Table A-1. Comparison of International and U.S. DTE/DCE Interface Standards (OSI Physical Layer)

A. INTERNATIONAL STANDARDS							
CCITT Recommendations	Physical Interfaces	X.21 bis				X.21[1]	
	Signaling Rate	max. 20 kb/s	to 100 kb/s	(V.35) 48 kb/s	(V.36) 48, 56, 64 72 kb/s	to 100 kb/s	to 10 Mb/s
	Electrical Characteristics	V.28	V .10 (X.26)	V.28[2]	V.11 (X.27) Option: V.10 (X.26)	X.26 [3] X.27	X.27
	Functional Characteristics	V.24	V.24 revised	V.24[2]	V.25 revised	X.24	X.24
ISO Standards: Mechanical Characteristics		2210[4]	4902[5]	2593[6]	4902	4903[7]	4903
B. EQUIVALENT U.S. STANDARDS							
EIA Standards		RS-232-C	RS-449 RS-423-A	No Equivalent U.S. Standards. V.35 Used for 56 kb/s Wideband Modems	RS-449 RS-422-A	RS-449[8,9]	RS-449 [8,9] RS-422-A
Federal Standards		None	1031 1030-A		1031 1020-A	None	

Notes:

1. No equuivalent U.S. standard.
2. A hybrid configuration: control circuits use V.28 (RS-232-C) electrical characteristics (unbalanced); functional characteristics of data interchange circuits are defined by V.24 (RS-232-C) but are balanced electrically.
3. To 9.6 kb/s: DTE uses X.26 or X.27 (with or without cable termination in the load); DCE must use X.27 (See ISO 4903 for mandatory pin wiring). >9.6 kb/s: Both DTE and DCE must use X.27 (with cable termination in the load).
4. 25-pin Type "D" connector (RS-232-C).
5. 37-pin Type "D" connector (RS-449) plus optional 9-pin "D" connector for secondary channel.
6. 34-pin Type "D" connector.
7. 15-pin Type "D" connector (no operational U.S. equivalent).
8. To 9.6 kb/s: DTE uses RS-423-A or RS-422-A; DCE must use RS-422-A. >9.6 kb/s: Both DTE and DCE must use RS-422-A.
9. Equivalency for electrical characteristics only; no U.S. equivalent for X.24 or 4903, above in table.

On terminology: The CCITT "V" series of Recommendations applies to "data transmission over telephone networks;" the "X" series applies to "data transmission over public data networks."

States DTE/DCE standards are, with some recent exceptions, stand-alone documents, as is EIA RS-232-C. By comparison, international specifications are typically composed of multiple documents. As shown in Table A-1, Recommendation V.24 specifies DTE/DCE functional characteristics, while Recommendation V.28 (adopted in 1972) specifies electrical characteristics, and ISO International Standard 2110 gives mechanical characteristics. This separation of reponsibilities between CCITT and ISO is by charter. The aggregate of these three documents constitutes the equivalent of RS-232-C. The CCITT 'V' series of Recommendations applies to data transmission over telephone networks and the 'X' series applies to data transmission over public data networks (CCITT, 1976). Beginning in the mid-1970's, CCITT working groups developed interface Recommendations with the intent of both 'V' and 'X' applications. These are referenced in Table A-1, as, for example, 'V.11 (X.27),' indicating that the two documents are identical. A new 'I' series of Recommendations has been initiated for the ISDN.

Separate interchange circuits, i.e., physical wires, are used in the RS-232-C interface (and the equivalent CCITT V.24) to enable performance of individual functions. All circuits are unbalanced, and a 25-pin connector is required. Basic operating limitations of RS-232-C include:

- restricted bit rate x path length product: maximum signaling rate of 20 kb/s over DTE/DCE cable length of 15 meters, using metallic twisted-wire pairs,

- both noise generation and noise susceptibility as the result of the unbalanced signaling technique (a single wire per interchange circuit and a common return),

- insufficient circuit capacity to control additional functions such as loopback testing for system fault isolation, and

- lack of user assurance that devices from various manufacturers are compatible, even though the RS-232-C interface is specified. This results from the proliferation of incompatible mechanical interface designs, hardware inclusion of nonstandard interface circuits with arbitrary pin assignments, and inconsistent uses of functional control circuits. Systems interoperability thus suffers. In a literal sense, these latter limitations may be termed <u>misuse</u> of RS-232-C, but they typically reflect designers' efforts to adapt the interface to new and more demanding applications for which it is no longer adequate.

