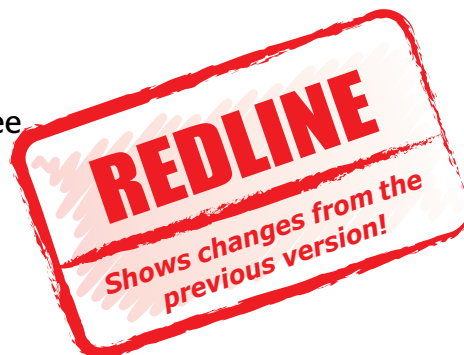


IEEE Guide on Shielding Practice for Low Voltage Cables

IEEE Power and Energy Society

Sponsored by the
Insulated Conductors Committee



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IEEE Guide on Shielding Practice for Low Voltage Cables

Sponsor

Insulated Conductors Committee
of the
IEEE Power and Energy Society

Approved 5 December 2012

IEEE-SA Standards Board

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Abstract: A concise overview of shielding options for various types of interference is discussed in this guide. Recommendations on shielding practices for low voltage cables are given. Suggestions on terminating and grounding methods are provided.

Keywords: cable shielding, cable terminations, electromagnetic interference, grounding, IEEE 1143™, low voltage cables

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Introduction

This introduction is not part of IEEE Std 1143-2012, IEEE Guide on Shielding Practice for Low Voltage Cables.

This project will provide a revision to the Guide on Shielding Practice for Low Voltage Cables. Insulated Conductors Committee (ICC) Working Group D11W, under ICC Subcommittee D, prepared this revision. The guide will be helpful for users of low voltage cable to understand how shielding works, to choose an appropriate shielding system to address the type of interference being encountered and to be able to be familiar with the test protocols to measure shielding effectiveness. The revision will focus on shielding techniques and defer the discussion of theory and sources of interference to other appropriate IEEE documents by reference. The document will be of greatest use to cable users for control systems in industrial plants, generating stations, and substations. The experts contributing to the document will be cable manufacturers, material suppliers, and knowledgeable engineers. The document will be useful to consultants and engineers in engineering firms who design and build control systems for various plants and facilities.

Background on 1994 version: A guide on the use of shielding on low voltage cables was proposed in Subcommittee No. 9 of the Insulated Conductors Committee due to the lack of a single source of information on this topic. For example, information on shielding of medium voltage and high voltage cables was available in several documents, but the same could not be said for low voltage cable. Subsequently, a task group was formed to develop the guide. The task group began its work by preparing a bibliography of the information by key topic. These topics eventually made their way into an outline of the guide. A first draft was prepared, and after review and comment, the draft was broken into two sections: Section I, covering shielding; and Section II, providing background information on the need for shielding. This approach was taken because an understanding of the need for shielding helps achieve the purpose of the guide—which is to provide the user with an understanding of cable shielding practices for low voltage cables.

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1. Overview

1.1 Scope

This function of this guide on shielding practice for low voltage cables is to inform and familiarize the reader with shielding practice. ~~An~~ Overviews of shielding practice, systems and test methods are provided. These tests may not be standardized; however, they are included to inform the reader and provide an overview as to what has been done to characterize shielding. This guide provides the following: a review of shielding techniques to ~~An enumeration of sources of~~ control electrostatic and electromagnetic interference for varying types of low voltage cable used for power, control and instrumentation services, including signal and communications cable; an overview of the functional characteristics of various types of shielding; suggested tests or techniques for measuring shielding effectiveness; recommendations on shielding practices, including suggestions on terminating and grounding methods.

1.2 Purpose

The main purpose of this guide is to show how shielding can ~~be used to~~ minimize the effects of ~~electrostatic and electromagnetic~~ interference ~~on low voltage cables. The~~ A secondary purpose is to ~~familiarize the user with the topic of shielding and~~ provide recommendations on shielding practice for various applications including suggestions on terminating and grounding methods ~~background information on the need for shielding. Alternate approaches will be given to achieve these purposes.~~

1.3 Application

This guide shall apply to low voltage (rated < 600 V) control and instrumentation or signal cables. This guide does not apply to fiber optic cables since such cables are immune to electromagnetic interference; see IEEE Std 1428TM-2004 [B61].^{1,2,3}

2. References

~~This guide should be used in conjunction with the following publications. When the following publications are superseded by an approved revision, the revision shall apply.~~

~~ANSI C63.4-1992, Methods of Measurement of Radio Noise Emissions from Low Voltage Electrical and Electronic Equipment in the Range of 9 kHz to 40 GHz¹.~~

¹The numbers in brackets correspond to those of the bibliography in Annex A.

