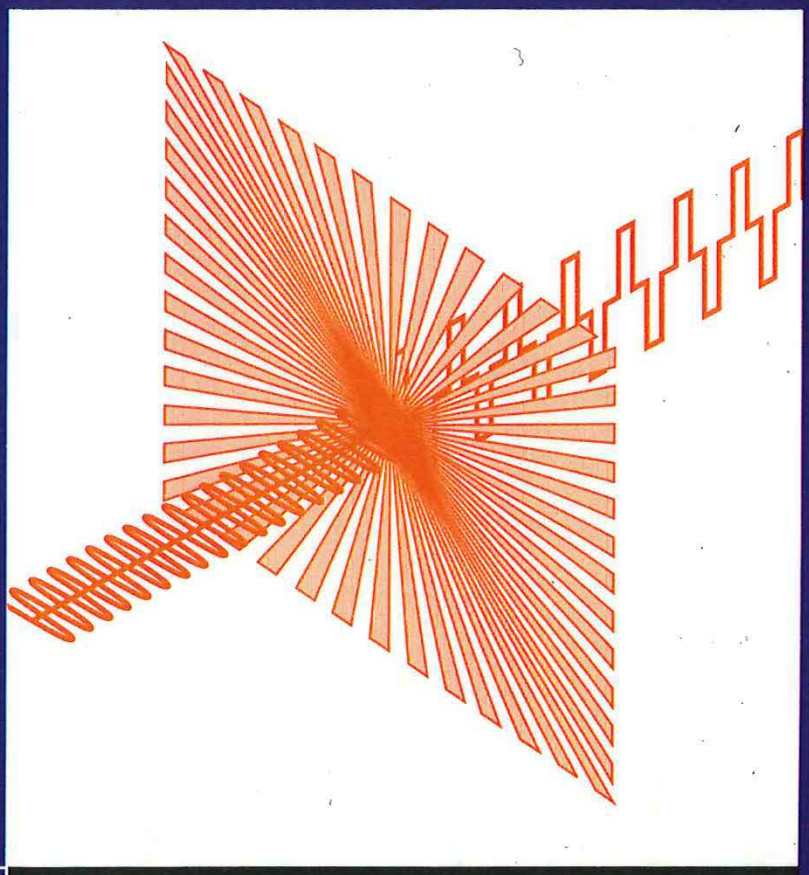
SUBSCRIBER LOOP SIGNALING AND TRANSMISSION HANDBOOK

DEVRY TORONTO LIBRARY
3 3642 00075599 1

DIGITAL

Whitham D. Reeve



IEEE TELECOMMUNICATIONS HANDBOOK SERIES
WHITHAM D. REEVE, *Series Editor*

 CommScope Exhibit 1017

Subscriber Loop Signaling and Transmission Handbook

CommScope Exhibit 1017

IEEE Telecommunications Handbook Series

Whitham D. Reeve, *Series Editor*

The *IEEE Telecommunications Handbook Series* is designed to provide the engineer and technical practitioner with working information in the three basic fields of telecommunications: inside plant, outside plant, and administration and regulatory. This integrated series of handbooks provides practical information on the link between field experience and formal telecommunications industry standards and practices. These books are essential tools for engineers and technical practitioners who require day-to-day engineering and technical information on telecommunication systems.

Published Books in the Series

Boucher	*Traffic System Design Handbook*, 1993
Reeve	*Subscriber Loop Signaling and Transmission Handbook: Analog*, 1992
Reeve	*Subscriber Loop Signaling and Transmission Handbook: Digital*, 1995

Future Books in the Series

Bhatnagar	*Network Synchronization*
Graham	*Telecommunications Power Systems*
Nellist	*Telecommunications Wiring for Commercial Buildings*
Nellist	*Understanding Telecommunications and Lightwave Systems*

If you are interested in becoming an author, contributor, or reviewer of a book in this series, or if you would like additional information about forthcoming titles, please contact:

Whitham D. Reeve
Series Editor, IEEE Telecommunications Handbook Series
Reeve Engineers
P.O. Box 190225
Anchorage, Alaska 99519-0225
907/243-2262
E-mail—*by CompuServe:* 71011.3642@compuserve.com
by Internet: w.reeve@ieee.org

Subscriber Loop Signaling and Transmission Handbook
Digital

Whitham D. Reeve
Reeve Engineers

IEEE Telecommunications Handbook Series
Whitham D. Reeve, Series Editor

IEEE PRESS

The Institute of Electrical and Electronics Engineers, Inc., New York

CommScope Exhibit 1017

IEEE Press
445 Hoes Lane, PO Box 1331
Piscataway, NJ 08855-1331

IEEE PRESS Editorial Board
John B. Anderson, *Editor in Chief*

R. S. Blicq
M. Eden
D. M. Etter
G. F. Hoffnagle
R. F. Hoyt
J. D. Irwin
S. Kartalopoulos
P. Laplante
A. J. Laub
M. Lightner
J. M. F. Moura
I. Peden
E. Sánchez-Sinencio
L. Shaw
D. J. Wells

Dudley R. Kay, *Director of Book Publishing*
Carrie Briggs, *Administrative Assistant*
Lisa S. Mizrahi, *Review and Publicity Coordinator*

Technical Reviewers

Steven Cowles, *GCI Network Systems*
Thomas Croda, *Sprint Communications*
Chester Damby, *Entergy*
C. David Dow, *PennTech*
Sam Fowler, *Questar Corporation*
Michael Newman, *CSI Telecommunications Engineers*
Roy Thompson, *TDS Telecom*

This book may be purchased at a discount from the publisher when ordered in bulk quantities. For more information, contact:

IEEE PRESS Marketing
Attn: Special Sales
P.O. Box 1331/445 Hoes Lane
Piscataway, NJ 08855-1331
1-800-678-IEEE

© 1995 by the Institute of Electrical and Electronics Engineers, Inc.
345 East 47th Street, New York, NY 10017-2394

All rights reserved. No part of this book may be reproduced in any form, nor may it be stored in a retrieval system or transmitted in any form, without written permission from the publisher.

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

ISBN 0-7803-0440-3
IEEE Order Number: PC3376

Library of Congress Cataloging-in-Publication Data

Reeve, Whitham D.
Subscriber loop signaling and transmission handbook : digital / Whitham D. Reeve.
p. cm. — (Telecommunications handbook series)
Includes bibliographical references and index.
ISBN 0-7803-0440-3 (case)
1. Telephone switching systems, Electronic. 2. Telecommunication--Standards. 3. Digital communications. I. IEEE Communications Society. II. Title. III. Series.
TK6397.R443 1995
621.387'83--dc20 94-30809
CIP

Contents

Preface xi

Introduction xiii

Chapter 1 Subscriber Loop Transmission Concepts and Signal Conversion 1
1.1 Subscriber Loops 2
1.2 Analog and Digital Transmission 4
1.3 Baseband and Passband Signals 4
1.4 Analog and Digital Modulation Methods 5
1.5 Digital Hierarchy 6
1.5.1 Multiplexing 9
1.5.2 Pulse Stuffing 13
1.5.3 Scrambling 14
1.6 Analog Signal Conversion and Channel Coding 15
1.6.1 A/D Conversion 15
1.6.2 D/A Conversion 33
1.7 Voice and Voiceband Encoding 33
1.7.1 Introduction 33
1.7.2 Compression 37
1.7.3 Voiceband Encoding Tradeoffs 37
1.7.4 ADPCM 38
1.7.5 Delta Modulation (DM) 41
1.7.6 Digital Speech Interpolation (DSI) 42
1.7.7 Variable Quantizing Level (VQL) 43
References 44

Chapter 2 Digital Loop Applications and Interfaces 46
2.1 Introduction 48
2.2 Services 48
2.3 Subscriber Line Interface Circuit 53
2.4 DLC 56
2.5 Digital Pair Gain Devices 60

2.6 RSTs 63
2.7 SRDLs 64
2.8 Switched 56 Loops 71
2.9 ISDN DSL 72
2.10 HDSL 76
2.11 Repeatered T1-Carrier 77
2.12 Fractional T1-Carrier (FT1) 78
2.13 ADSL 80
2.14 Loop Applications of Optical Fibers 82
2.15 Problems Associated with Digital Loop Planning 85
2.16 Jack and Plug Connector Interfaces 90
2.17 Digital Loop Equipment Operating Constraints 93
2.17.1 Operating Voltages 93
2.17.2 Environmental Requirements 96
References 97

Chapter 3 Digital Loop Frame Structures and Line Codes 99
3.1 Frame Structures 100
3.1.1 Frame Structure Types 101
3.1.2 T1-Carrier Frame Structure 101
3.1.3 ISDN Primary Rate Interface 124
3.1.4 ISDN Basic Rate Interface 124
3.1.5 Subrate Digital Loop 128
3.1.6 High Bit-Rate Digital Subscriber Line 131
3.2 Line Coding 136
3.2.1 Typical Line Codes 138
3.3 Spectrum Management and Compatibility 148
3.3.1 Waveforms and Frequency Spectra 148
3.3.2 Federal Communications Commission Requirements 160
References 163

Chapter 4 Timing and Synchronization 167
4.1 Introduction 168
4.2 Clocking and Timekeeping 177
4.3 Engineering Rules for Synchronization 186
4.4 Timing Impairments 187
4.5 System Clocks 193
4.6 Building Integrated Timing Supply (BITS) 197
4.7 Primary Reference Sources (PRSs) 198
4.8 Synchronization Management 200
References 201

Chapter 5 Loop Transmission Impairments 203
5.1 Noise 204
5.1.1 Noise Objectives 211
5.1.2 Background Noise and Longitudinal Noise 212
5.1.3 Balance 215
5.1.4 Inductive Coordination and Noise Mitigation 219

5.2 Crosstalk 220
5.2.1 Spectrum Management 220
5.2.2 Manifestations and Types of Crosstalk 221
5.3 Impulse Noise 227
5.4 Pulse Detection Errors 234
5.5 Distortion 236
5.5.1 Attenuation Distortion 236
5.5.2 Impedance Distortion 239
5.5.3 Delay Distortion 244
5.6 Absolute Delay 246
5.7 Jitter and Wander 250
5.8 Signal Detection and Regeneration 251
5.9 Digital Pads 254
References 254

Chapter 6 Transmission Quality and Performance 257
6.1 Quality of Service 258
6.2 Line Performance 260
6.3 Specifying Error Performance 261
6.3.1 General Considerations 261
6.3.2 An International Perspective of Digital Transmission System Performance 266
6.4 Transmission Operational Problems 283
6.4.1 Framing Errors 283
6.4.2 BPVs 285
6.4.3 CRC Codes 286
6.4.4 Loss of Signal 287
6.4.5 Summary of Error Monitoring Capabilities of SF and ESF 287
6.5 Performance Monitoring and Measurements 288
6.5.1 Monitoring Systems 288
6.5.2 Alarms 289
6.5.3 Measurements 291
6.6 Performance Requirements for Analog Circuits on Digital Loops 294
6.7 Performance Limitations of ADPCM Encoding in a DLC Environment 294
References 297

Chapter 7 Loop Transmission Media, Part I—Twisted Pair Metallic Cables 300
7.1 General Considerations 300
7.2 Environment 302
7.3 Service Classifications 304
7.4 General Cable Construction Attributes 304
7.5 Other Outside Plant Equipment 305
7.6 Twisted Pair Transmission Media: Physical and Electrical Characteristics 307
7.6.1 Introduction 307

7.6.2 Physical Characteristics 307
7.6.3 Electrical Characteristics 331
References 345

Chapter 8 Loop Transmission Media, Part II—Fiber Optic Cables .. 348
8.1 Introduction, Physical and Electrical Characteristics 349
8.2 Physical Characteristics 349
8.2.1 Fiber Optic Cable Specifications 349
8.2.2 Outer Jacket 350
8.2.3 Armor and Inner Jacket 350
8.2.4 Buffering 351
8.2.5 Strength Member 359
8.2.6 Media 360
8.2.7 Color Coding 363
8.3 Feeder and Distribution Cables 365
8.4 Fiber Access 365
8.5 Direct Buried and Underground Installations 366
8.6 Summary of Fiber Optic Cable Physical Characteristics .. 368
8.7 Fiber Optic Cable Costs 368
8.8 Optical Fiber Electrical Characteristics 369
8.8.1 Fiber Refractive Index and Cladding 369
8.8.2 Transmission Characteristics 370
8.9 Splices and Connectors 375
8.10 Couplers 394
8.11 Optical Sources and Detectors 399
8.12 Fiber Optic Cable Purchase Checklist 401
References 402

Chapter 9 Transmission Engineering, Part I—Repeatered T1-Carrier 405
9.1 Repeatered T1-Carrier Span Lines 406
9.1.1 Interference Considerations 406
9.1.2 Repeatered Span Line Design 412
9.1.3 Intermediate Section Loss: 2-Cable Operation (and Compartmental Core Cable), *Method 1* 416
9.1.4 Intermediate Section Loss: 2-Cable Operation (and Compartmental Core Cable), *Method 2* 422
9.1.5 Intermediate Section Loss: 1-Cable Operation 423
9.1.6 End-Section Loss 430
9.1.7 Route Junctions 433
9.1.8 Designing for Improved Error Performance 435
9.1.9 Span Line Powering 438
9.1.10 Repeatered T1-Carrier Loop Qualification 441
9.1.11 Fault Locating Systems 443
9.1.12 Order Wire 449
9.2 Line Terminating Equipment 450
9.3 Digital Cross-Connect Equipment 455
9.3.1 Manual DSX 457
9.3.2 Electronic DCS 463
References 467

Chapter 10 Transmission Engineering, Part II—Non-repeatered Digital Loops Including Fiber Optics 468
10.1 Compatibility 469
10.2 Subrate Digital Loops 469
10.2.1 Interference Considerations 469
10.2.2 SRDL Design 474
10.2.3 SRDL Qualification 492
10.3 Switched 56 Loop 494
10.4 ISDN DSL 497
10.4.1 Interference Considerations 497
10.4.2 DSL Design 498
10.4.3 DSL Qualification 504
10.5 HDSL 507
10.5.1 Interference Considerations 507
10.5.2 HDSL Design 507
10.5.3 HDSL Loop Qualification 510
10.6 Optical Fiber Loop Transmission Design 511
References 526

Chapter 11 Premises Cabling Systems 528
11.1 General Considerations 528
11.1.1 Environmental Considerations 532
11.1.2 Electromagnetic Compatibility 532
11.1.3 Safety 533
11.2 Structured Cabling Systems 534
11.3 Transmission Media Considerations 542
11.3.1 Twisted Pair 542
11.3.2 Twisted Pair Connection Devices 554
11.3.3 Optical Fiber and Coaxial Cable 558
11.3.4 Media Applications and Compatibility 558
11.4 Jacks and Plugs 559
11.5 Premises Applications of ISDN 561
References 575

Appendix A Twisted Pair Cable Designation Cross-Reference 577

Appendix B Exchange Cable Transmission Characteristics 583

Appendix C Cable Core Assembly Drawings 609

Appendix D Operational Information for DSX-1 Patch Panels 623

Index 635

7 Loop Transmission Media, Part I—Twisted Pair Metallic Cables

Chapter 7 Acronyms

AL	acceptance limit	ML	maintenance limit
AMI	alternate mark inversion	Neper	One Neper = 8.686 dB
AWG	American wire gauge	NESC	National Electrical Safety Code
DSL	digital subscriber line	PIC	polyolefin insulated cable
ECCS	electrolytic chrome-coated steel	PSTN	public switched telephone network
EHS	extra high strength	PVC	polyvinyl chloride
EMI	electromagnetic interference	REA	Rural Electrification Administration
FAC	facility area connector	RMS, rms	root-mean-square
FCC	Federal Communications Commission	RZ	return-to-zero
HDSL	high bit-rate digital subscriber line	SAI	serving area interface
I/O	inside/outside wire	SNR	signal-to-noise ratio
IAL	immediate action limit	UG	utilities grade
ICEA	Insulated Cable Engineers Association	XC	cross-connect
ISDN	integrated services digital network		

7.1 General Considerations

The most commonly used transmission media in present-day digital loop applications is twisted pair metallic (copper) cable, but fiber optic cables are seeing significantly more and more use. Although both media transmit electromagnetic waves, their spectra are very widely separated, and the transmission and reception of signals depend on completely different propagation mechanisms. Because of the breadth of information, the descriptions of transmission media are broken into two parts. Part I (this

chapter) covers twisted pair metallic cables and Part II (next chapter) covers fiber optic cables.

In spite of the lack of similarity between the two transmission media, the materials used in the outer (protective) layers of both cable types have many things in common and are identical in many respects. In many cases, the cables are installed under identical service conditions, and the associated loops and networks serve identical purposes.

There are cases, however, in which each cable type (twisted pair or fiber) can serve purposes the other cannot either because of economy or service requirements. For example, current use of twisted pair cable is exclusively for the final portion of the subscriber loop, commonly called "the last mile", because of its economy. On the other hand, fiber optic cable is used as a replacement for twisted pair feeder cables between the central office and remote switching terminals or digital loop carrier systems because of its economy in backbone and feeder applications. Work is under way by several large telephone companies to find economical methods to replace twisted pair cables altogether, but this is not expected to happen for many more years.

An economic trigger point is widely considered the best rationale for mass deployment of fiber optics in the loop. This point already has been reached for backbone and feeder plants. This point will be reached for the remaining portions of the loop (distribution and service drop) when the incremental cost of fiber over twisted pair is equal or close to zero, and when users demand services that can only be provided by fiber.