The only other basic DTE/DCE interface standard developed during the 1960's was CCITT Recommendation V.35, for 48 kb/s service. (An exception is

CCITT V.25 on automatic calling.) As indicated in Table A-1, V.35 is a hybrid configuration employing a mix of existing CCITT and ISO specifications. There is no equivalent U.S. standard, but V.35 has been adopted domestically as a de facto standard for wideband modems at the slightly higher signaling rates of 50 and 56 kb/s.

A.3. Second-Generation DTE/DCE Standards:

In the early 1970's, U.S. and international standards organizations began intensive efforts toward development of new DTE/DCE interface standards in response to the recognized limitations of EIA RS-232-C and CCITT V.24. New telecommunications requirements had developed for relatively error-free data transmission at higher bit rates, over longer interchange cable lengths, and for more efficient compatibility with integrated circuit technology.

The first of several second-generation standardized DTE/DCE interfaces developed with these targeted goals was CCITT Recommendation X.21, initially adopted in 1972. Maximum bit rate x path length product was increased to 10 Mb/s x 10 meters (or 200 kb/s x 1000 meters), and integrated circuit technology was exploited for the first time. The interchange-circuit-per-function approach of RS-232-C and V.24 was replaced with a character-oriented control procedure which yields higher interchange circuit efficiency by means of coded characters to execute multiple functions over a single physical circuit. This technique reduces the number of pin connectors to 15 from the 25 required for RS-232-C and V.24.

Recommendation X.21 was developed for improved user access to circuit-switched public data networks -- prior to the widespread implementation of packet switching technology by data networks in the late 1970's and early 1980's. Synchronization protocol of X.21 is not compatible with X.25, the CCITT Recommendation for packet-switched data networks (Folts, 1981), which was initially adopted in 1976 and is rapidly growing in use worldwide. There has yet been little implementation of X.21 (Yanoschak, 1981) in spite of its improvements over first-generation interfaces. No equivalent U.S. standard has been adopted, although second-generation U.S. standards are electrically compatible (see Table A-2).

The second-generation U.S. standard for functional specification of the DTE/DCE interface is EIA RS-449 (development, begun in 1972, culminated in 1977 adoption):

Table A-2 (Sheet 1 of 3). Basic Characteristics of U.S. and International DTE/DCE Interface Standards (OSI Physical Layer)

U.S. Standard	EIA RS-232-C	EIA RS-449 Two options for various interface circuits and data rates EIA RS-423-A	EIA RS-449 Two options for various interface circuits and data rates EIA RS-422-A
Max. Data Rate/Max. DTE-DCE Cable Length	20 kb/s 15 meters	100 kb/s[1]/13 meters 3 kb/s/1200 meters[3]	10 Mb/s/13 meters[2] 100 kb/s/1200 meters[3]
Circuit Configuration	Unbalanced	Unbalanced Circuits, Balanced Receiver	Fully Balanced
Transmission Quality	Degraded by Noise Pickup Due to Unbalanced Circuits	Improved Noise Performance Due to Balanced Receiver; Approaches Balanced Circuit Performance	Outstanding Noise Performance Resulting from Fully Balanced Circuits
Connectors	25-Pin "D" Type	37-Pin "D" Type + Optional 9-Pin "D" Type (Option for Secondary Channel Operation)	
Comments	Most Widely Used Interface; Transmission Performance Inadequate for many New Applications	Backward Compatibility with EIA RS-232-C Facilitates Evolutionary New Technology Accommodation	Receiver Identical to RS-423-A
EIA Standards Compatibility	RS-423-A[5,6]	RS-232-C[5,6] RS-422-A	RS-423-A
Federal Standard Counterparts	None	1031/1030-A	1031/1020-A

Notes:

1. Can be increased to several hundred kb/s, using good engineering practices (per the Standard).
2. Can be increased to tens of meters, using good engineering practices.
3. Can be increased to several kilometers, using good engineering practices.
4. Control circuits are CCITT V.28 (unbalanced); data interchange circuits are functionally defined by CCITT V.24, but are balanced.
5. Only if correct (optional) RS-449 circuitry is specified by equipment manufacturer.
6. See EIA Industrial Electronics Bulletin number 12 for RS-232-C/RS-449 interfacing.