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~~ANSI/NEMA WC55-1992/TCEA S-82-552, Instrument Cables and T. C. Wire.² ANSI/NEMA WC57-1990/TCEA S-73-532, Standard for Control Cables. ANSI/NFPA 70-1993, National Electrical Code (NEC).³~~

~~EIA/TIA 455-181 (Feb. 1993), FOTP-181, Lightning Damage Susceptibility Test for Fiber Optic Cables with Metallic Components.⁴~~

~~IEEE Std 422-1986 (W1994), IEEE Guide for the Design and Installation of Cable Systems in Power Generating Stations.⁵~~

~~IEEE Std 518-1982 (Reaff 1990), IEEE Guide for the Installation of Electrical Equipment to Minimize Electrical Noise Inputs to Controllers from External Sources (ANSI).⁶~~

~~IEEE Std 525-1992, IEEE Guide for the Design and Installation of Cable Systems in Substations (ANSI).~~

~~IEEE Std 576-1989, IEEE Recommended Practice for Installation, Termination, and Testing of Insulated Power Cable as Used in the Petroleum and Chemical Industry (ANSI).~~

~~IEEE Std 690-1984 (W1994), IEEE Standard for the Design and Installation of Cable Systems for Class IE Circuits in Nuclear Power Generating Stations.⁷~~

~~IEEE Std 789-1988 (Reaff 1994), IEEE Standard Performance Requirements for Communications and Control Cables for Application in High Voltage Environments (ANSI).~~

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³ANSI/NFPA publications are available from Publications Sales, National Fire Protection Association, 1 Batterymarch Park, P.O. Box 9101, Quincy, MA 02269-9101, USA.

⁴EIA/TIA publications are available from Global Engineering, 1990 M Street NW, Suite 400, Washington, DC, 20036, USA.

⁵IEEE Std 422-1986 has been withdrawn; however, copies can be obtained from the IEEE Standards Department, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

⁶IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

⁷IEEE Std 690-1984 has been withdrawn; however, copies can be obtained from the IEEE Standards Department.

~~IEEE Std C62.41-1991, IEEE Recommended Practice for Surge Voltages in Low Voltage AC Power Circuits (ANSI).-~~

~~NEMA WC-61-1992, Transfer Impedance Testing (Modified MIL-C-85485 Test Method).⁸~~

2. Acronyms

NOTE—Definitions are in Annex B.⁴

ASD adjustable speed drive

CAT category cable

CATV community antenna television

CW continuous wave

EFT electrical fast transient

EGC equipment grounding

EIA Electronic Industries Alliance

EMC electromagnetic compatibility

⁴Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

~~⁸NEMA publications are available from the National Electrical Manufacturers Association, 2101 L Street NW, Washington, DC 20037, USA.~~

<u>EMI</u>	<u>electromagnetic interference</u>
<u>EPR</u>	<u>ethylene propylene rubber</u>
<u>ESD</u>	<u>electrostatic discharge</u>
<u>FCC</u>	<u>Federal Communications Commission</u>
<u>FEXT</u>	<u>far end crosstalk</u>
<u>F/UTP</u>	<u>foil / unshielded twisted pair</u>
<u>FTP</u>	<u>foil twisted pair</u>
<u>IED</u>	<u>intelligent electronic device</u>
<u>LAN</u>	<u>Local Area Network</u>
<u>MATV</u>	<u>Master Antenna Television</u>
<u>NEXT</u>	<u>near end cross talk</u>
<u>PET</u>	<u>polyester</u>
<u>PiMF</u>	<u>pairs in metal foil</u>
<u>PoE</u>	<u>Power over Ethernet</u>
<u>RF</u>	<u>radio frequency</u>