Economic considerations aside, the application of either twisted pair or fiber optic cables is predicated on their

- Physical characteristics
- Mechanical performance
- Electrical performance

Physical characteristics have to do with the geometry of the cable and transmission media. For example, the individual conductors of a twisted pair have a certain geometry, so they conform to a specified gauge and provide the necessary transmission characteristics. Similarly, optical fibers have a particular geometry associated with core and cladding, as well as dimensional requirements, which provide the necessary transmission characteristics.

Mechanical performance is related to the strength, abrasion resistance, and fatigue resistance of cables and the enclosed transmission media. This performance is specified in different ways for twisted pair and fiber optic cables. The same is true for electrical performance, which is due to their radically different transmission characteristics. The general physical characteristics and mechanical performance of both cable types and the specific physical and electrical characteristics of twisted pair cables are discussed in this chapter. Chapter 8 discusses the similar physical and electrical attributes of fiber optic cables.

7.2 Environment

Outside plant cables are subjected to a number of environmental hazards and conditions throughout their life. Some of these affect twisted pair cables differently than fiber optic cables. Each cable design attempts to mitigate any adverse effects over the anticipated cable life. Outside plant cables generally last at least 15 years, but in most regulated utility applications, their usefulness extends 25 to 35 years.

Environmental conditions of concern to the engineer are:

- Moisture
- Animal attack
- Electric fields
- Atmospheric disturbances (lightning)
- Temperature variations
- Absolute temperatures
- Snow and ice loading
- Wind loading
- Vibration
- Ultraviolet radiation (above ground only)

Moisture affects twisted pair and fiber optic cables through different mechanisms. Penetration and permeation of moisture into a twisted pair cable increases the attenuation by increasing the capacitance between conductors of a twisted pair. It also will corrode mechanical splices. When liquid water is present and it freezes, the expansion of the ice can crush the insulation or damage cable jackets from the inside. Such damage may not be apparent until the cable thaws and the pairs become shorted. In fiber optic cables, the crushing forces can fracture the fibers or cause microbending, both of which increase losses. Also, long-term exposure to moisture deteriorates the fiber's tensile strength.

Rodent attacks are a significant problem in some parts of the country.* The rodent's powerful jaws can easily penetrate plastic sheaths and allow moisture penetration. Also, the transmission media can be severed unless armoring is provided against the attack.

Strong electric fields from high voltage powerlines can lead to failure of the plastic sheath materials from corona discharge and arcing. Induction from powerlines can cause damaging current flow on conductive portions of the cables (armor, shields, and conductors in twisted pair cables; conductive strength members and armor in fiber optic cables).

Lightning is particularly troublesome in some parts of the country.† It can cause extremely large currents to flow on conductive portions of a cable. Also, large and

*For example, see page 246 of [1] for areas prone to gopher attack.

†See pages 3–5 of [2] or pages 2–5 of [3].

sudden currents from a lightning discharge can cause the cable to buckle as a result of mechanical forces and burn the insulation and sheaths. Rapid thermal expansion of the soil and moisture in it can exert significant forces on nearby buried cables. This damage can occur in completely dielectric fiber optic cables if they are buried near conductive material such as twisted pair or power cables.

Diurnal and seasonal temperature variations cause expansion and contraction of the materials used in cables. In some areas, the temperature can vary annually over a 90 °C range, and daily variations can easily exceed a 35 °C range. In twisted pair cables, temperature variations affect the attenuation but otherwise have no direct effect on modern cables. Older filled cables used a filling compound that flowed under high ambient temperatures; this compound would then drain out of cables used as risers. Modern filling compounds for cables have flow temperatures of 65 °C or 80 °C.

In areas of extremely cold temperatures, aerial twisted pair cables can contract enough to damage splices or supporting structures. Similarly, high temperatures increase the sag in aerial cables and allow accidental contact with vehicles or other moving objects. In fiber optic cables, the mechanical movement due to expansion and contraction can cause excessive bending loss.

Snow and ice loading can damage the cables as well as supporting structures through excessive weight. For example, one-half inch of radial ice on a one-half inch diameter cable weighs approximately 68 lb per 100 feet of length. One inch of radial ice on this same cable weighs about 200 lb per 100 feet. Snow and ice also increase the cross-sectional area of aerial cables and can amplify the adverse effects of wind.

Wind loading normally only affects aerial facilities; however, in especially windy areas, ground-mounted equipment may need special anchoring. The adverse effects of wind are manifested in four ways:

- As a transverse load on the supporting structure (for example, wooden poles)
- As a transverse load on the cable and messengers, which are coupled to the supporting structures
- Through vibration
- Through cable whipping and dancing

The transverse load, if large enough, can damage the supporting structures. Vibration, whipping, and cable dancing cause fatigue in supporting structures and in the cable itself. Even very small winds can cause large-amplitude vibrations on long sections of aerial line. Another source of vibration is road traffic, and over a long period, this source of vibration can lead to catastrophic failures of supporting structures. It is difficult to build vibration damping into cables, so external means are frequently employed, including specially made sails, spiraling the lashed cable, additional strands above the supporting strand and attached to it, and shorter spans between supports. In extreme cases of cable dancing, the only alternative is to bury the cable or change the route.

Sunlight can damage cable sheaths through breakdown of the plastic materials

from ultraviolet radiation. Any facility exposed to the sun is subject to this problem, and special materials or coatings are used to combat it.

7.3 Service Classifications

All telecommunication cables are categorized according to their service classifications, as shown in Table 7-1. These classifications are universal, but general, in nature. Most cables are not specifically made for a single service classification, so a given cable type may be used wherever it is suitable. For example, filled twisted pair cable normally is considered for direct buried applications, but it is also used in aerial and underground service. Armored cable may be used in aerial as well as direct buried service. The selection of general cable types is aided by the flow chart in Figure 7-1.

As previously noted, cables used in an outside environment normally last 25 to 35 years. Although indoor cables are manufactured for a similar life, technological advances of equipment connected to indoor cables and user requirements for more and more bandwidth may render the cables obsolete long before their physical life is exhausted. This is especially true of most existing twisted pair cables. With the widespread deployment of fiber optic cables and high-performance twisted pair cables in buildings, the threat of premature obsolescence is somewhat eased.

Table 7-1 Cable Service Classifications

Classification	Application
Indoor	Plenums in buildings (CMP)[a] Risers in buildings (CMR) General use in buildings (CM)
Aerial	Lashed to separate messenger or self-supporting on above-ground structures
Buried	Buried directly in earth
Underground	Installed underground in duct or raceway

[a]The designations in parentheses for indoor cable indicate classifications defined in Article 800 of the National Electrical Code.

7.4 General Cable Construction Attributes

Both twisted pair and optical fiber cables have similar external physical attributes, which are illustrated in Figure 7-2. All cables have an outer jacket, which for twisted pair and fiber optic cables is identical. This also is true of the armor (with an optional inner jacket), although fiber optic cables are equipped with armor in more applications than twisted pair cables. The buffering, strength member, and transmission media are radically different.

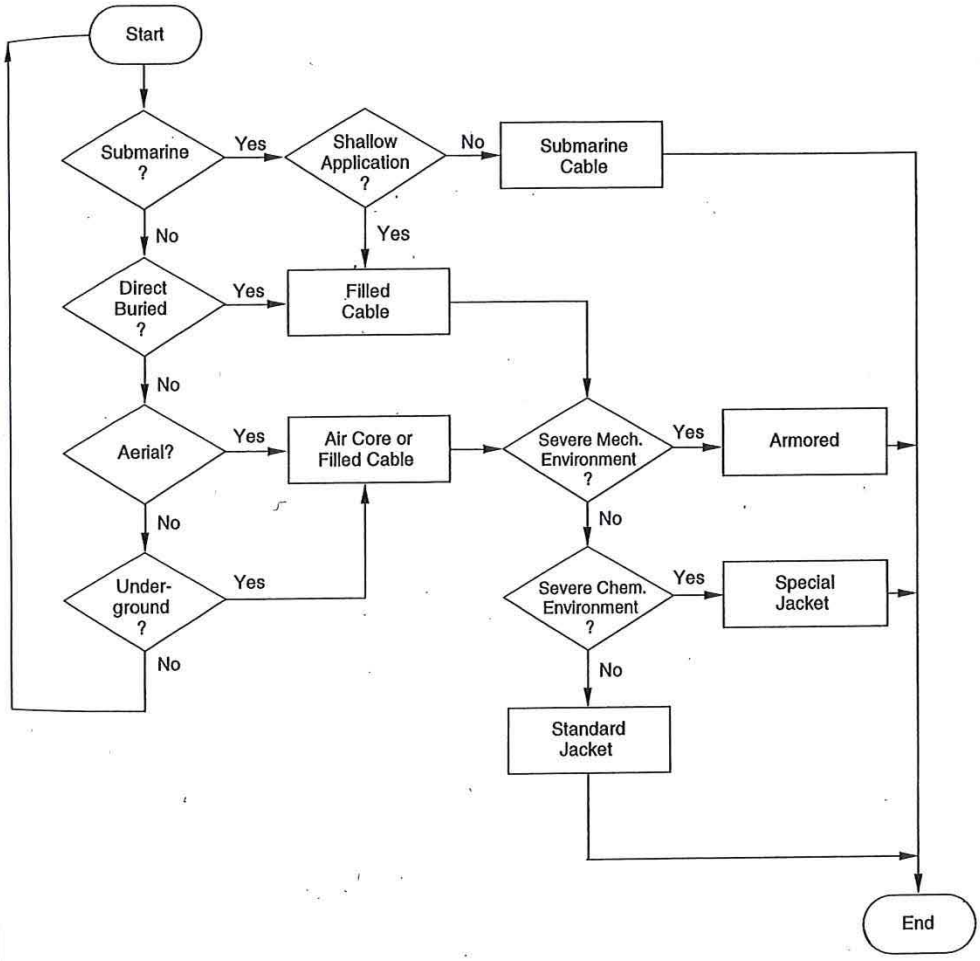


Figure 7-1 Cable selection flow chart [4]
Reeve, © 1992 Institute of Electrical and Electronics Engineers. Reprinted with permission

7.5 Other Outside Plant Equipment

Although twisted pair cables represent the highest proportion of outside plant investment, they are not the only transmission equipment found outdoors. The cables and other facilities used with digital transmission systems or digital loops are frequently shared with analog loops. Except for digital loop carrier, remote switching systems, and all present optical fiber transmission systems, digital and analog sub-

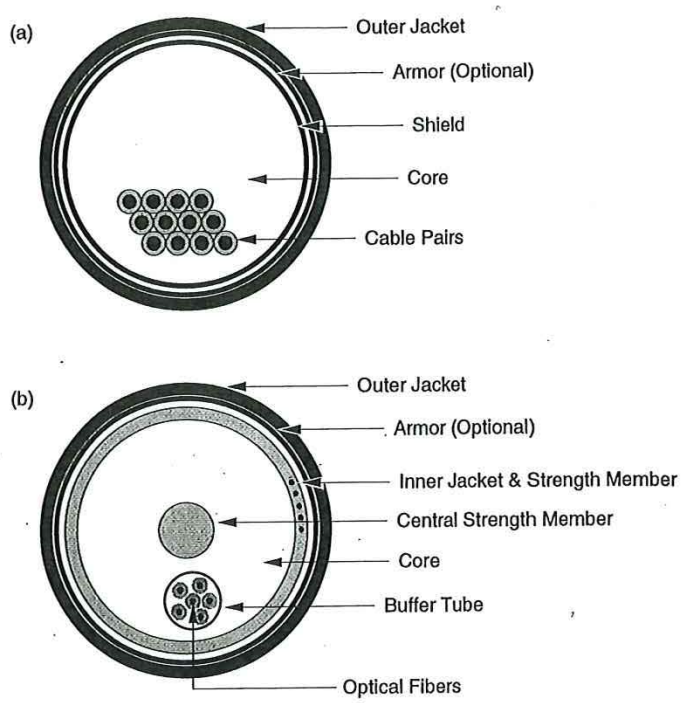


Figure 7-2 Cable construction attributes: (a) Twisted pair cable; (b) Fiber optic cable

scriber loops require access at frequent intervals. Access is typically at every pole in aerial systems installed in urban areas, or at least once in every city block (and frequently more often) for buried or underground systems.

The equipment used for access to subscriber loops depends on the type of plant. Aerial plant is accessed through "ready access" or sealed fixed-count terminals located adjacent to the pole and in-line with the cable. The aerial terminal has provisions for shield bonding and grounding, and connection of service wires to distribution pairs. In buried or underground plant, access is at pedestal or outdoor housings. The pedestals sometimes contain loop carrier equipment, loading coils, cross-connect blocks, or other devices, including protectors, for connecting distribution plant to service wires.

Digital loops frequently are used as backbone facilities to feed digital loop carrier and remote switching systems, which may be separated from the central office by several miles. Access to the digital loop in these cases is not necessary except at repeater points. Repeaters on twisted pair cables typically are about five to seven kilofeet apart for repeatered T1 systems. Fiber optic transmission systems used in digital loop applications do not require repeaters because of their relatively short lengths, so access is not required anywhere along the route except at reel-end splice points.

Repeatered T1 repeater housings used with twisted pair cables are available in a variety of sizes and forms, from one repeater to several dozen. The housings have printed wiring board connectors and mounting provisions for one or more repeater cards, grounding and bonding, and lightning protection. Some housings also may have order wire and fault location equipment, which are used for maintenance and troubleshooting. Repeater housings can be pressurized with an inert gas or with dry air through cable pressurization systems to keep out moisture. Sealed units have provisions for venting in case of excessive pressure build-up.

7.6 Twisted Pair Transmission Media: Physical and Electrical Characteristics

7.6.1 Introduction

The twisted pairs in all modern polyolefin insulated cables (PICs) are enclosed in a heavy-duty plastic sheath. Although pulp-insulated cables are still manufactured for in-kind replacements, this chapter is concerned with PIC exclusively. First, the physical aspects and non–transmission-related electrical characteristics are described in detail. Then the electrical transmission characteristics are described for a frequency range extending to 5 MHz, which covers all present digital loop applications.

7.6.2 Physical Characteristics

7.6.2.1 Twisting

Each cable pair consists of two twisted insulated conductors. The twist is used to decrease electromagnetic interference due to crosstalk between adjacent pairs in a cable. The twist also helps keep the conductors of the pair balanced with respect to the shield and other pairs.

Neighboring pairs in a given 25-pair group have a different twist length to further reduce crosstalk between them. The twist length (or pitch) is usually left-hand (counterclockwise), and it varies from two to six inches. It is optimized to reduce crosstalk at higher frequencies (hundreds of kilohertz and above), since it is in this region where crosstalk can become a problem.

The requirement for adequate crosstalk performance in all telecommunication cables is highly stressed during their design and construction. Crosstalk due to cable pair irregularities is managed by tightly controlling capacitance unbalance (pair-to-pair, pair-to-shield, and pair-to-ground) and resistance unbalance during the manufacturing process.

7.6.2.2 Feeder and Distribution Cables

Feeder cables comprise the loop from the central office to main junction points called serving area interfaces (SAIs), facility area connectors (FACs), cross-connects (XCs), or control points. The actual name depends on the company, but the function

is to provide a point at which feeder cable pairs can be administered and connected to individual distribution cable pairs.

Distribution cables comprise the loop from the main junctions to distribution terminals such as pedestals or aerial terminals. In any given geographic area, there are generally more distribution pairs than feeder pairs. This allows efficient use of larger and more expensive feeder cables through easier administration and assignment of subscribers.

The most widely used feeder and distribution cable size is 24 American wire gauge (AWG). This is due to economic tradeoffs that take into account the typical loop length. Relatively short loops in metropolitan environments are typically 26 AWG.

In the smaller cable sizes, good design practice calls for using cables that are multiples of the basic 25-pair unit (25 and 50). Pair counts of 6, 12, 18, and 37 are avoided unless other factors make their use clearly more economical than 25- or 50-pair sizes. There is very little difference between the installed cost of 6- or 12- and 25-pair cables or 37- and 50-pair cables in most applications.

The extra pairs not only give extra insurance to accommodate unforeseen growth, but also allow pairs in the field to be allocated and used more logically due to the multiple 5-pair and 25-pair color coding scheme. The long-term result, of course, is easier administration and maintenance.

With twisted pair cables, each pair may be made available at many different locations in a "preferred count" splicing scheme, or at predetermined single locations in a "dedicated count" splicing scheme. Generally, feeder cables serve a given area on an express basis, while distribution cables serve the individual subscribers in that area. Large cables cannot be provided in lengths of more than 1,000 or 2,000 feet and so must be frequently spliced along long routes. The splice, connector, and access points are required to use the facility properly. Splices and connectors add very little to the overall transmission loss in the cable route.*

7.6.2.3 Service Wires

Service wires (also called *service drops* or *service cables*) make up the final portion of the metallic loop. They are installed between the distribution terminal and network interface device. This can be at an office building or residential establishment. Beyond the network interface device are premises wiring systems, which are described in Chapter 11.

Service wires can be one pair or up to hundreds or thousands of pairs, depending on the establishment to be served. In many situations there is nothing to distinguish a service cable from a distribution cable, except for the point of termination. Exactly the same materials may be used for the cables themselves.