Table A-2 (Sheet 2 of 3)

CCITT Recommendation	X.21 bis			
	Four options for various interface circuits and data rates			
	CCITT V.24/V.28	CCITT V.10 (X.26)	CCITT V.35/V.28	CCITT V.36/V.11 (X.27)
Max. Data Rate/Max. DCE/Cable Length	20 kb/s/not Specified, but Equivalent to EIA RS-232-C	100 kb/s[1]/10 meters[3] 3 kb/s/1000 meters[3]	48 kb/s only/not Specified	48, 56, 64, 72 kb/s only/10^{-7} BER[7] given for 2500 km Reference Circuit
Circuit Configuration	Unbalanced	Unbalanced Circuits; Balanced Receiver	Hybrid[4]	Fully Balanced, (Option: V.10, Unbalanced Circuits, Balanced Receiver)
Transmission Quality	Same Comments as EIA RS-232-C	Same Comments as EIA RS-449/423-A		For Fully Balanced Version, EIA RS-449/ RS-422-A Comments Should Apply
Connectors	25-Pin "D" Type	37-Pin "D" Type	34-Pin "D" Type	37-Pin "D" Type
Comments	Same Comments as EIA RS-232-C	International Equivalent of EIA RS-423-A. Same Comments Apply	Used by Several U.S. Manufacturers for 56 kb/s Wideband Modem Interface	Essentially Updated Version of CCITT V.35, with Improved Performance
EIA Standards Compatibility	RS-232-C	RS-449/RS-423-A	None	RS-449/RS-422-A
Federal Standard Counterparts	None	1031/1030-A	None	1031/1020-A

Notes:

1. Can be increased to several hundred kb/s, using good engineering practices.
2. Can be increased to tens of meters, using good engineering practices.
3. Can be increased to several kilometers, using good engineering practices.
4. Control circuits are CCITT V.28 (unbalanced); data interchange circuits are functionally defined by CCITT V.24, but are balanced.
5. Only if correct (optional) RS-449 circuitry is specified by equipment manufacturer.
6. See EIA Industrial Electronics Bulletin number 12 for RS-232-C/RS-449 interfacing.
7. V.11 specifies 10 Mb/s/10 m; 100 kb/s/1000 m for terminated interchange circuit.
   V.11 specifies 1 Mb/s/10 m; 10 kb/s/1000 m for unterminated interchange circuit.

Table A-2 (Sheet 3 of 3)

CCITT Recommendation	X.21	
	Two Options	
	CCITT X.26/X.27	CCITT X.27
Max. Data Rate/Max. DTE-DCE Cable Length	100 kb/s[1]/10 meters 1 kb/s/1000 meters[3]	10 Mb/s/10 meters[2] 100 kb/s/1000 meters[3]
Circuit Configuration	>9.6 kb/s, Fully Balanced (X.27). To 9.6 kb/s, Balanced/ Unbalanced Options	Fully Balanced
Transmission Quality	Similar to EIA RS-449/423-A	Same Comments as EIA RA-449/422-A
Connectors	15-Pin "D" Type	15-Pin "D" Type
Comments	Physical Interface Specification for Circuit-Switched Public Data Networks	
EIA Standards Compatibility	Electrical Characteristics <u>only</u>: RS-449	Electrical Characteristics <u>only</u>: RS-449/RS-422-A
Federal Standard Counterparts	None	None

<u>Notes</u>:

1. Can be increased to several hundred kb/s, using good engineering practices.
2. Can be increased to tens of meters, using good engineering practices.
3. Can be increased to several kilometers, using good engineering practices.

> ...This Standard, together with EIA Standards RS-422 and RS-423, is intended to gradually replace EIA Standard RS-232-C as the specification for the interface between ... DTE and ... DCE employing serial binary data interchange. With a few additional provisions for interoperability, equipment conforming to this standard can interoperate with equipment designed to RS-232-C. This standard is intended primarily for data applications using analog telecommunications networks ... (excerpted from Foreword of RS-449).

The above-referenced standards RS-422 and RS-423 (recent updating of both is designated by 'A' suffixes), previously adopted in 1975, give user-optional electrical specifications for the RS-449 interface.