<u>RFI</u>	<u>radio frequency interference</u>
<u>S/FTP</u>	<u>screened / foil twisted pair</u>
<u>S/UTP</u>	<u>screened / unshielded twisted pair</u>
<u>ScTP</u>	<u>screened twisted pair; same as s/ftp</u>
<u>SEED</u>	<u>evaluation device</u>
<u>SPD</u>	<u>surge protective device</u>
<u>SRL</u>	<u>structural return loss</u>
<u>SSTP</u>	<u>shielded screened twisted pair</u>
<u>STP</u>	<u>shielded twisted pair</u>
<u>TCP/IP</u>	<u>transmission control protocol/internet protocol</u>
<u>TEM</u>	<u>transverse electromagnetic cell</u>
<u>TIA</u>	<u>Telecommunications Industry Association</u>
<u>UTP</u>	<u>unshielded twisted pair</u>
<u>UV</u>	<u>ultraviolet light</u>
<u>VFD</u>	<u>variable frequency drive</u>

VSD variable speed drive

WAN Wide Area Network

3. Definitions

~~3.1 absorbing clamp: A portable testing device that is effective at detecting electromagnetic radiation. The absorbing clamp has a great capacity for electromagnetic compatibility cable measurements in the frequency range of 30-1000MHZ, and is non-destructive to the specimen. The test fixture clamps over the sample cable and inductively detects signal leakage.~~

~~3.2 aeolian flexure: Flexure of cables caused by the wind.~~

~~3.3 bonded sheath: Cable shielding that is bonded to a plastic jacket by means of a plastic coating on the shielding.~~

~~3.4 braidd shield: Cable shield that consists of groups of metallic strands, one set woven in a clockwise direction and interwoven with another set in a counter clockwise direction. Braided shields provide superior structural integrity, while maintaining good flexibility and flex life.~~

~~3.5 broadband (electrical noise, interference): Electrical noise that contains energy covering a wide frequency range. Contrast with: narrowband electrical noise.~~

~~3.6 capacitance: The ratio of a conductor's electrostatic charge to the potential difference between conductors(required to maintain that charge).~~

~~3.7 capacitive coupling: See: electrical coupling.~~

~~3.8 chop: A sudden cessation of the flow of arc current during circuit interruption.~~

~~3.9 combination effect: An electric disturbance not caused by one of the following mechanisms, but to some extent by a combination of them: normal-mode noise (transverse or differential), common-mode noise (longitudinal), and common-mode to normal-mode conversions. See also: common-mode noise (and longitudinal); normal-mode (transverse or differential).~~

~~3.10 common-mode noise (and longitudinal): The noise voltage that appears between each signal conductor to ground caused by electrostatic induction and/or induction.~~

~~3.11 continuous wave (CW): A sinusoidal wave that has reached a steady state value. Continuous wave noise would be noise at a single frequency (e.g., 60 Hz "hum").~~

~~3.12 corner frequency: The frequency at which the skin depth is equal to the thickness of the shield.~~

~~3.13 Crawford cell: See, transverse (TEM) cell~~

~~3.14 crosstalk: An electromagnetic field in the space surrounding a cable circuit created by an electrical signal. This field induces currents and electromotive forces in other circuits located close enough to the disturbing cable circuit to be affected.~~

~~3.15 cutoff frequency: The frequency below which a waveguide fails to transmit a signal in the differential mode.~~

~~3.16 dropouts: A subset of gain hit, dropouts are a loss of data caused by a decrease in signal, usually greater than 12dB and lasting longer than 4 ms. Dropouts interrupt the information flow between two modems. Furthermore, even when the signal returns, some modems will take additional time to recover. Experience suggests that dropouts occur less often than the other types of transients. However, each dropout causes modem errors. See also: gain hit or change; phase hit or change.~~

3.17 electrical coupling: ~~Electrical charges in conductors of a disturbed circuit formed by electrical induction. Since the ratio of a conductor's electrostatic charge to the potential difference between conductors (required to maintain that charge) is the general definition of capacitance, electrical coupling is also called capacitive coupling. Its magnitude depends on the cable geometry and the cable insulation properties: dielectric constant and dissipative losses. Magnetic coupling introduces electromotive force in the disturbed circuit due to magnetic induction. This electromotive force opposes the change in the current that generated it. Syn: capacitive coupling.~~

3.18 electric field: ~~The field surrounding a charged object. See also: magnetic field.~~