Service wires in the smaller sizes are not always twisted because they are usually short and do not measurably degrade transmission quality. Aerial service wires are usually 18 or 19 gauge, whereas buried service wires are usually 19, 22, or 24

*The loss of an individual twisted pair splice connector is not easily measured because it is so small; therefore, splice loss is not considered a factor in feeder and distribution design.

gauge. Highly pure copper is the most widely used conductor material for feeder and distribution cables and underground service wires, whereas copper with special alloying (or other means for strength) is used for aerial service wires.

7.6.2.4 Current Limitations

The maximum continuous current-carrying capacity of any given conductor gauge depends on many factors, such as ambient temperature, allowable temperature rise, number of conductors in a bundle, and insulation type. Table 7-2 shows the values for various copper conductor gauges, assuming a 25 °C ambient temperature and 40 °C rise. These are provided to give an idea of current magnitudes and not as design values.

In analog applications, the maximum loop current available from an analog central office line circuit is in the range of 45 to 145 mA, although some older systems can supply at least 175 mA. Modern digital equipment limits loop current to approximately 50 mA. The current magnitude normally drops off as loop length increases beyond a certain limit. Many digital central offices use current-limiting type line circuits to limit loop current on short loops.

Digital loop circuits may be arranged to not carry any dc loop current at all, but this is to be avoided. Sealing current of 10 to 20 mA is used to keep mechanical splices and connections free of high-resistance metal oxides. Repeatered lines for digital loop carrier systems are usually loop powered with 60 to 140 mA dc. The lower value is preferred in order to reduce power consumption and dissipation in repeaters and digital line terminal equipment.

For signaling and control applications outside of the digital transmission arena, loop current normally is limited to 350 mA. In some special applications, a loop current up to 1.3 amps is sometimes allowed. This higher value coordinates with 26 AWG cable. In public switched telephone network (PSTN) applications, the local exchange carrier always will limit current to this value.

In premises wiring applications, the Federal Communications Commission (FCC) regulates the maximum allowed currents on cable pairs connected to the public telephone network. The FCC limits currents, as shown in the right-hand column of Table 7-2. The FCC does not list a value for 19 AWG conductors but does give the allowable currents of 7.5 A and 10 A for 20 AWG and 18 AWG, respectively. Also, a 45 °C rise is used for 22, 20, and 18 AWG, and de-rating is required where ambient temperatures exceed 25 °C.

Also shown in Table 7-2, for reference, is the approximate fusing current for each gauge, which is the point at which the conductor will fuse open. These are

Table 7-2 Exchange Cable Pair Current Ratings

AWG	Approx. Fusing Current (0.1 Seconds)	Max. Current Capacity (40 °C Rise)	Max. Current per FCC Rule 68.215 [5]
19	600 A	8 A	See text
22	300 A	5 A	5.0 A
24	190 A	2 A	2.1 A
26	110 A	1.3 A	1.3 A

approximations; actual values depend on many variables and published information varies widely. Fusing currents and fusing times are inversely related. For example, if the current is increased by a factor of 3, the fusing time will decrease by a factor of about 1/10.

7.6.2.5 Twisted Pair Cable Specifications

Telecommunication cables are manufactured for an intended application according to a specification prepared by the cable customer. In many cases, these specifications are generic and are in wide use throughout a segment of the telecommunications industry. Of particular interest are the telecommunication cable standards published by the Insulated Cable Engineers Association (ICEA) [6–9], Rural Electrification Administration (REA) [10–17], and BELLCORE [18–25].*

Generally, the specifications include, among other requirements, an insulation breakdown voltage, a high-voltage proof test, and insulation resistance. The insulation breakdown voltage (or dielectric strength) is the voltage at which the insulation will fail. It is usually specified in volts per mil† of insulation thickness. Typical insulation thickness is around 10 to 14 mils, but this differs among cable types and manufacturers. Cable specifications normally only show an insulation breakdown voltage, and the manufacturer then applies enough of the particular material to satisfy the requirement.‡

The high-voltage proof test is at a somewhat lower voltage than the insulation breakdown voltage. It is the voltage at which cables are tested after manufacture and before shipment to the customer. The actual values depend on such factors as cable gauge, whether filled or air core, and solid or expanded foam insulation. All proof tests are made for three seconds. The cable is not expected to withstand these voltages indefinitely.

Insulation resistance is a measure, in MΩ-miles, of the leakage between a given conductor and the other conductors and shield in the cable. By inspecting the units, it is clear that insulation resistance decreases with increasing length. For example, an air core cable five miles long will measure at least 2,000 MΩ (10,000 MΩ-miles/five miles). Insulation resistance tests are usually made at around 550 V for new cables at the factory, or 250 V for cables in the field. The higher the resistance, the better. Table 7-3 shows the ratings for typical outside plant telecommunication cables.

Unlike power cables, telecommunication cables usually do not have a specified maximum working voltage. Nevertheless, most telecommunication cables are considered to have a working voltage across the tip and ring of any given pair, and between pairs of 300 V.§

---

*The listed BELLCORE documents are representative of the available outside-plant cable technical references. Additional specifications can be found in [26].

†One mil is one one-thousandth of an inch.

‡This is not an arbitrary process because the insulation thickness affects cable capacitance, which is very tightly controlled, and conductance.

§The working voltage considered here is root-mean-square (rms) or dc.

Table 7-3 Exchange Cable Voltage and Insulation Ratings

PARAMETER	RATING
Insulation breakdown voltage	300 to 1,200 volts/mil
High-voltage proof test (3 seconds)	
Conductor-to-conductor	2 to 7 kV
Conductor-to-shield	10 to 20 kV
Insulation resistance (@ 100 to 550 V)	
Air core cable	10,000 MΩ-miles
Filled cable	1,000 MΩ-miles

This does not mean the user can arbitrarily apply 300 V to the cable pairs. As expected, for equipment connected to the PSTN, FCC Part 68 has certain maximum voltage and current limitations for terminal equipment in various configurations that preclude such operation.* Basically, the terminal equipment cannot apply more than 56.5 Vdc to a loop connected to an off-premises station, or supply more than 140 mA to the loop under any circumstances. During ringing, no more than 300 V peak-to-peak can be applied to the loop.† The reasons for these limitations are obvious: safety and network harm. Some telephone company tariffs may specify more stringent voltage and current limitations.

The voltage and current limitations discussed above, as imposed by the FCC on equipment connected to the loop, do not apply to the telephone companies themselves. Although the working voltage of cable pairs is considered to be 300 V, telephone companies will use higher voltages under certain conditions. These are always associated with special equipment located outside the central office. For example, the line repeaters in long digital loop carrier span lines may be powered by up to 360 V at the central office. This voltage dwindles to much lower values along the span line due to voltage drop across the repeaters, and resistive voltage drop in the cable pairs.

Cable specifications also include requirements for resistance, capacitance, crosstalk, and loss at particular frequencies. Although the exact details of industry specifications may vary with the market segment (that is, REA, BELLCORE, AT&T, GTE, and others), the overall effect on transmission performance is not significant except in the most demanding applications (for example, at high bit rates where specially designed cables might be used).

Other basic requirements of virtually all specifications are the marking requirements for outer jackets. These include sequential marks at two-foot intervals, cable type, pair count, gauge, and manufacturer. Some cables have two sets of interval markings when shipped from the factory. Normal marking usually is white, but if this is unusable for any reason, a second interval marking is made in yellow. Also, as required in 1993 by the National Electrical Safety Code (NESC), the outer jacket must be marked with a telephone handset symbol to differentiate the communications cable from power cables (NESC Sec. 35, par. 350.6) [27].

*Par. 68.306 of [5].

†300 V peak-to-peak corresponds to about 106 V RMS, assuming a sinusoidal ringing voltage.

7.6.2.6 Splices

Copper conductors are easily spliced by a number of means. Because of requirements for long life, reliability, and fast installation, all splicing in the telecommunications industry is by specially designed insulation displacement mechanical connectors. Single-pair or bulk (25 pair at a time) splice connectors are available. All require special tools or jigs to assemble the splice properly and to ensure a long and reliable life. Twisting together of bare conductors is never used to splice exchange cables.

Of special concern in outside plant applications is the need for a weatherproof splice connector. Even when splices are enclosed in a sealed splice case, enough moisture can enter to corrode the splice connections and introduce high loss or noise. All splice connectors are available with filling compounds that prevent moisture problems. Although these type of connectors find the widest use in direct buried cable applications, they are also recommended for use with pressurized plant.

The splice connectors used in the telecommunications industry have negligible loss at all frequencies encountered in twisted pair transmission systems. Nevertheless, proper care must be taken in choosing splice connectors and the splice cases that enclose them. Without this care, the expected service reliability and availability will never be obtained over any significant period.

7.6.2.7 Summary of Twisted Pair Cable Physical Characteristics

The previously described physical characteristics are summarized in Table 7-4 for modern copper telecommunication cables. Figure 7-3 illustrates the construction of a few cable types.

Table 7-4 Outdoor Twisted Pair Cable Physical Characteristics

Parameter	Characteristic
Insulation	Polyethylene Polypropylene Dual expanded polyethylene Expanded polypropylene
Conductors Pair Count	19, 22, 24, 26 AWG, copper 6, 12, 18, 25, 37, 50, 75, 100, 150, 300, 400, 600, 900, 1,200, 1,500, 1,800, 2,100, 2,400, 2,700, 3,000, 3,600, 4,200[a]
Core Shield	Air or filled Bonded aluminum (8 mils), copper (5 or 10 mils) or copper alloy (6 mils)
Armor Sheath (jacket)	Bonded steel (6 mils) when separate from the shield Polyethylene jacket Special high-temperature jacket
Special features	Compartmental core Low capacitance External wire armor

[a]Not all pair counts are available in all gauges.

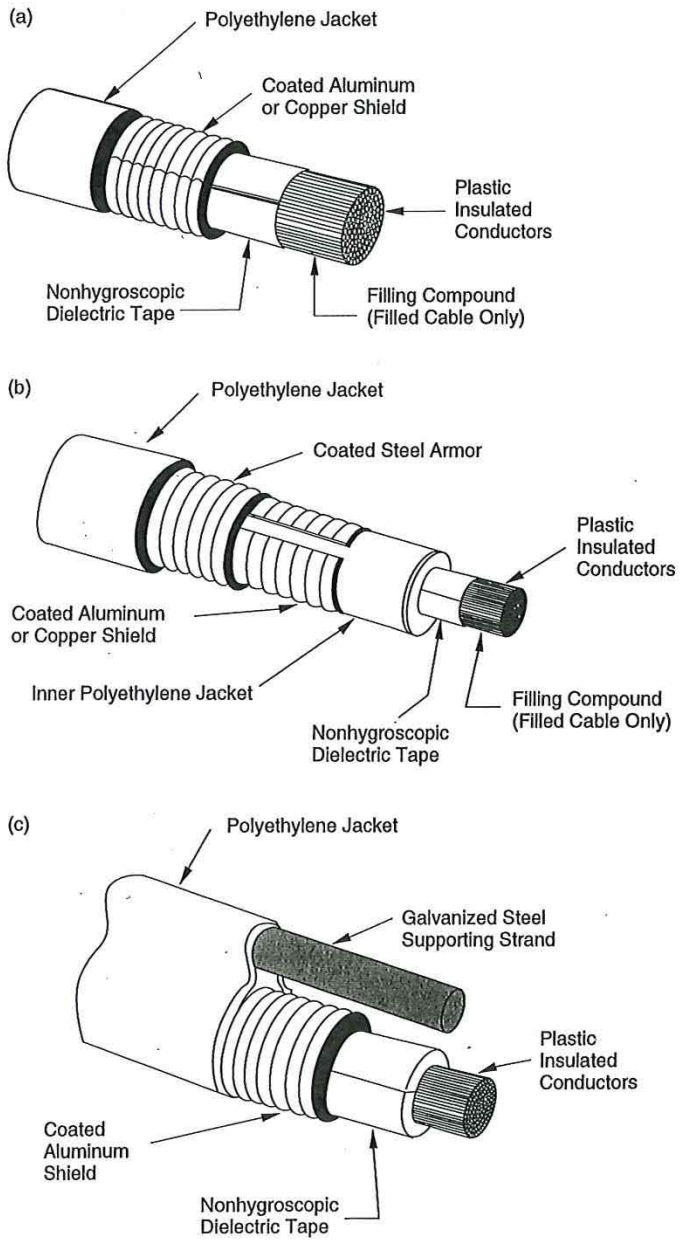


Figure 7-3 Twisted pair cable constructions, [4]
Reeve, © 1992 Institute of Electrical and Electronics Engineers. Reprinted with permission

7.6.2.8 Description of Each Construction Attribute

This section describes the cable constructions used in subscriber loop applications; refer to Figure 7-3. Various coding schemes have been used in the telecommunications industry to simplify cable manufacturing and ordering. One of the more common schemes is described in Appendix A.

Outer Jacket

The outer jacket (sheath) protects and cushions the cable core. It also offers resistance to chemical deterioration and abrasion. In all modern telecommunication cables, the outer jacket is a tough plastic, the thickness of which varies with size and type of cable. For outdoor twisted pair cables, it varies from approximately 60 mils on cables with diameter of 0.75 inch, to 110 mils or more on cables with a two-inch or larger diameter.

The sheath thickness for indoor cables typically is less than comparable outdoor cables, because indoor cables are usually installed in a relatively benign environment. In those cases in which an indoor cable is installed in an abusive environment, special outer jacket constructions can be provided by cable manufacturers.

The type of plastic used in outer jackets varies with the application. A polyvinyl chloride (PVC) material that will not support a flame and has nontoxic combustion products is used for riser cables in buildings. For plenum applications in buildings, which is the most demanding service in terms of fire rating, cables typically have a fluoropolymer resin (for example, TEFLON™*) jacket. Low-density, high molecular weight polyethylene (or ethylene copolymer) or high-density polyethylene is used in outside applications. These types of polyethylene are typical choices for the outer jacket because they have:

- Relatively low humidity permeability
- Good mechanical properties, such as high resistance to abrasion, weathering, and environmental stress cracking
- Good chemical properties, including high resistance to deterioration from sunlight
- Low coefficient of friction, which is important when pulling cables through conduits and duct systems

The disadvantages of polyethylene are its stiffness and flammability, both of which preclude its use in an indoor environment.

In aerial applications, the cable is lashed to a supporting messenger (commonly called *suspension strand* or just *strand*), which varies from 3/16 inch to 7/16 inch in diameter, depending on the strength required and the material used. Lashed aerial construction is illustrated in Figure 7-4(b). Table 7-5 shows the breaking strengths for messengers used in telecommunications applications. The messenger tension never

*"Teflon" is a trademark of DuPont-Nemours, Delaware.

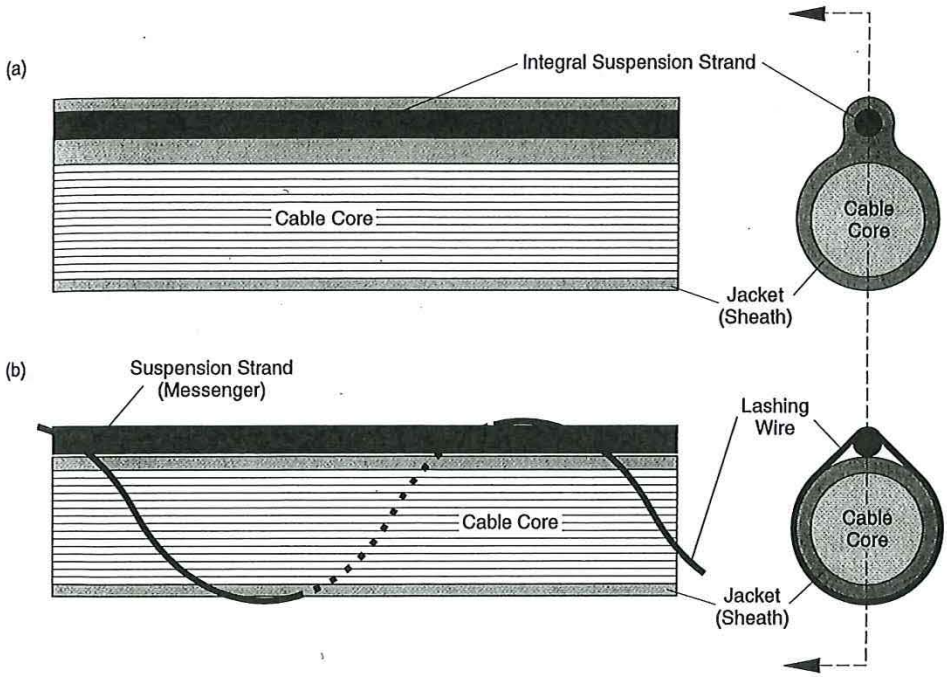


Figure 7-4 Cross-sections of aerial construction: (a) Figure 8; (b) Lashed

Table 7-5 Messenger Strand Breaking Strengths

Designation	Strand Size	Breaking Strength (lb)
6M	3/16 inch extra high strength (EHS)	6,000
6M	1/4 inch utilities grade (UG)	6,000
10M	5/16 inch EHS	10,000
10M	3/8 inch UG	10,000
16M	3/8 inch EHS	16,000
16M	7/16 inch UG	16,000

exceeds 60% of the breaking strength, under all mechanical loading conditions, in a properly designed aerial plant.*

In some aerial applications, a self-supporting cable is used, as shown in Figure 7-4(a). This cable incorporates a built-in supporting messenger along with the outer sheath. This cable is called "figure 8" because of its shape. Due to strength limitations, figure 8 cable generally is not available in cable pair counts above 300 pairs (26 AWG), 200 pairs (24 AWG), 100 pairs (22 AWG), or 50 pairs (19 AWG).