The above quotation summarizes the primary goal of RS-449: to provide an improved interface which permits (through the optional RS-423-A electrical specification -- see Table A-2) backward compatibility with the ubiquitous RS-232-C, and therefore an evolutionary approach to advancing technology accommodation as opposed to the X.21 'all-new' approach. The standard is thus a compromise, as can be seen from the summary of Table A-2:

- Noise performance for RS-449 is improved over RS-232-C (measurably for the partially balanced RS-423-A option, dramatically for the fully balanced RS-422-A option). Since electrical specifications are compatible with the two options of X.21, performance may be considered comparable.

- Specification of integrated circuit technology applications is comparable between RS-449 and X.21.

- Bit rate x path length product for RS-449 is measurably increased over RS-232-C and is comparable to X.21.

- The lack of adequate circuit capacity of RS-232-C has been overcome for RS-449 by addition of new interchange circuits. This results, however, in requirements for a 37-pin connector plus an optional 9-pin connector for secondary-channel operation to permit functions such as network control. This compares unfavorably both with the 25-pin connector for RS-232-C (and V.24) and the 15-pin connector for X.21.

- As reflected by the connector requirements, RS-449 continues the RS-232-C philosophy of one interchange circuit per function. The standard has been considered by the CCITT, but not adopted. Therefore it remains a U.S.-only specification (Cowder and Merkel, 1982).

The RS-449 standard has been considered by at least a portion of U.S. industry as an interim interface (op. cit.), predicated on its emphasis on interoperability with RS-232-C and (to a limited degree) X.21 as a transition to the 'Mini Interface' proposed in 1981. (See Section 1.4 for discussion of current evolution of this Recommendation.) There has been limited hardware implementation of RS-449, U.S. manufacturers apparently adopting a 'wait and see' attitude (Cowder and Merkel, 1982), which emphasizes the importance of next-generation interface standards.

In 1976, the CCITT adopted Recommendation V.36, an updating of V.35 (48 kb/s), an interface specification for broadband transmission at the explicit rates of 48 kb/s, 56 kb/s, 64 kb/s, and 72kb/s. The last second-generation DTE/DCE interface specification to be adopted was CCITT Recommendation X.21bis ('bis' is Latin for 'additional' or 'second').

Recommendation X.21bis was developed and adopted as an interim specification for an undefined time period -- in reality, as long as required for the anticipated transition to X.21. As seen in Tables A-1 and A-2, X.21bis is a blanket specification including existing functional Recommendations V.24, V.10, V.35, and V.36 (along with their accompanying Recommendations for electrical and mechanical characteristics) and, as well, maps very closely to EIA RS-232-C and RS-423-A, the partially balanced option of RS-449. Thus, in a literal sense, X.21bis is not a new specification, but rather constitutes a formalized acceptance of an aggregate of previously adopted Recommendations (which, pragmatically, are widely implemented), as a transition toward an interface more suitable for advancing digital telecommunications requirements.

In the 10 years since its adoption, X.21 has not been widely accepted as the solution for these requirements, which in the meanwhile have grown both more demanding and more complex. Section 1.4 of this report describes current work on third-generation interface specifications whose goals are to delineate more successful and longer term solutions for digital requirements.

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15. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

A review of EIA and CCITT data interface standards identifies three generations, namely: first (1960's), second (1970's), and third (1980's and beyond). The User/Network physical interface for the pending Integrated Services Digital Network is an example of third-generation standards. Wideband channel requirements under discussion by the CCITT will be limited by transmission media in the implementation of future interchange circuits. Conventional wire pairs and coaxial cables used in such interchange circuits are limited in the transmission rate and distance combinations by pulse distortion.

A figure of merit applicable to coaxial cable, wire pairs, and optical fiber waveguides is derived, based on physical and geometric properties. The distortion-limiting performance characterization of representative examples of the different media is presented. A recent survey of U.S. manufacturers' off-the-shelf optical fiber digital links is summarized to show evidence of viabiliy for high-bit-rate, medium-distance interchange circuits.

16. Key Words *(Alphabetical order, separated by semicolons)*

ANSI, CCITT, coaxial cable, Common Physical Interface, digital transmission lines, DTE/DCE interface, EIA, fiber optics, impulse response, Integrated Services Digital Network, ISDN User/Network Interface, optical fiber waveguide, telecommunication standards, twisted-wire pair

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