3.19 electrical noise: ~~Unwanted voltage or current, or both, that appears in an electrical system. For given system characteristics, electrical noise may or may not impair proper functioning. The unwanted noise can have effects that range from totally undetectable to system malfunction or even damage or destruction.~~

3.20 electromagnetic compatibility (EMC) (of an electrical system): ~~An electrical system's ability to perform its specified functions in the presence of electrical noise generated either internally or externally by other systems. The goal of EMC is to minimize the influence of electrical noise.~~

3.21 electromagnetic field: ~~The energy field radiating from a source and containing both electric and magnetic field components. See also: electric field; magnetic field.~~

3.22 electromagnetic induction (EMI): ~~See: electromagnetic.~~

3.23 electromagnetic interference (EMI): ~~Electromagnetic energy from sources external or internal to electrical or electronic equipment that adversely affects equipment by creating undesirable responses (degraded performance or malfunctions). EMI can be divided into two classes: continuous wave (CW) and transient. Syn: electromagnetic induction. See also: continuous wave (CW); electrical noise; transient electrical noise.~~

~~3.24 electromagnetic pulse (EMP): A high-energy electromagnetic pulse initiated by a nuclear reaction (e.g., upper atmospheric detonation of a nuclear weapon).~~

~~3.25 electrostatic discharge (ESD): Electrical discharges of static electricity that build up on personnel or equipment, generated by interaction of dissimilar materials.~~

~~3.26 foil shield: A thin, self-supported, metallic tape wrapped longitudinally or spirally around the cable core, and intended to act as a shield against EMI.~~

~~3.27 gain hit or change: A sudden increase or decrease in amplitude, usually not exceeding 12 dB of the received signal. Gain hits last at least 4 ms but may continue for hours. (Example: Modems that use amplitude modulation carry the information by the level of the signal, and a gain hit may look like data to these modems.) Contrast with: **impulse noise**.~~

~~3.28 galvanic action: Noise currents due to the junction or thermal potentials resulting from a combination of different metals. This current can be a part of the disturbing current passing through the conductors or shield of the signal cable.~~

~~3.29 harmonic distortion: Nonlinear distortion that appears as harmonics of a single frequency input~~

~~3.30 hum test: Measures low-frequency shield effectiveness against electric field coupling (dc to 100 kHz)~~

~~3.31 impulse noise: A component of the received noise signal that is much greater in amplitude than the normal peaks of the message circuit noise, and that occurs as short-duration spikes or energy bursts.~~

~~3.32 induction zone (of EMI): The area where the distance to the source of electromagnetic interference is less than the wavelength of the interference. In the induction zone the circuit or system will be affected by transverse or longitudinal fields. Contrast with: **radiation zone (of EMI)**.~~

~~3.33 **Inter modulation distortion:** Nonlinear distortion of multiple frequency inputs that shows up as harmonics of the individual inputs plus the sum and difference products of the inputs and their harmonics.~~

~~3.34 **agnetic coupling:** See: **electrical coupling.**~~

~~3.35 **agnetic field:** The field surrounding any current-carrying conductor. See also: **electric field.**~~

~~3.36 **narrowband electrical noise:** A disturbance at a single frequency or in a narrowband of frequencies about a single frequency.~~

~~3.37 **onlinear:** The amplitude of the output is not linearly proportional to the input. If a true sine wave were transmitted through a nonlinear device, its shape would be changed.~~

~~3.38 **nonlinear distortion:** The generation of new signal components not present in the original transmitted signal.~~

~~3.39 **normal mode (transverse or differential):** The voltage that appears differentially between two signal wires and that acts on the circuit in the same manner as the desired signal.~~

~~3.40 **phase hit or change:** A sudden change in the received signal phase (or frequency) lasting longer than 4 ms. Since two common modulation techniques for high-speed data transmission are phase and frequency modulation, phase hits cause errors by looking like data. See also: **dropouts; gain hit or change.**~~

~~3.41 **radiation zone (of EM):** The area where the distance to the source of electromagnetic interference is greater than the wavelength of the interference. In the radiation zone, the circuit or system will be affected by plane waves. Contrast with: **induction zone (of EME).**~~

3.42 surge impedance: The impedance of an electrical circuit under surge conditions (which may differ significantly from the impedance of a circuit under steady state conditions).