*Mechanical loading conditions and design criteria are covered in [27–29].

Many older outdoor twisted pair cables have a lead sheath, which acts as both a shield and outer covering. Because of their age and construction, few lead sheath cables are used in high-speed digital transmission service. Some modern cables use a lead sheath over a polyolefin jacket for added protection in highly corrosive environments.

Armor

A steel tape armor can be placed under the outer jacket if desired, and in some applications it is mandatory. The armor provides increased physical protection and strength. The tape is usually (but not always, especially on smaller cables) corrugated and about six mils thick. It is polymer coated on both sides to reduce corrosion. The tape material is typically an electrolytic chrome-coated steel (ECCS), although stainless steel and copper alloys also are used. In copper cables, the properties of both shield and armor can be combined in a single corrugated tape. A copper/iron alloy (six mils thick) or extra thick (ten mils) copper is used in this case. An inner jacket, which is similar in construction to the outer jacket, may be used in armored cables to reduce the chances of a kink or buckle in the cable.

Armored cables find applications in areas infested by gophers, beavers, squirrels, or other chewing rodents. The armor does not guarantee that rodents will not damage the cable, because rodents have incredibly powerful jaws; it does, however, reduce the likelihood of damage. Another application for armored cables is when they are installed in a severe physical environment, such as direct burial in sharp, broken rocks, where bedding sand is not available (or economical); or in lakes or stream crossings, where anchor or other boat-caused damage is possible.

In lakes and river crossings, a cable with a lead antimony alloy armor can be used to offset the natural buoyancy and weight the cable down. Otherwise, the cable can be installed with a submersible plow or weighted at intervals. Freshwater has a density of 62.4 lb/feet^3 and seawater has a density of 64 lb/feet^3. The volume of water displaced is that of a cylinder equal in dimensions to the cable. If the cable weight exceeds the weight of the water displaced, the cable will not float.

Specially made armored cables are available for true submarine service in oceans and deep lakes. Figure 7-5 is a photograph of heavily armored twisted pair and fiber optic cables for submarine service such as lakes and river crossings, and Figure 7-6 is a drawing of the cable components (in this case, a heavily armored fiber optic cable for water crossings). Special jacket materials can be provided for highly corrosive, potentially damaging, or chemically contaminated environments. The added protective layers are usually applied over standard cables.

Shielding

Outside plant twisted pair cables are most commonly shielded with corrugated aluminum or copper tape. Copper alloys and copper-clad stainless steel also are used. To increase corrosion resistance, the aluminum shield is bonded to a thin plastic (copolymer). This coating is not necessary with copper shields. A corrugated rather than smooth surface is used to increase shield strength and flexibility. The shield isolates the enclosed conductors from outside sources of electromagnetic interference (EMI), such as induction from powerline harmonic frequencies. The ability of a

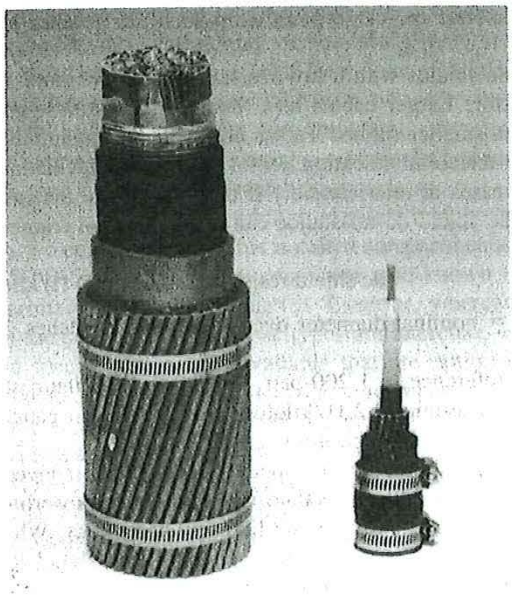


Figure 7-5 Comparison of heavily armored twisted pair and fiber optic cables
Taken from [30], with permission of AT&T Network Systems

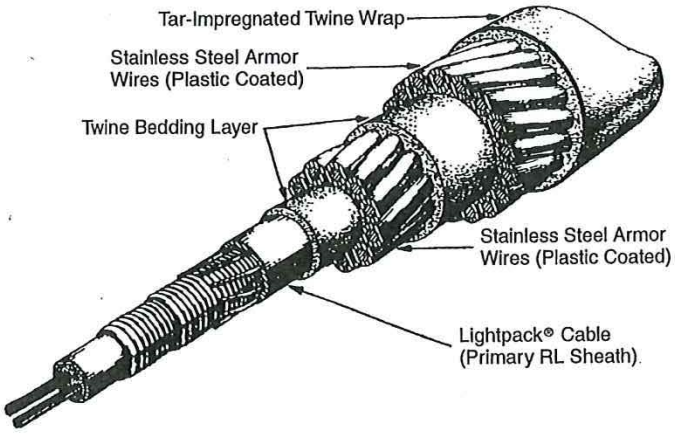


Figure 7-6 Components of heavily armored fiber optic cable
Taken from [30], with permission of AT&T Network Systems

shield to isolate the cable pairs from such interference is determined by its shield factor.

Cable shields with a low resistance and low mutual impedance have a higher shield factor. Larger cables have both these features, and so offer a better shield factor than smaller cables. Tables are available to simplify the calculation of shield factor for telecommunication cables, but these calculations are only needed in exceptional cases of interference.* If the diameter of the cable over the outer shield is known, the shield dc resistance can be determined from:

$$\text{dc shield resistance} = 0.75/D\ \Omega/\text{kilofoot}$$

where D = nominal diameter over the shield, in inches

For reference, a 1,200-pair, 24 gauge, aluminum shielded cable has a shield resistance of around 0.2 Ω/kilofoot; a 100-pair, 24 gauge cable has a shield resistance of almost 0.7 Ω/kilofoot.

The thin aluminum or copper shield used in conventional telecommunication cables does very little to isolate the pairs from powerline interference at the fundamental frequency (60 Hz) and first few harmonics. When it is necessary to shield a cable from these specific frequencies, an iron shield (for example, iron conduit) works best. The aluminum or copper shield is most effective at higher harmonic frequencies, which are annoying to the subscriber in analog service or can cause problems with digital transmission, due mostly to equipment upset. Since the telephone instrument and other terminal equipment—digital or analog—are designed to have little response at 60 Hz, induction at the fundamental powerline frequency usually is not a problem.

The shield in a given cable provides almost twice the shielding (induced voltage cut almost in half) at 540 Hz than it does at 60 Hz. Also, a cable with four times the diameter of another cable will provide twice the shielding. These low frequency-induced voltages have little direct interference on digital signals because of the relatively wide bandwidths used in digital transmission systems. If large enough, however, these voltages can upset the electronic circuitry used in digital regenerators or transmission equipment and cause the system to fail or produce excessive errors.

The shield thickness is generally 0.008 inch (eight mils) for aluminum and 0.005 inch (five mils) for copper. The different thicknesses are used to give approximately the same strength. Coated aluminum is the preferred shield because it is cheaper and is usable in all but the most demanding applications (such as some highly corrosive environments).†

---

*See [31] for calculation methods. If a particular interference problem is severe enough to require these calculations, it may be easier or more economical simply to reroute the cable or use a different transmission method. For example, fiber optic transmission systems are inherently immune to all forms of EMI in the outside plant environment.

†The cost of twisted pair cables naturally varies with the costs of the materials used to make them. The biggest variables are the costs of aluminum and copper. There may be times when a copper-shielded cable is cheaper than the same cable with an aluminum shield.

The shield is made continuous through splice points, such as vaults, manholes, aerial terminals, and pedestals, and connected to earth ground at regular intervals. Aerial messengers must be grounded at least four times per mile to comply with National Electrical Safety Code requirements.*

Shield continuity and grounding are very important; otherwise, the cable pairs are susceptible not only to noise but to damaging overvoltages during lightning activity, power faults, and power system switching transients.

For digital carrier applications, an additional shield may be used that separates the cable pairs into two compartments. This is called compartmental core or screened cable. "Z-Screen," "D-Screen," or "T-Screen" are well-known trade names. The last indicates the primary application, which is T-carrier, whereas the first two indicate the shape of the core separator. These types are interchangeable in almost all applications. Some special designs are available that are optimized for the digital rate to be carried on the cable. For example, the core separator in cables designed for T1C (DS-1C rate of 3.152 Mbps) service has more overlap, and provides more immunity to crosstalk at the higher frequencies, than cables optimized for repeatered T1 (DS-1 rate of 1.544 Mbps) service.

In a given cable, the transmit pairs are put in one compartment and the receive pairs are put in the other compartment. The separation is necessary to reduce crosstalk between the transmit and receive circuits of the transmission system.

The cross-section of a compartmental core cable is illustrated in Figure 7-7. The core separator, or screen, is made electrically continuous at all splice locations, but it is not deliberately grounded or connected to the cable shield (this is an important, but often overlooked, requirement).

Wrapped between the shield and the cable core of modern cables is a nonhygroscopic dielectric tape that provides additional insulation to increase the pair-to-shield withstand voltage.

Buffering

The term *buffering*, as it is used here, is borrowed from fiber optic technology, where it describes the protective measures used in fiber optic cable constructions.

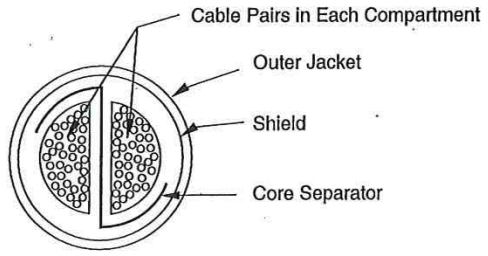


Figure 7-7 Compartmental core cable cross-section, [4] Reeve, © 1992 Institute of Electrical and Electronics Engineers. Reprinted with permission

*See section 92C of [27].

The term is easy to envision for any cable construction, however, and it is used here for that reason. In twisted pair cables, buffering is naturally provided by the outer jacket, armor (if used), and the conductor insulation itself, and no additional specific measures are required (unlike optical fibers as explained in the next chapter).

Strength Member

Unlike fiber optic cables, twisted pair telecommunication cables normally do not employ a separate strength member (although one can be specified if needed). Instead, the strength mostly comes from the conductors themselves and the jacket/shield/armor assembly.

When calculations are made to determine the maximum pulling tension for underground copper twisted pair cables, the following formula is used:

$$\text{Tmax} = 0.008 \times \text{CM} \times \text{N} \times 80\% \text{ lb}$$

where Tmax = maximum pulling tension in lb
CM = conductor area in circular mils
N = number of conductors (N = 2 × number of cable pairs)

The maximum tension formula can be rewritten for the common cable gauges, as follows:

$$\text{Tmax}(19) = 16.5 \times \text{no. pairs}$$

$$\text{Tmax}(22) = 8.2 \times \text{no. pairs}$$

$$\text{Tmax}(24) = 5.2 \times \text{no. pairs}$$

$$\text{Tmax}(26) = 3.3 \times \text{no. pairs}$$

where Tmax(AWG) is the maximum tension in lb for the gauge indicated

The foregoing formulas assume a pulling eye is used. A pulling eye is soldered to each individual conductor to transfer the pulling strain uniformly throughout the cable cross-section. Pulling eyes are difficult to apply in the field (they are usually factory installed), so basket grips are used in a large number of installations. If a basket grip is used, the maximum pulling tension is the calculated Tmax or 1,000 lbs, whichever is less. The lesser tension takes into account that the pulling force is transferred directly to the sheath and only indirectly to the conductor itself.

Cable Pairs

Probably the most significant part of a twisted pair digital loop, in terms of investment, is the outside plant cable pair itself. An individual pair comprised of tip and ring conductors is inherently bidirectional; that is, it will work just as well for transmission or reception in either direction. In common digital loop applications, however, with the exception of basic rate integrated services digital network (ISDN) digital subscriber line (DSL), and the high bit-rate digital subscriber line (HDSL), two cable pairs (four conductors) are used to provide independent transmit and re-

ceive paths. Associated with each cable pair of either the 2-wire or 4-wire digital loop are ancillary devices for protection and termination, and repeaters for regenerating the digital signal on long loops.

Twisted pair copper telecommunication cables can be obtained in any of four gauges, as shown in Table 7-6. Aluminum conductors have seen limited use in telecommunications. Aluminum conductors provide approximately the same conductivity as copper when they are two gauge sizes larger. For example, a 20 AWG aluminum conductor provides approximately the same conductivity as a 22 AWG copper conductor.

Table 7-7 gives the dc loop resistance per unit length for the different copper cable pair gauges at different temperatures. The loop resistance at temperatures not shown in the table can be found from:

$$R_T = R_{T0}[1 + \rho_{T0}(T - T_0)]$$

where R_T = resistance at temperature T
R_{T0} = resistance at reference temperature T_0
ρ_{T0} = temperature coefficient of resistivity per °C at temperature T_0

For copper, ρ_{T0} = 0.00401/°C at 15 °C and 0.00393/°C at 20 °C. Figure 7-8 shows the loop resistance as a function of loop length for each gauge at typical design temperatures.

For economic reasons, analog and digital signals may be carried on the same cable. When combined service is used, the cables are commonly referred to as exchange cables. When a cable is dedicated to digital service between central offices, it is sometimes referred to as a trunk cable.* Exchange cables are available in stan-

Table 7-6 Twisted Pair Copper Conductor Gauges[a]

American Wire Gauge (AWG)	Diameter (inch)	Cross-Section (CM)[b]	Equivalent Diameter (mm)
19	0.03589	1,288	0.912
22	0.02535	642.4	0.643
24	0.02010	404.0	0.511
26	0.01594	254.1	0.404

[a]Source: [32]
[b]CM = circular mils = (diameter in mils)^2

Table 7-7 DC Loop Resistance of Copper Twisted Pairs (Ω/kilofoot)

Design Temperature	19 AWG	22 AWG	24 AWG	26 AWG
13 °C (55 °F)	15.9	31.7	50.3	81.1
38 °C (100 °F)	17.4	34.8	55.3	89.2
60 °C (140 °F)	18.9	37.7	59.8	96.5

*A trunk cable is more strictly defined as a cable not providing exchange service to individual subscribers, but instead providing trunk service between exchanges. In the digital transmission environment the difference becomes less clear.

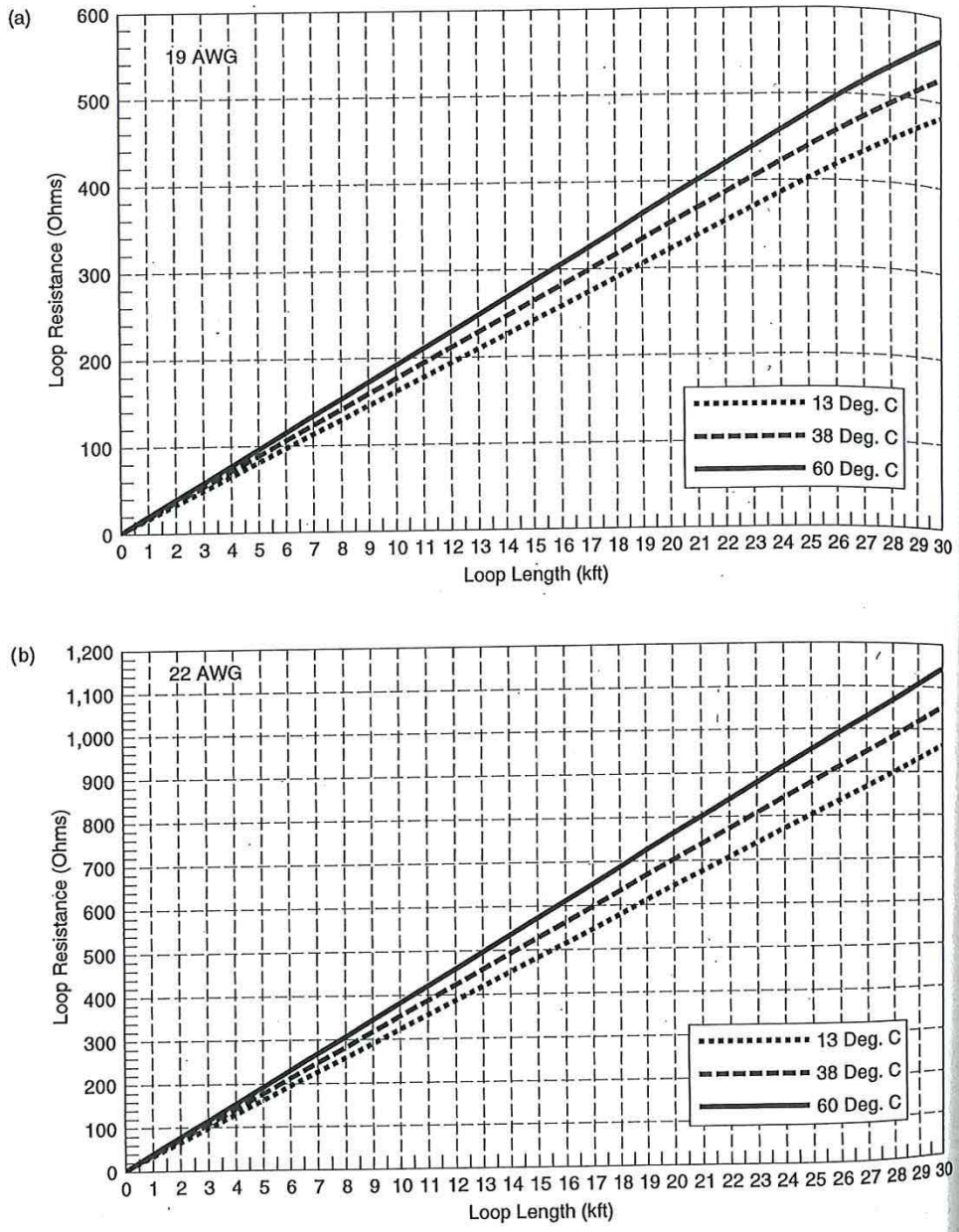
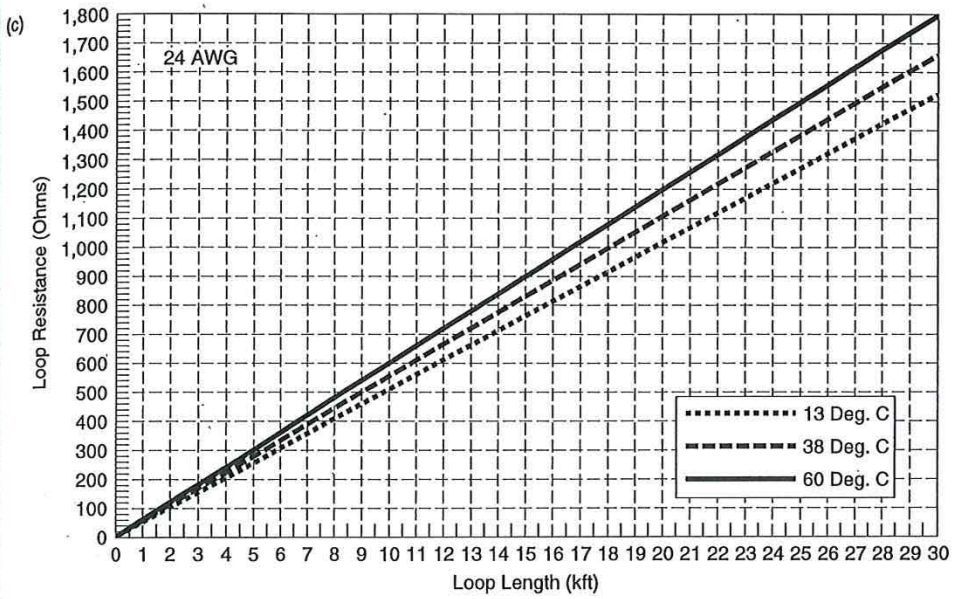