3.43 transient electrical noise: An electrical disturbance that occurs in a time interval separated from other interferences. Transient electrical noise may be superimposed on other transients or on continuous waves. Transient electrical noise may be of several types, such as pulse, step, or oscillatory. It may occur as a response to a network to one of these types. Sources of transient affecting low voltage circuits are impulse noise, power switching, or lightning.

3.44 transverse electromagnetic (TEM): A wave that propagates with the electric field and magnetic field vectors transverse (at right angles to) the direction of propagation. (At high frequencies waves may also propagate in transverse electric [TE] or transverse magnetic [TM] waves that bounce back and forth between guiding structures such as waveguides.)

3.45 transverse electromagnetic (TEM) cell: A rectangular transmission line segment that produces a transverse electromagnetic (TEM). Cables, cable/connector assemblies, and/or electronic devices are placed inside the cell. Alternatively, the cell can be used as a detector to measure radiation emitted by a cable or device inside the cell. *See also:* **absorbing clamp**. *Syn:* **Crawford cell**.

Section I: Shielding

3. Nature of interference

3.1 General

The source of interference may be anywhere; it may be produced within the system containing the sensitive circuit or outside of the system. It may be man-made or natural. The effect on the circuit is somewhat independent of the origin of the interference, but the protection techniques applied will depend on whether the designer controls the source or treats the source as a part of the operating environment of the circuit. This clause provides only a rudimentary overview of the nature of interference to help provide a foundation for the need for shielding. There are many IEEE standards that describe in detail the nature of interference. Some pertinent standards are summarized in the next paragraphs.

[IEEE Std 1100™-2005 \[B58\] provides recommendations for powering and grounding telecommunications and signaling systems in industrial facilities. Chapter 9 includes the sources of interference, electrical and electromagnetic protection devices, and shielded cabling. Subclauses provide information on susceptibility issues and the factors that improve immunity. A summary of the specific types of power variations and grounding related issues that most commonly cause system upsets. Annex 9F classifies surges and lightning exposure. Annexes K and L provide the fundamental concepts of surge protection. It should be noted that it is recommended that surge protective devices be used with shielded cable.](#)

[Chapter 10 describes the grounding and wiring methods to minimize the impact of interference, or noise, on industrial systems. Principles and practices for noise mitigation techniques are provided. Basic noise control theory, shielding mechanisms, and common industrial interference sources and receptors are covered in this chapter.](#)

[IEEE Std 518TM-1982 \[B51\]](#) covers the techniques for the installation of controllers and control systems so that proper operation can be achieved in the presence of electrical noise. Shielding techniques are also covered.

[IEEE Std 141TM-1993 \[B49\]](#) provides guidance on the design, construction and continuity of an overall industrial electrical power system to provide voltage regulation and surge protection.

[IEEE Std 519TM \[B52\]](#) covers the use of non-linear loads connected to electrical power systems. Non-linear loads may change the sinusoidal nature of the ac power current resulting in harmonic currents into the ac power system. These harmonic currents can cause interference with the signal and communication circuits.

[IEEE Std C62.82.1TM-2010 \[B68\]](#) establishes a procedure for selecting insulation that will withstand the impulse voltage created by lightning and switching.

[IEEE Std C62.62TM-2010 \[B67\]](#) provides users, laboratories and manufacturers with test methods and specifications applicable to surge protective devices (SPDs) in order to limit transient over voltages.

3.2 Definition of sources

For the purpose of this guide, electrical noise is defined as an unwanted electrical signal that produces undesirable effects in the circuits of the system in which it occurs. As such, it may cause malfunctioning of electrical equipment.

In its simplest terms, before an electrical noise problem can exist, three basic elements are required:

- a) A source of noise
- b) A circuit sensitive to noise

- c) A means of interaction between source and circuit

The solution to this three-element problem is obtained by controlling any one of the three elements. This means that if an installation is malfunctioning because of electrical noise, it can be made to work correctly by suppressing the noise at its source, eliminating the way the noise is getting into the system, or making the equipment insensitive to the noise. The possibility of eliminating the source or the sensitive circuit should also be considered.