Figure 7-8 dc loop resistance vs. loop length: (a) 19 AWG; (b) 22 AWG; (c) 24 AWG; (d) 26 AWG



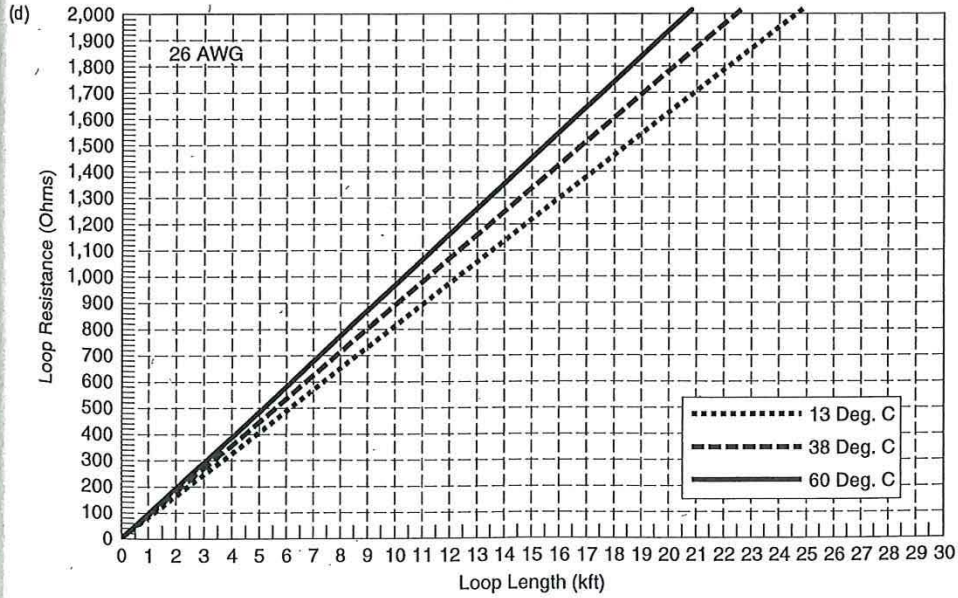


Figure 7-8 Continued

dard pair counts, from six to 4,200 pairs. The smaller sizes (up to 150 or 200 pairs) present particular problems with high-speed digital transmissions because of crosstalk between the unavoidably close-spaced transmit and receive pairs.

To alleviate the crosstalk problem, compartmental core cables are available in cables sizes from 12 to 200 pairs. In larger, noncompartmental core cables, the transmit and receive pairs are physically separated, and crosstalk reduced, by appropriate selection of binder groups for each transmission direction. If separation is not possible, repeater spacing or loop length must be reduced.

When cables up to around 1,200 pairs are manufactured for direct burial and aerial applications, the core may be filled with a polyethylene/petroleum jelly, extended thermoplastic rubber, or extended petroleum wax to prevent insulation damage and higher attenuation from moisture intrusion. Alternately, these cables may be built with an air core (absence of a filling compound) and then pressurized after installation with dry air to prevent moisture ingress. All larger cables (above 1,200 pairs) are pressurized unless the cables are specially ordered with a filling compound.

Moisture in a cable increases its capacitance. With higher capacitance comes higher attenuation, which can be as much as 40% over dry values at voice frequencies. Expanded foam cables are always filled because they are especially sensitive to moisture.

It is virtually impossible to keep moisture out of unpressurized, air core cables installed in an outdoor environment over a long period, regardless of the service classification. This applies to aerial, direct buried, and underground cables. If pressurization is not available, or if the cable is relatively small, filled cables provide much better long-term service than unpressurized, air core cables in all service classifications. Contrary to fairly common practice among some companies, unpressurized air core cables never should be placed underground or directly buried if the goal is long-term, trouble-free service.

Historically, telecommunications terminal equipment has been sensitive to the polarity of the tip and ring conductors. For switched subscriber loops, the tip conductor normally is at ground potential and the ring conductor is at battery potential (−48 V nominal). Conductors in pairs used for dedicated digital loops normally have no specified polarity, even though these frequently are designated tip and ring.

Color Coding

Many pairs are combined together to form the cable. The individual pairs are formed into units and the units are then assembled, or cabled, into cores (much like a rope). The basic unit of most modern cables contains 25 pairs, which are color coded for identification, as shown in Table 7-8.* Note also the repetitive color code for the tracer every five pairs. When necessary, the basic unit is divided into subunits of 12 or 13 pairs to attain cable roundness and the desired pair count.

The color code is used as follows. The basic color of the tip conductor insulation material is the first color shown in the table. The insulation has a striped tracer

*Appendix D provides cable core layout details for most cable types.

Table 7-8 Telephone Pair Color Code—25-Pair Unit Binder Group

Pair No.	Color (Tip-Ring)	Pair No.	Color (Tip-Ring)	Pair No.	Color (Tip-Ring)
1	White-blue	11	Black-blue	21	Violet-blue
2	White-orange	12	Black-orange	22	Violet-orange
3	White-green	13	Black-green	23	Violet-green
4	White-brown	14	Black-brown	24	Violet-brown
5	White-slate	15	Black-slate	25	Violet-slate
6	Red-blue	16	Yellow-blue		
7	Red-orange	17	Yellow-orange		
8	Red-green	18	Yellow-green		
9	Red-brown	19	Yellow-brown		
10	Red-slate	20	Yellow-slate		

of the second color. The reverse is true of the ring conductor; that is, the basic color is the second color shown in the table and the tracer is the first color. For example, the basic color of pair 1 tip conductor is white and the tracer is blue, and the basic color of the ring conductor is blue and the tracer is white.

In cables larger than 25 pairs, the groups (or units) are wrapped with a colored tracer ribbon (unit or group binder) according to a similar color coding scheme, as shown in Table 7-9. For example, a 100-pair cable contains four groups of 25 pairs each. The first group (pairs 1 to 25) is wrapped with a white-blue binder, the second group (pairs 26 to 50) is wrapped with a white-orange binder, and so on. Since there are 25 basic colors in the color code, up to twenty-five 25-pair groups can be identified this way. Only 24 are used, however, which takes care of cables up to 600 pairs. Beyond 600 pairs, "super unit binders" are used. Each 600-pair super unit is wrapped with an appropriate binder. This color code is shown in Table 7-10. Figure 7-9 shows the unit and super unit relationships in a 3,000-pair exchange cable.

Table 7-9 Group Binder Color Code[a]

Pair Group	Group No.	Color (Tip-Ring)	Pair Group	Group No.	Color (Tip-Ring)
1–25	1	White-blue	301–325	13	Black-green
26–50	2	White-orange	326–350	14	Black-brown
51–75	3	White-green	351–375	15	Black-slate
76–100	4	White-brown	376–400	16	Yellow-blue
101–125	5	White-slate	401–425	17	Yellow-orange
126–150	6	Red-blue	426–450	18	Yellow-green
151–175	7	Red-orange	451–475	19	Yellow-brown
176–200	8	Red-green	476–500	20	Yellow-slate
201–225	9	Red-brown	501–525	21	Violet-blue
226–250	10	Red-slate	526–550	22	Violet-orange
251–275	11	Black-blue	551–575	23	Violet-green
276–300	12	Black-orange	576–600	24	Violet-brown

[a]In cables of 100 pairs (4 groups) or fewer, the white binder is optional.

Table 7-10 Super Unit Binder Color Code

Super Unit	Binder Color
Pairs 1 to 600	White
Pairs 601 to 1,200	Red
Pairs 1,201 to 1,800	Black
Pairs 1,801 to 2,400	Yellow
Pairs 2,401 to 3,000	Violet
Pairs 3,001 to 3,600	Blue
Pairs 3,601 to 4,200	Orange

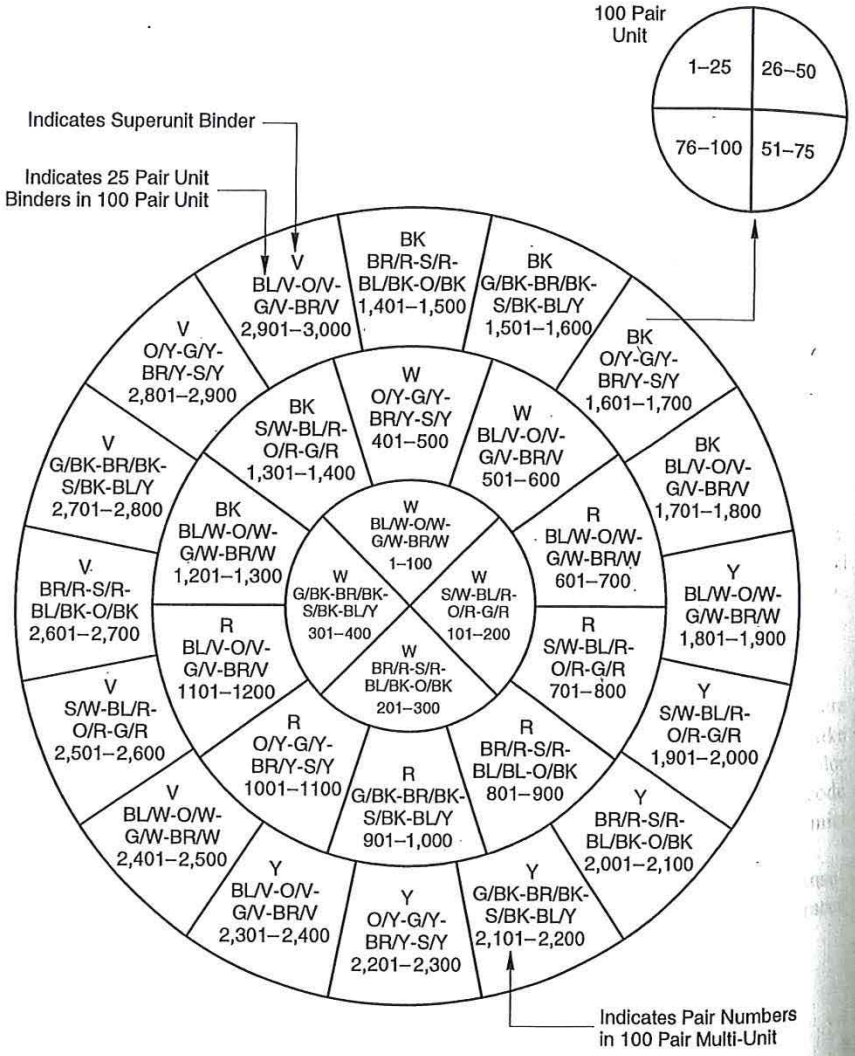


Figure 7-9 Super unit cable layout

On large exchange cables consisting of 1,200 pairs or more, the mirror-image color code and unit arrangement can be obtained, if desired. This color code is sometimes called the "Bell Design" and differs from the unit and super unit binder groups described above. For mirror-image cables, the 25-pair units are assembled into 100-pair multi-units. Each unit is identified by a standard color sequence binder: blue (pairs 1 to 25); orange (pairs 26 to 50); green (pairs 51 to 75); and brown (pairs 76 to 100).

Multi-units in a mirror-image cable are identified by a two-color binder and layering scheme. The first multi-unit in each layer has a green binder, which designates the "marker" unit. Marker units are situated radially, and a red and a blue unit are placed on each side, as shown in Figure 7-10, for a 3,000-pair mirror-image cable. The second color in the multi-unit binder indicates the layer and alternates between yellow and black. The outermost layer is yellow, second layer in is black, third layer in is yellow, and so on. Therefore, the outermost marker will have a green-yellow binder, and the marker for the "second layer in" will have a green-black binder.

With one's back to the central office, the pair counts of mirror-image cables start with the centermost marker multi-unit, with pairs 1 to 100, and continue clockwise to pairs 101 to 200 in the second multi-unit (red), and so on. The count continues through subsequent layers by following the same counting rules, always starting with the marker unit.

The most common residential type station wire (also known as "quad" or inside/outside wire, I/O) consists of four conductors, with the color code shown in Table 7-11. Quad normally is not recommended for digital service because of its limited twisting (and higher crosstalk), but it can be used on short runs (<50 feet) at subrates when nothing else is available.

Other types of multipair station wire will conform to the color code shown in Table 7-8. In addition, various other color codes are used for wiring electronic equipment, some of which may be used in telecommunication systems.

Table 7-11 Quad Station Wire Color Code[a]

Pair No.	Color (Tip-Ring)
1	Green-red
2	Black-yellow

[a]The yellow conductor (or yellow and black conductors together) is used as a ground lead, if required, by the terminal equipment.

Conductor Insulation

All modern cable conductors are insulated with a polyolefin (plastic) formed by an extrusion process. Older cables use a paper (or pulp) insulation. PIC, as defined earlier, is a general term used to describe all modern plastic insulated cables. Such cables may use solid, cellular foam, or foam skin (skinned foam) insulation. The actual insulation type may be classified as solid (polyethylene or polypropylene) or expanded foam (dual expanded polyethylene or expanded polyethylene, PVC).

CommScope Exhibit 1017

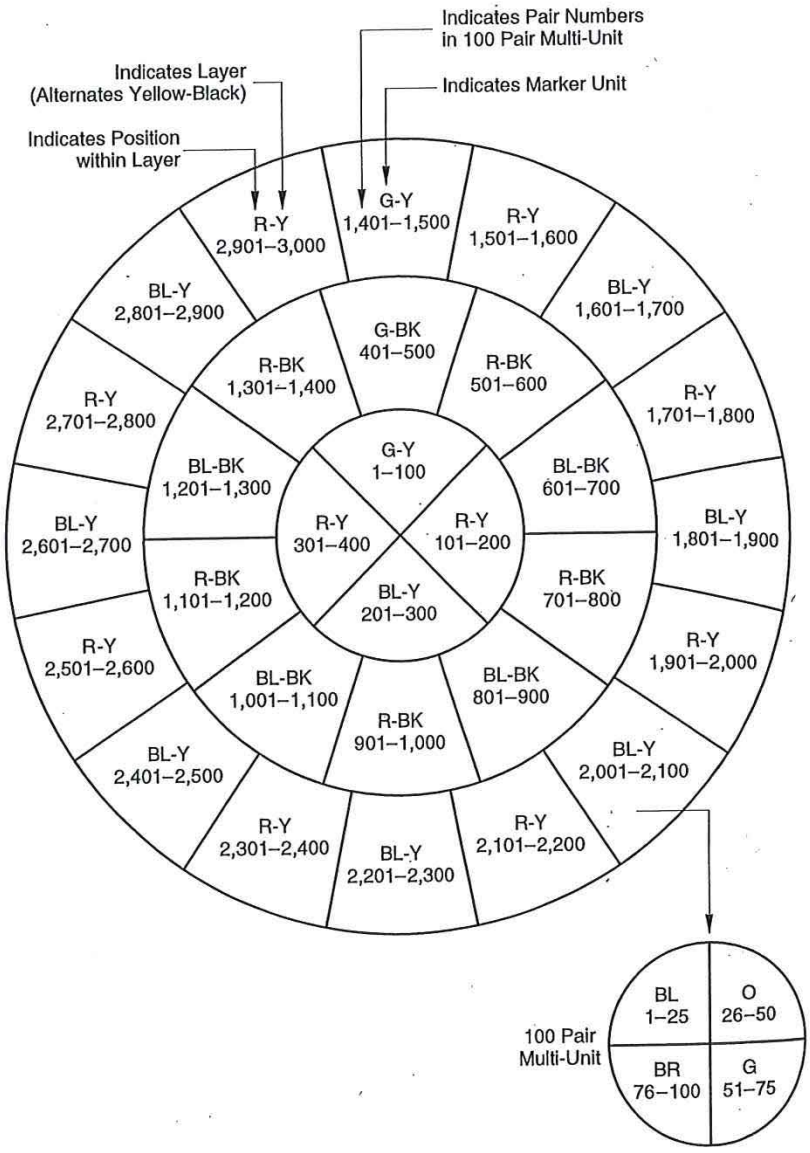


Figure 7-10 Mirror-image cable pair layout

A combination of solid and foam insulation is used in foam skin cables. In these cables, the regular foam insulation is covered by a solid plastic skin of about 2-mil thickness for added strength. Expanded foam cables have found widespread use since about 1980.

The dimensions and dielectric constant of the insulation and surrounding material determine the capacitance of twisted pair cables. The dimensions are shown in Figure 7-11 for each of the common cable gauges. The dielectric constant of solid plastic insulations used in exchange cables is about 2.3, whereas the dielectric constant of the expanded foam is about 1.6. Insulation thicknesses vary from about 10 mils for solid insulations, used in air core cables and filled foam cables, to about 14 mils for solid insulations used in filled cables. The relationship for twisted pair capacitance is

$$C = \frac{K\varepsilon}{\log\left(\frac{1.5D}{d}\right)} \text{ nF/length}$$

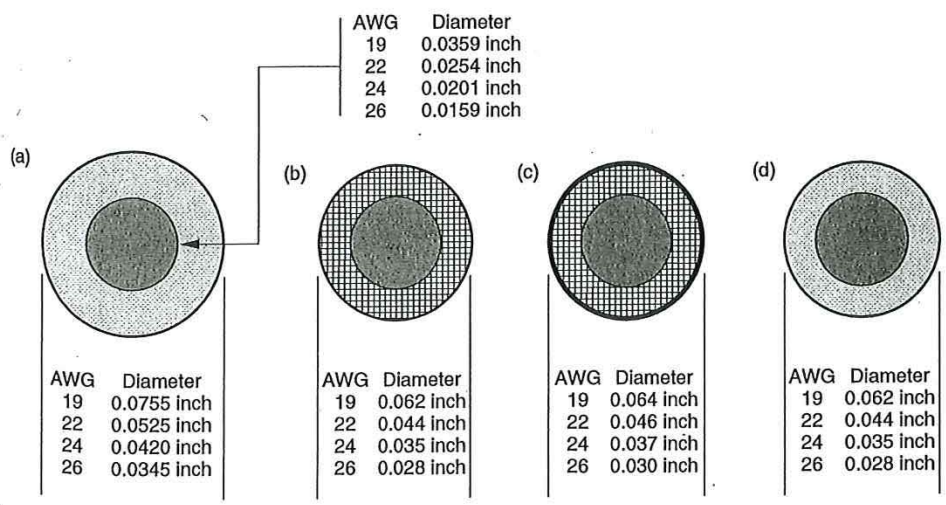


Figure 7-11 Twisted pair insulation and conductor dimensions: (a) Filled core/solid insulation; (b) Filled core/foam insulation; (c) Filled core/skinned-foam insulation; (d) Air core/solid insulation

CommScope Exhibit 1017

where K = constant of proportionality, which depends on the dielectric properties of the medium surrounding the insulation (either air or filling compound)
ε = dielectric constant of the insulating material
D = diameter of the insulation
d = diameter of the conductor (units of D and d must be the same)

The transmission performance of the different conductor insulations is the same at voiceband frequencies, but this is not the case at the higher frequencies. The transmission performance of expanded foam cables at digital carrier frequencies falls between solid insulated air core and solid filled core cables at 772 kHz, which is the Nyquist frequency for repeatered T1-carrier.

A key indicator of performance is attenuation, which is given in Table 7-12 for various insulation types and frequencies. The values shown are averages for a wide variety of cables. Significant deviations exist for specific cable types at 772 kHz. A more complete list is given for this frequency in Chapter 9.

Table 7-12 Average Attenuation of PICs at 20 °C (68 °F)

AWG	1 kHz	150 kHz	772 kHz
		Solid Insulation—Filled Core	
19	0.23 dB/kft	1.3 dB/kft	2.8 dB/kft
22	0.34 dB/kft	1.8 dB/kft	4.0 dB/kft
24	0.43 dB/kft	2.4 dB/kft	5.0 dB/kft
26	0.55 dB/kft	3.5 dB/kft	6.4 dB/kft
		Foam or Foam-Skin—Filled Core	
19	0.23 dB/kft	1.4 dB/kft	3.2 dB/kft
22	0.34 dB/kft	2.0 dB/kft	4.5 dB/kft
24	0.43 dB/kft	2.7 dB/kft	5.6 dB/kft
26	0.55 dB/kft	3.7 dB/kft	7.0 dB/kft
		Solid Insulation—Air Core	
19	0.23 dB/kft	1.4 dB/kft	3.3 dB/kft
22	0.34 dB/kft	2.0 dB/kft	4.6 dB/kft
24	0.43 dB/kft	2.7 dB/kft	5.7 dB/kft
26	0.55 dB/kft	3.6 dB/kft	7.2 dB/kft

7.6.2.9 Cable Costs

Twisted pair cable costs vary considerably with gauge, construction, and the current cost of copper and aluminum (if that type of shield is used). Nineteen gauge cable can be twice as expensive as 24 gauge cable for a given pair count. Filled cable is 10 to 25% more expensive than air core cable, depending on the gauge and pair count. Expanded foam insulation cables are less expensive than comparable solid insulation cables by 7 to 20%, depending on the gauge and pair count.

Tables 7-13 and 7-14 give multipliers to find the relative material costs for various cable gauges and sizes. Multipliers for adding a compartmental core separator (screen) to exchange cables are shown in Table 7-15. The use of each cable is explained in the note below it.

Table 7-13 Relative Costs of Twisted Pair Cable Gauges and Sizes Compared to 24 AWG

	Pairs							
AWG	12	25	50	100	200	400	900	1,200
26	0.72	0.73	0.82	0.78	0.77	0.76	0.77	0.76
24	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
22	1.18	1.21	1.41	1.31	1.43	1.40	1.36	1.37
19	1.94	2.33	2.59	2.59	2.56	2.57	N/A	N/A

This is a vertically oriented matrix where costs are shown relative to 24 gauge, filled PIC, 8-mil aluminum shield. For example, a 26 AWG, 100-pair cable is 78% of the cost of a 24 AWG, 100-pair cable, and a 22 AWG, 400-pair cable is 140% of the cost of a 24 AWG, 400-pair cable.

Table 7-14 Relative Costs of Twisted Pair Cable Sizes for a Given Gauge

	Pairs							
AWG	12	25	50	100	200	400	900	1,200
26	0.22	0.34	0.57	1.00	1.86	3.72	8.18	10.44
24	0.23	0.35	0.54	1.00	1.91	3.71	8.31	10.73
22	0.20	0.32	0.58	1.00	2.08	3.96	8.62	11.22
19	0.17	0.31	0.54	1.00	1.88	3.68	N/A	N/A

This is a horizontally oriented matrix where costs are shown relative to a 100-pair cable of a given gauge. For example, a 26 AWG, 50-pair cable is 57% of the cost of a 26 AWG, 100-pair cable, and a 22 AWG, 400-pair cable is 396% of the cost of a 22 AWG, 100-pair cable.

Table 7-15 Multiplier for Adding Compartmental Core Separator to a Cable

	Pairs							
AWG	12	25	50	100	200	400	900	1,200
26	1.19	1.16	1.12	1.10	1.06	1.08	1.07	N/A
24	1.15	1.13	1.10	1.08	1.05	1.06	1.06	N/A
22	1.23	1.22	1.14	1.13	1.08	1.10	1.10	N/A
19	1.18	1.16	1.11	1.09	1.06	N/A	N/A	N/A

This matrix gives multipliers for adding a compartmental core separator (screen) to a cable of given size and gauge. For example, to determine the cost of adding a screen to a 26 AWG, 50-pair exchange cable, multiply its cost by 1.12, and to determine the cost of adding a screen to a 22 AWG, 200-pair exchange cable, multiply its cost by 1.08.

7.6.3 Electrical Characteristics

7.6.3.1 Bandwidth

Digital loops consist of one or two cable pairs. The cable pair is a transmission line, and it has predictable electrical characteristics. Twisted pair cables are not used presently with digital transmission systems requiring more than several megahertz of bandwidth for several reasons, as will be discussed. For comparison with voice-

band applications, the usable bandwidth on an analog loop is considered to be limited to around 3,100 Hz (300 to 3,400 Hz) [4]. The limitation is due to the coupling transformers and other devices connected to voiceband loops.

In digital loops, a much wider bandwidth is needed for information transmission. This point is often missed in preliminary considerations of the advantages of digital transmission and cannot be overemphasized. For example, a digitally encoded voicegrade (3,100 Hz) circuit could actually require a transmission line bandwidth of as much as 64 kHz.

It is important to realize the difference between circuit bandwidth and transmission bandwidth. Figure 7-12 shows the power spectral density of a hypothetical voiceband signal that has been encoded at an 8 kHz rate into 8-bit samples (64 kbps), filtered by a first-order Butterworth lowpass filter, and transmitted using a return-to-zero (RZ), bipolar, alternate mark inversion (AMI) line code. The main lobe of the spectrum is centered at 32 kHz and extends out to at least 64 kHz.

The frequency response of a loop derived entirely from twisted pairs extends down to dc (zero frequency). Digital loop transmission systems avoid using dc for information carrying, so the loops can be transformer-coupled to regenerators. DC continuity is still required in the metallic loop circuit, however, for loop powering schemes and sealing current. When signals with frequency content approaching zero frequency are placed on the loop, the transmission is considered to be in the baseband.

A twisted pair digital loop has no precise upper frequency limit. Transmission systems using the loop are designed to accommodate its attenuation characteristics over the required bandwidth. For example, the T1C system, which operates at 3.152

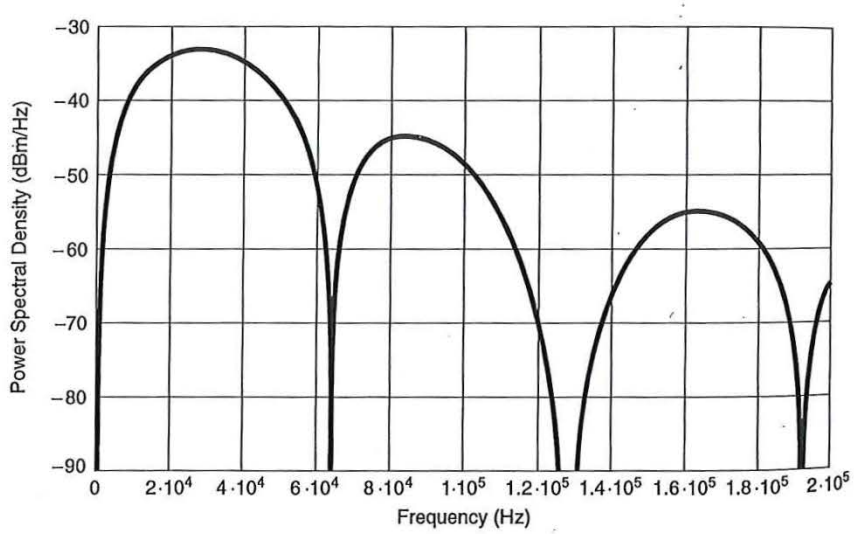


Figure 7-12 Power spectral density of a 64 kbps digitally encoded voiceband signal using bipolar AMI transmission

Mbps, has a bandwidth requirement of about 3.152 MHz. This one-for-one bit rate to bandwidth correspondence does not hold for all digital transmission systems. The T1C has the highest bandwidth requirements (and bit rate) of digital loop systems using twisted pair cable considered in this book.*

7.6.3.2 Transmission Line Primary Constants

Like all transmission lines, twisted pairs can be described by their fundamental electrical characteristics, or primary constants.† The primary constants are series inductance L, shunt capacitance C, shunt conductance G, and series resistance R. These are described in customary electrical units per unit length. Figure 7-13 shows a T-equivalent circuit commonly used to represent telecommunication transmission lines.

Inductance L of the typical cable pair depends on the geometry of the conductors and is affected by the magnetic flux distribution within and around them. It is around 0.19 mH/kilofoot at voice frequencies for air core PIC and about 7 to 10% higher for filled PIC. Due to skin effect, inductance starts to decrease at about 20 kHz and continues to decrease to at least 5 MHz.‡

Capacitance C depends on the geometry of and dielectric medium between the two conductors of the twisted pair. It is standardized during manufacture at 12.5 or 15.7 nF/kilofoot (66 or 83 nF per mile), although cables with different values are available. Cable with 15.7 nF/kilofoot capacitance is the most common in digital loop applications, but a special low-capacitance cable, with 12.5 nF/kilofoot, is preferred for higher bit-rate systems such as the 3.152 Mbps T1C system. For all practical purposes, capacitance is independent of frequency.

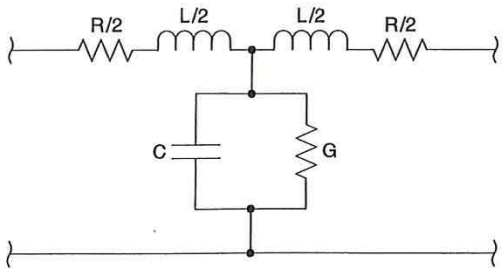


Figure 7-13 Transmission line T-equivalent circuit in terms of primary constants

*The differences between digital loop systems, digital backbones, and digital trunk transmission systems are becoming less clear as these systems become more prevalent. It is arguable whether a digital system operating at the DS-3 rate (45 MBPS) can be considered a digital loop system.

†As will be seen, the primary constants are not really constant, but the terminology is traditional and will be used here.

‡Skin effect is the tendency for higher-frequency currents to travel near the outside surface of a conductor rather than be distributed evenly throughout the entire cross-section.

Conductance G depends on the dielectric medium between the conductors and is negligible at about 0.04 microsiemen (μS) per kilofoot at 1 kHz for modern cables. It increases by a factor of ten for each decade (factor of ten) increase in frequency. The value can vary considerably from those given here, due to different insulation types and core filling compounds.

Resistance R, measured in Ω/kilofoot, depends on the resistivity of the conductors and the current distribution within them. It is constant at lower frequencies (less than a few hundred hertz) but is approximately proportional to the square root of frequency at higher frequencies (above several tens of kilohertz) where skin effect and proximity effect dominate. The resistance of each conductor gauge is different due to the different cross-sectional area.

The primary constants are affected by temperature in different ways. Some primary constants depend on whether the cable has a filled or air core. The following summarizes the temperature effects:

- Inductance varies only slightly with temperature (1.8% from −18 to +49 °C).
- Capacitance of filled cables decreases linearly at a rate of 0.016% per °C over the frequency range of 1 kHz to 3 MHz. This is attributed to a decrease in insulation density, cable expansion, and a decrease in dielectric constant with temperature increase. In air core cables, the capacitance varies only slightly with temperature over the same frequency range [38].
- Conductance varies only negligibly with temperature.
- Resistance is highly temperature dependent, increasing by about 4% for each 10 °C increase in conductor temperature at voice frequencies and 2 to 3% at frequencies higher than 10 kHz.

Tables 7-16 and 7-17 give the primary constants for typical cable pair gauges at selected frequencies [33]. A more complete listing of outside plant characteristics is given in Appendix C. Figure 7-14 shows the variation of the primary constants with frequency in graphical form (capacitance is not shown because it is frequency independent).

7.6.3.3 Secondary Parameters

The propagation constant ($\rho = \alpha + j\beta$) and characteristic impedance (Z_0) are the secondary parameters used to describe transmission line characteristics.* These parameters, which are functions of frequency, can be found from the primary constants from

$$\rho = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)}$$

where ω is the radian frequency, 2πf.

*The secondary parameters are mathematically derived from the primary constants in [4]. Simplified analyses of twisted pair cable secondary parameters when the primary constants are known, and primary constants when secondary parameters are known, are covered rather well in [34]. There are numerous other sources of information on twisted pair transmission characteristics; see [33–37].

Table 7-16 Air Core PIC, Exchange Cable Pair Primary Constants, 20 °C

FREQUENCY (kHz)	R (Ω/KFT)	L (mH/KFT)	C (nF/KFT)	G (μS/KFT)
		19 AWG		
1	16.1	0.182	15.7	0.0398
40	18.7	0.173	15.7	1.58
192	35.3	0.156	15.7	7.58
772	70.2	0.144	15.7	30.4
1,576	98.9	0.140	15.7	62.0
		22 AWG		
1	32.4	0.184	15.7	0.0398
40	34.2	0.177	15.7	1.58
192	50.4	0.167	15.7	7.58
772	100.8	0.151	15.7	30.5
1,576	141.2	0.146	15.6	62.0
		24 AWG		
1	51.3	0.181	15.7	0.0398
40	53.0	0.175	15.7	1.58
192	67.0	0.167	15.7	7.58
772	127.7	0.151	15.7	30.5
1,576	182.1	0.145	15.6	62.0
		26 AWG		
1	82.0	0.183	15.7	0.0398
40	83.6	0.177	15.7	1.58
192	94.4	0.172	15.7	7.59
772	159.8	0.159	15.7	30.5
1,576	230.3	0.152	15.7	62.0

The propagation constant is a complex number consisting of real and imaginary parts. In general, it describes the attenuation and phase characteristics of any transmission line. The real portion of the propagation constant, denoted Re(ρ), is called the attenuation constant α, and the imaginary portion, denoted Im(ρ), is called the phase constant β. The attenuation constant is expressed in Nepers per unit length and the phase constant, in radians per unit length.*

The characteristic impedance is independent of length. It, too, can be found from the primary constants:

$$Z_0 = \sqrt{\frac{(R + j\omega L)}{(G + j\omega C)}}$$

The equations for the secondary parameters can be simplified somewhat for modern outside plant PIC, as follows:

$$\rho = \sqrt{-\omega^2 LC + j\omega RC} \text{ for frequency } < 500 \text{ kHz, and}$$

*A more convenient unit than the Neper is the decibel such that 1 Neper = 8.686 dB.

Table 7-17 Filled Core PIC, Exchange Cable Pair Primary Constants, 20 °C

FREQUENCY (kHz)	R (Ω/KFT)	L (mH/KFT)	C (nF/KFT)	G (μS/KFT)
		19 AWG		
1	16.1	0.212	15.7	0.0398
40	18.2	0.202	15.7	1.58
192	32.8	0.189	15.7	7.58
772	63.8	0.178	15.7	30.5
1,576	89.6	0.174	15.6	62.0
		22 AWG		
1	32.4	0.212	15.7	0.0398
40	33.9	0.205	15.7	1.58
192	47.7	0.196	15.7	7.59
772	93.0	0.182	15.7	30.5
1,576	129.4	0.178	15.7	62.0
		24 AWG		
1	51.3	0.212	15.7	0.0398
40	52.7	0.206	15.7	1.58
192	64.1	0.199	15.7	7.58
772	117.4	0.186	15.7	30.5
1,576	165.5	0.180	15.6	62.0
		26 AWG		
1	82.0	0.212	15.7	0.0398
40	83.3	0.205	15.7	1.58
192	92.1	0.200	15.7	7.59
772	149.4	0.190	15.7	30.5
1,576	212.7	0.183	15.7	62.0

See text for discussions of R, L, C, and G.

$$\rho = \frac{R}{2}\sqrt{\frac{C}{L}} + j\omega\sqrt{LC} \text{ at higher frequencies}$$

with

$$\alpha = \mathrm{Re}(\rho) \text{ and } \beta = \mathrm{Im}(\rho) \text{ as before}$$

$$Z_0 = \sqrt{\frac{L}{C} - j\frac{R}{\omega C}} \text{ for frequency } < 500 \text{ kHz}$$

$$Z_0 = \sqrt{\frac{L}{C}} \text{ at higher frequencies}$$

The characteristic impedance also is a complex number. At low frequencies (around 1 kHz), the real and imaginary parts are about equal in magnitude. At higher frequencies (above 100 kHz), the imaginary part becomes small, and the impedance is essentially constant and real at approximately 100 Ω.

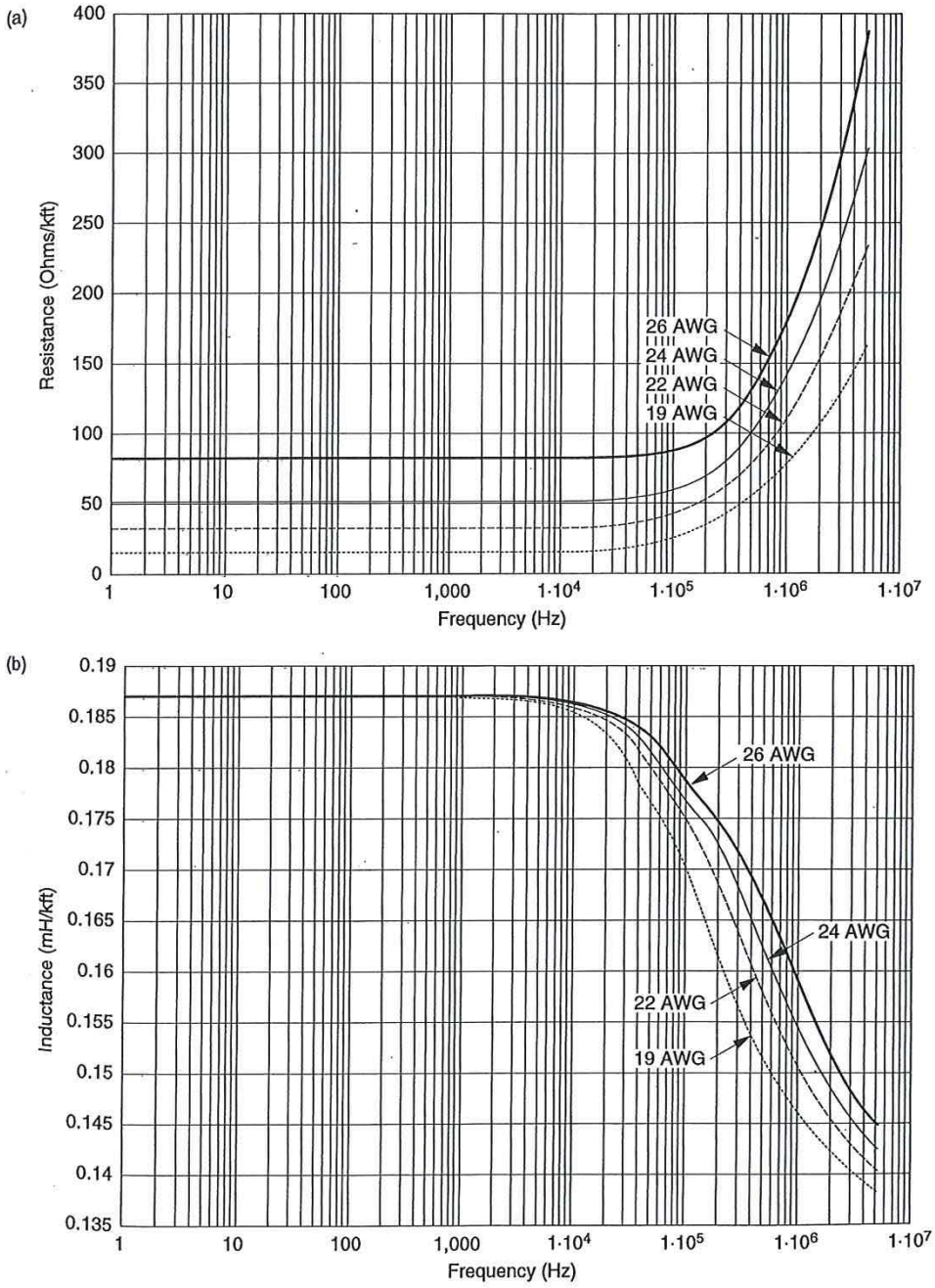


Figure 7-14 Twisted pair primary constants for typical PIC at 21 °C: (a) Resistance vs. frequency; (b) Inductance vs. frequency; (c) Conductance vs. frequency

 CommScope Exhibit 1017

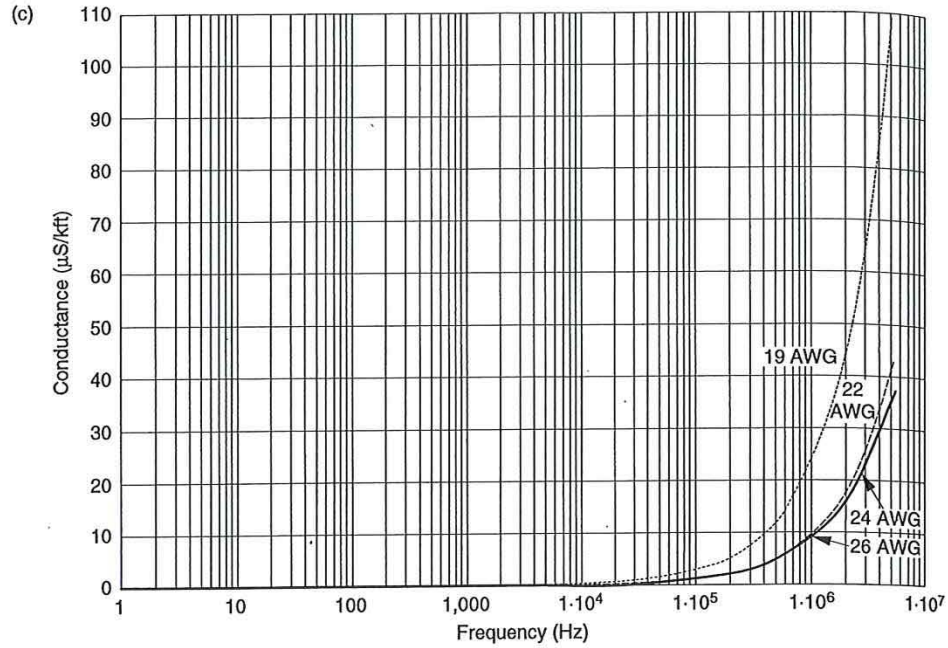


Figure 7-14 Continued

For perfectly matched transmission lines, the characteristic impedance is independent of transmission line length. A constant real impedance is easy to match with modern terminal equipment. In some applications, however, due to impedance mismatching of the loop by its terminations, the actual circuit input impedance (as opposed to the theoretical cable pair characteristic impedance shown above) varies with loop length. An expression for the input impedance of a real loop is:

$$Z_{in} = Z_0\{[Z_T + Z_0 \tanh(\rho l)]/[Z_0 + Z_T \tanh(\rho l)]\}$$

where Z_T = impedance of the load connected to the loop
tanh = hyperbolic tangent function
l = length
Z_0 and ρ have been previously defined

The secondary parameters are shown in Figures 7-15 and 7-16 for exchange cables. The values shown are sufficiently accurate for many practical situations, such as insertion loss and impedance matching problems. If greater accuracy is required, actual test data can be obtained from the cable manufacturers or actual field installations.

As with the primary constants, secondary parameters are temperature dependent. Attenuation is related to temperature such that the higher the temperature, the

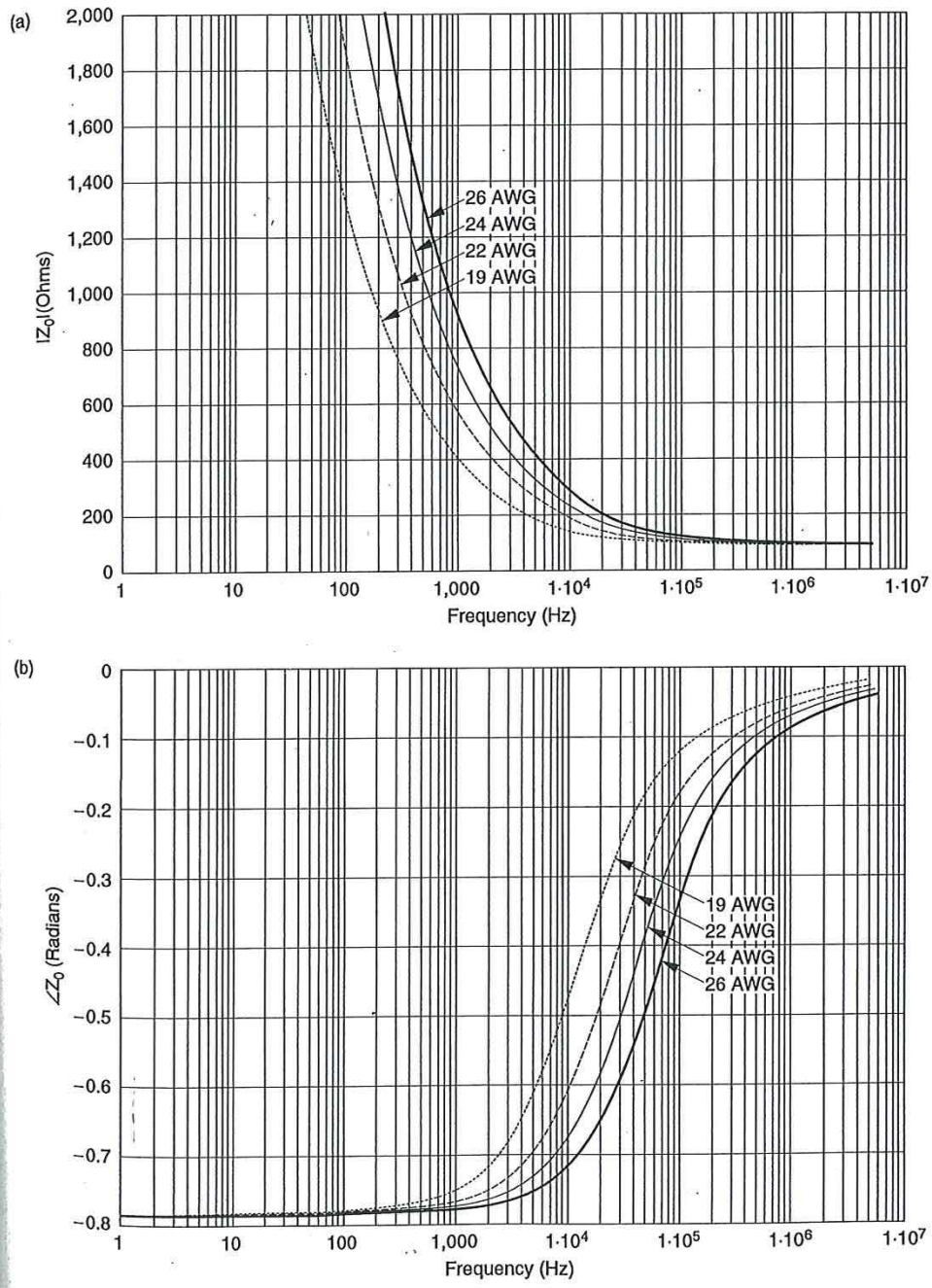


Figure 7-15 Twisted pair secondary parameters, characteristic impedance: (a) Impedance magnitude; (b) Impedance angle

 CommScope Exhibit 1017

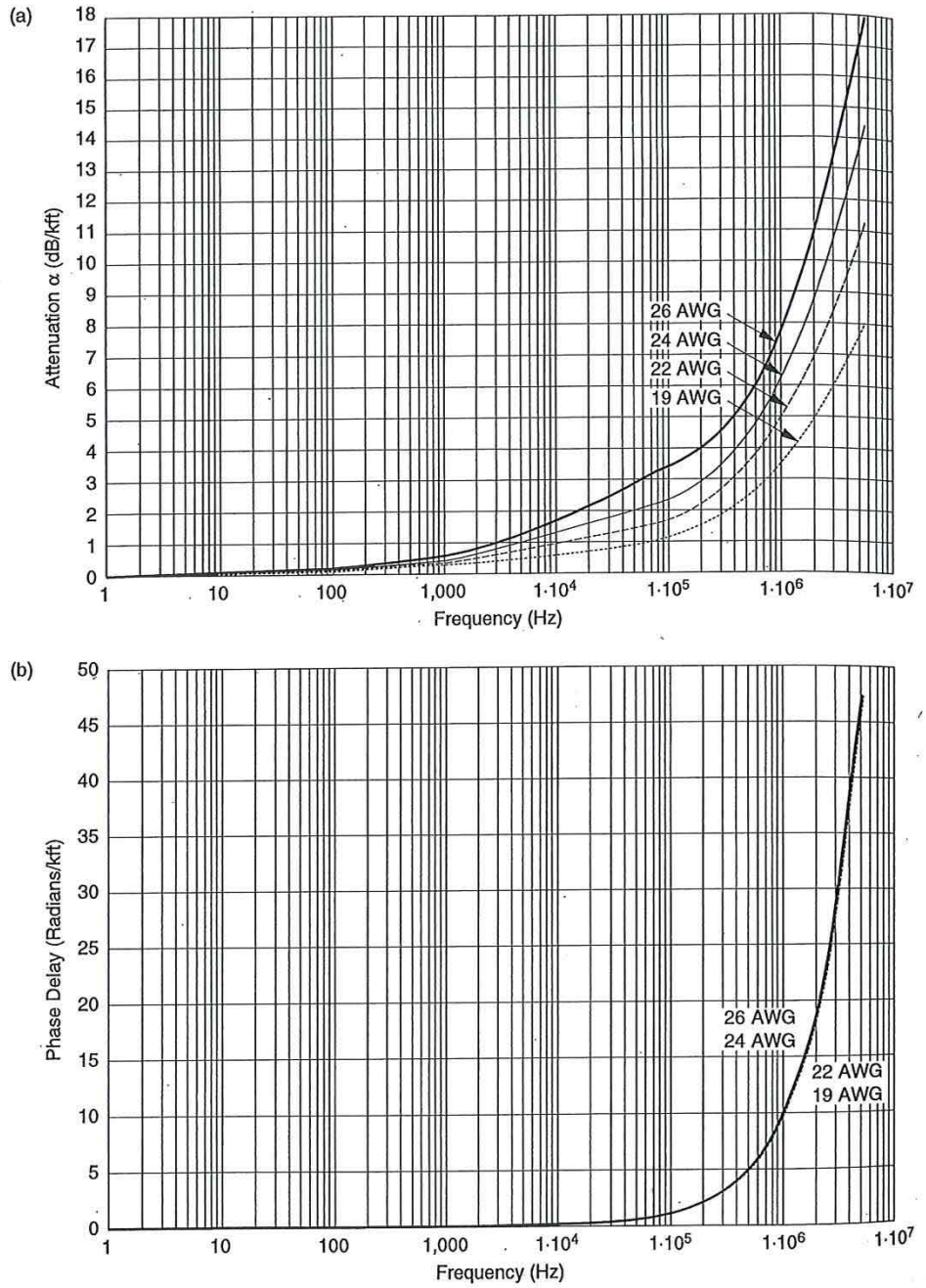


Figure 7-16 Twisted pair secondary parameters: (a) Attenuation vs. frequency; (b) Phase delay vs. frequency

higher the attenuation. The relationship is nonlinear and due primarily to changes in conductor resistance. Transmission parameters provided on cable manufacturer's data sheets usually are given at 55 °F (12.8 °C) or 68 °F (20 °C). Current digital loop design methods require the quoted values to be adjusted (corrected) to the maximum expected temperature of operation.

The attenuation characteristics of PIC frequently are modeled using a single parameter. The single-parameter model assumes attenuation is proportional to $\sqrt{f}$. Therefore, if the attenuation $\alpha(f_0)$ is known at frequency f_0, the attenuation $\alpha(f)$ at any other frequency f can be obtained from:

$$\alpha(f) = \alpha(f_0)\sqrt{\frac{f}{f_0}}$$

This model assumes that skin effect causes the predominant impact on attenuation, which is not true at low frequencies. Therefore, although fairly accurate above 200 kHz, the single-parameter model is useless in many digital loop applications, particularly the ISDN DSL and subrate digital loops.

7.6.3.4 Transmission Requirements

The fundamental transmission requirements of digital loops follow the same principles as analog loops.* On any digital loop:

- The signal must have adequate level so the presence of a signal element may be reliably detected, and
- The signal level must be sufficiently higher than the noise to ensure reliable differentiation between the signal elements and noise (high enough signal-to-noise ratio, SNR).

Adequate level is provided by controlling circuit loss for a given transmitter power output. Adequate SNR is provided by controlling crosstalk and taking care to limit the adverse effects of impulse and other noise through proper shielding.

For reference, it is informative to know what the acceptable SNRs are for various types of circuits. Digital loops operate with acceptable error performance if the SNR is above approximately 15 dB. As a rule of thumb, each dB of change in SNR will change the error rate by a factor of ten for error rates in the vicinity of 10E-6. For example, if the error rate is 10E-6 with 14 dB SNR, it will be 10E-5 at 13 dB SNR. Generally, the SNR for individual analog circuits should be at least 30 dB for voice calls (based on subscriber satisfaction) and 15 to 20 dB on data calls using analog modems (based on the specified error rate, coding, and modulation method). These figures are end-to-end. Each portion of the transmission system (loops, switching systems, terrestrial and satellite radio systems, and so on) contribute to lowering

*See [4] for analog transmission requirements.

the SNR. It follows that the SNR for any given part of the overall connection must be higher than the overall requirement.

For an analog voice circuit being transmitted on a digital loop carrier system, poor error performance of the digital loop manifests itself indirectly to the listener in terms of distortion, dropouts, and other annoyances. A degraded channel in this case may still be usable for voice transmission. Digital data circuits, on the other hand, are directly affected by error performance in that bit integrity is a requirement of digital transmission. Tolerable error levels on a digital data circuit are always much less than on a voice circuit. It should be noted there is no correlation between the attenuation of an analog signal and attenuation of the digital signal that represents it.

7.6.3.5 Loop Transmission Loss

Loop transmission loss is highly dependent on the frequency of operation. Equipment design compensates for this dependency by employing a number of equalization techniques. Digital loops have frequency components over a wide frequency range. To simplify the loop design process, a nominal frequency is chosen based on the frequency of peak energy or an upper frequency limit of significant energy for a particular loop type and the loss specified for that frequency. This nominal frequency depends on the transmission format, pulse shape, and a number of other factors.

A typical maximum loss of 32 to 42 dB at the nominal frequency is used, but the actual value depends somewhat on the technology. Also, the maximum quoted loss value may have to be reduced to counteract the adverse effects of crosstalk or other transmission impairments.

Some digital loop types require a minimum loss, which depends on the ability of the loop interface electronics to equalize the received signal automatically. For repeatered T1-carrier, the minimum loss is 7.5 dB unless the repeaters have built-in pads. If necessary, this minimum loss can be provided by external attenuators placed in the line at the receive end.

From this point forward, attenuation, as determined from the secondary parameters, is used interchangeably with insertion loss (or just loss). This is only strictly correct when the digital loop is terminated in the complex conjugate of its characteristic impedance (Z_0). In practice, this does not always happen (if ever), but for practical problems it is sufficiently accurate.

7.6.3.6 Transmission Levels

Adequate signal power at the receive end of a circuit is essential to providing satisfactory error rates in any digital transmission system. It is obvious this is not possible unless loop loss is thoroughly controlled and enough signal level is provided at the loop input.

Too much signal power, on the other hand, can overload the transmission facilities or terminal equipment and cause distortion and crosstalk. Because digital loop systems frequently share transmission facilities with other systems, such as voice and analog carrier systems, mutual interference is a potential problem. Therefore,

the signal powers in these systems are coordinated with each other. This requires close attention to power levels at particular frequencies or particular frequency bands.

In digital systems, the signal power is not specified in the same way as with analog systems, where power levels (for example, in dBm) are referenced to a standard impedance (for example, 600 Ω). Instead, the digital levels are specified by pulse shape and maximum voltage level into a standard load impedance (typically 100 or 135 Ω). These two parameters serve to determine the spectral limits of the digital pulse train, and crosstalk considerations ensure noninterference.

7.6.3.7 Presentation of Transmission Parameters

Loss and noise directly affect regenerator and equipment error performance. The loss and noise parameters can be presented in a variety of ways. Typically, a range, variability, or other distribution of a particular parameter is specified. There should be some predetermined agreement between the design value and the measured value, but the measured value always will show some variability due to:

- Test equipment calibration
- Environmental variations that affect the circuit components as well as the measuring equipment
- Human factors associated with reading meters or displays
- Position of the test equipment or lead lengths
- Cable splicing techniques
- Cable and equipment manufacturing tolerances

These effects will influence the measurements of a large number of loops so that the results show some type of distribution. Therefore, when the transmission parameters of a digital loop are determined, they really can only be specified on a statistical basis.

For voicegrade (analog) applications, the Institute of Electrical and Electronic Engineers (IEEE) has identified three forms for the results of transmission parameter calculations or estimations [39]:

- A cumulative distribution
- A histogram
- An analytical distribution function

Although these forms are proposed by IEEE for voicegrade applications, they are generic in nature and apply just as well to digital applications.

Other forms, or variations of the above forms, can be used. The most typical, of course, is the single-value specification; for example, "The digital loop loss shall be 23.2 dB." More typically, in digital applications, the specification might read, "The equipment shall function with a digital loop loss between 7.5 and 35.0 dB." This provides a lower and upper bound only. The exact loss value for any loop does not matter as long as it falls within the specified bounds. Similarly, a cumulative

distribution would specify "95% of the loop losses shall fall between 7.5 and 33.0 dB." This specification allows some loops to have a loss outside of the boundaries, but no specification is given as to how far outside. A better specification would state "95% of the loop losses shall fall within 7.5 and 33.0 dB, and no loop shall have a loss less than 5.5 dB nor greater than 35.0 dB." If a normal distribution curve is used to specify the parameters, a mean value and a standard deviation are given. For example, "mean loop loss shall be 22.0 dB with standard deviation of 7.0 dB."

The normal distribution curve is shown in Figure 7-17. The various points labeled on the curve illustrate how transmission parameters are typically quantified. The average, or mean, value for the parameter is at the peak of the normal distribution curve. This is the value used for most field transmission calculations. At the outer edges, representing a small percentage of circuits, are the immediate action limits (IALs). If a parameter measurement gives an IAL or worse, immediate remedial action is required. Closer toward the mean are the maintenance limits (MLs). A parameter measurement falling between the ML and the IAL will receive remedial action during routine maintenance. The acceptance limits (ALs) are used when a new circuit or system is installed; these are necessarily tighter than the other limits to give allowance for equipment aging and other variations.

Because of this statistical nature, it would seem that individual parameters for several loop segments in tandem could not be combined by simple addition. This is

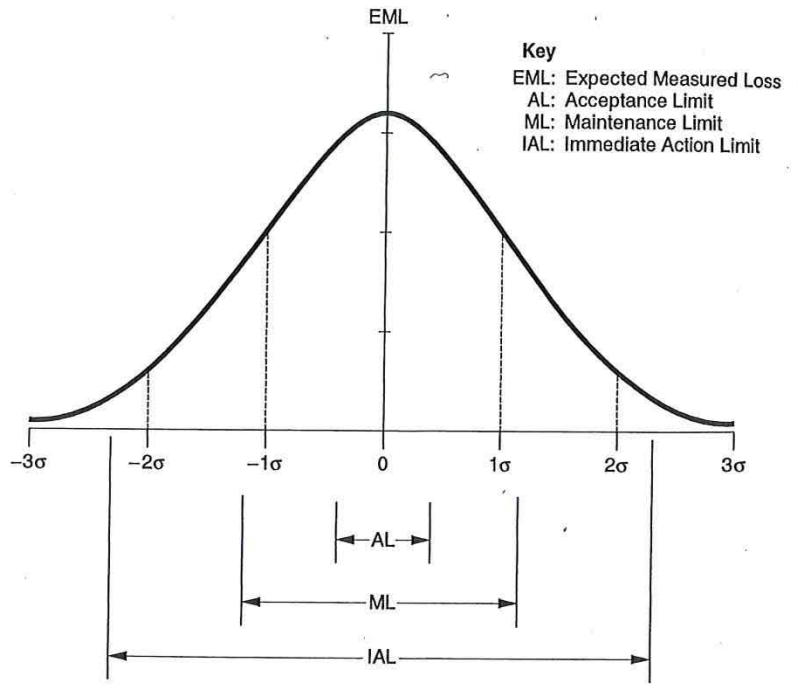


Figure 7-17 Normal distribution curve with circuit performance limits

indeed true, and various mathematical techniques are used to describe the entire connection.* For most field problems, however, parameter distributions are ignored, and simple addition is frequently used with satisfactory results.

7.6.3.8 Twisted Pair Cable Purchase Checklist

The checklist below is useful during the development of twisted pair exchange cable purchase specifications.

1. Specification? (ICEA, REA, BELLCORE) ☐
2. Deviations from the referenced specification? (specify) ☐
3. Pair gauge? (19, 22, 24, 26 AWG) ☐
4. Pair count? (not all pair counts are available with all cable gauges) ☐
5. Screened cable required? (T1, T1C, or T-Screen, D-Screen, Z-Screen) ☐
6. If screened, service pair requirements? (specify) ☐
7. Use? (direct buried, underground, aerial, riser, aerial self-supporting, service wire) ☐
8. Jacket environment? (severe, normal, submarine, rodent infested) ☐
9. Shield? (coated aluminum, copper) ☐
10. Armor? (heavy copper, steel, copper alloy) ☐
11. Factory pulling eyes required? (yes, no) ☐
12. Lengths required? (standard, custom; specify) ☐
13. Reel size or weight limitations? (specify) ☐
14. Reel requirements? (standard, wood, steel) ☐
15. Reel protection requirements? (none, wood lagging, pressboard) ☐
16. Shipping instructions? (specify) ☐

References

[1] Miller, S., Kaminow, I. *Optical Fiber Telecommunications II*. Academic Press, 1988.

[2] *Grounding, Bonding, and Shielding for Electronic Equipments and Facilities*, Vol. 1 of MIL-HDBK-419, Jan. 1982.

[3] *Grounding, Bonding, and Shielding Practices and Procedures for Electronic Equipments and Facilities*, Vol. 1: Fundamental Considerations. Federal Aviation Administration Report FAA-RD-75-215, NTIS Order No. ADA-022332.

[4] Reeve, W. *Subscriber Loop Signaling and Transmission Handbook: Analog*. IEEE Press, 1992.

*See, for example, Appendix B of [39].

[5] *Connection of Terminal Equipment to the Telephone Network*. 47 CFR Part 68. US Government Printing Office.

[6] Insulated Cable Engineers Association. *Standard for Polyolefin Insulated Communication Cables for Outdoor Use*. ANSI/ICEA S-56-434-1983. Available from ICEA.

[7] Insulated Cable Engineers Association. *Standard for Telecommunications Cable, Filled, Polyolefin Insulated, Copper Conductor Technical Requirements*. ANSI/ICEA S-84-608-1988. Available from ICEA.

[8] Insulated Cable Engineers Association. *Standard for Telecommunications Cable, Aircore, Polyolefin Insulated, Copper Conductor Technical Requirements*. ANSI/ICEA S-85-625-1989. Available from ICEA.

[9] Insulated Cable Engineers Association. *Standard for Telecommunications Cable, Buried Distribution and Service Wire Technical Requirements*. ANSI/ICEA S-86-634-1991. Available from ICEA.

[10] *REA Specification for Filled Telephone Cables*, Bulletin 345-67. PE-39, Jan. 1987. Available from Rural Electrification Administration (REA).

[11] *REA Specification for Filled Telephone Cables with Expanded Insulation*, Bulletin 1753F-208, June 1993.

[12] *REA Specification for Aerial and Underground Telephone Cable*, Bulletin 345-13. PE-22, Jan. 1983.

[13] *REA Specification for Self-Supporting Cable*, Bulletin 345-29. PE-38, Feb. 1982.

[14] *REA Specification for Filled Buried Wire*, Bulletin 345-70. PE-54. (Note: This specification was rescinded by REA in March 1987, but cables meeting it still are available from some suppliers. Specification PE-86 replaces PE-54.)

[15] *REA Specification for Filled Buried Service Wire*, Bulletin 345-86. PE-86, Oct. 1982.

[16] *REA Specification for Parallel Conductor Drop Wire*, Bulletin 345-36. PE-7, Jan. 1983.

[17] *REA Specification for Terminating (TIP) Cables*, Bulletin 345-87. PE-87, Dec. 1983.

[18] *Generic Requirements for Metallic Telecommunications Cables*. BELLCORE Technical Reference TR-TSY-000421, Sept. 1991.

[19] *PIC Filled ASP Cable*. BELLCORE Technical Reference TR-TSY-000100, June 1988.

[20] *Aircore PIC ALPETH Cable*. BELLCORE Technical Reference TR-TSY-000101, June 1988.

[21] *PIC Self Support Cable*. BELLCORE Technical Reference TR-TSY-000102, June 1988.

[22] *Underground Foam-Skin PIC Bonded STALPETH Cable*. BELLCORE Technical Reference TR-TSY-000106, June 1988.

[23] *PIC Filled Screened ASP Cable*. BELLCORE Technical Reference TR-TSY-000109, June 1988.

[24] *PIC Riser Cable*. BELLCORE Technical Reference TR-TSY-000111, June 1988.

[25] *Generic Requirements for Multiple Pair Buried Wire*. BELLCORE Technical Reference TR-TSY-000124, Sept. 1991.

[26] *Catalog of Technical Information*. BELLCORE Special Report SR-NWT-000264, July 1992–July 1993.

[27] *National Electrical Safety Code,* ANSI C2-1993. Available from IEEE.

[28] REA TE&CM Section 635: *Construction of Aerial Cable Plant*. Feb. 1962, with 1966 and 1979 addenda. Available from REA.

[29] *Outside Plant Engineering Handbook*. AT&T Document Development Organization, 1990.

[30] "When Even More Protection Is Needed." Lightguide Digest, No. 1, 1992, AT&T Network Systems.

[31] REA TE&CM Section 451.2: *Shield Continuity,* April 1984. Available from REA.

[32] Westman, H., ed. *Reference Data for Radio Engineers,* 4th Ed. ITT, 1964.

[33] *Understanding Transmission,* Vol. 7. Lee's ABC of the Telephone, 1976. Available from ABC Teletraining, Inc.

[34] Hamsher, D. *Communication System Engineering Handbook*. McGraw-Hill Book Company, 1967.

[35] *Understanding Transmission,* Vol. 8. Lee's ABC of the Telephone, 1976. Available from ABC Teletraining, Inc.

[36] *Transmission Systems for Communications*. Bell Telephone Laboratories, Inc. 1982. Available from AT&T Customer Information Center.

[37] REA TE&CM Section 406: *Transmission Facility Data*. Aug. 1977. Available from REA.

[38] Goldberg, B., ed. "Transmission properties of filled thermoplastic insulated and jacketed telephone cables at voice and carrier frequencies," in *Communication Channels: Characterization and Behavior*. IEEE Press, 1976.

[39] *IEEE Standard Methodologies for Specifying Voicegrade Channel Transmission Parameters and Evaluating Connection Transmission Performance for Speech Telephony*. IEEE Std 823-1989. Available from IEEE.