3.3 Source-circuit interaction

When ~~For~~ a circuit is ~~to be~~ affected by interference from a source, the electromagnetic waves produced by the source ~~must~~ interact with elements of a ~~the~~ sensitive circuit. This interaction involves propagation of waves through free space or along guiding structures (such as wires, transmission lines, and cables) between the source and the system. Upon arriving at the system, coupling of the electromagnetic fields to elements of the system induces currents, voltages, and electromagnetic fields on the system. These currents, voltages, and fields ~~must then~~ penetrate the system to reach the ~~internal~~ sensitive circuit of concern.

These three aspects of interaction are particularly important to systems that have natural or deliberate shields. The shields can be used to separate the interaction ~~problem~~ into external and internal interactions. The propagation, coupling, and penetration apply to both the external interaction ~~problem~~ and to the internal interaction situations ~~problem~~.

3.3.1 Propagation

Propagation of a space wave occurs if [a](#) ~~the~~ source launches [a](#) ~~the~~ wave into a medium, such as air or vacuum. Radio and radar transmissions, distant lightning, and other atmospheric noise are examples of space waves that may interfere with systems ~~that do not wish to receive them~~. Guided waves propagate along conductors, such as power lines and interconnecting cables. Switching transients, [50 Hz or](#) 60 Hz "hum," and lightning transients are examples of guided waves that propagate to [a](#) ~~the~~ system along power and communication lines. (Guided waves have been called "conducted interference" and space waves have been called "radiated interference" in the literature.)

3.3.2 Coupling

Coupling is the interaction of electromagnetic fields with conductors to induce currents and voltages on the conductors. Magnetic fields parallel to a conducting surface induce a current density on the surface; electric fields [can](#) ~~perpendicular to a conducting surface~~ induce a charge density on [a](#) ~~conducting~~ ~~the~~ surface [placed in the electric field](#). Time-varying electric fields induce current on the surface of a conductor or, if the ~~electric field is produced by the~~ voltage on another conductor [produces the electric field](#), the conductors are said to be capacitive coupled. Time-varying magnetic fields induce voltages in loops. If the ~~magnetic field is produced by the~~ current in another conductor [produces a magnetic field](#), the coupling is described as mutual inductance or inductive coupling. (The coupled currents and voltages have been improperly called "radiated interference" in the literature.)

3.3.3 Penetration

Penetration is the entry of ~~an the~~ electromagnetic interference into ~~a the~~ system of concern. It is presumed that ~~this system is surrounded by~~ some form of barrier or boundary ~~that~~ separates ~~the system~~ ~~it~~ from the outside. In protected systems, the barrier might be a metal case or housing with openings for air flow, light transmission, and wires for energy supply and data input and output. Interference penetration may occur on these wires from electromagnetic fields that enter through the openings and from fields that diffuse through the metal walls of the housing.

3.4 Types of interference

Interference may be characterized as transient, repetitive, or narrowband. [Also see Chapter 9 IEEE Std 1100-2005 \[B58\].](#)

3.4.1 Transient interference

Transient interference is an individual electromagnetic event, such as a lightning ~~stroke flash~~, a switching transient, or an electrostatic discharge. A transient is completely characterized by its waveform (amplitude as a function of time). For many practical purposes, ~~transients may be characterized by their~~ peak amplitude, rate-of-rise, energy, charge transfer, or ~~another other~~ property ~~that affects the sensitive~~ circuit [may be used to characterize transients](#). Transients tend to be a problem for broadband systems, such as digital electronic circuits and computer-controlled systems.

3.4.2 Repetitive interference

Repetitive interference is [a discontinuous](#) ~~an~~ electromagnetic wave that is repeated periodically (or nearly periodically). Repetitive interference is characterized by its waveform. For many practical purposes, repetitive interference may be characterized by its peak amplitude, fundamental frequency, and harmonic or spectral content. Repetitive interference may degrade analog circuit performance by reducing the signal-to-noise ratio, particularly if the operating frequency coincides with a harmonic of the interference. It also degrades digital circuit performance if the amplitude is large or if the repetition frequency coincides with the digital circuit operating frequency.

3.4.3 Narrowband interference

Narrowband interference is a nearly sinusoidal wave or the sinusoidal equivalent of broadband noise in a narrow bandwidth. Narrowband interference is completely characterized by its amplitude, frequency, and bandwidth or by its power spectral density and frequency. Narrowband interference affects the signal-to-noise ratio of [an](#) ~~a radio receiver, and it may similarly affect~~ analog circuit operating at low levels [particularly if the interfering frequency is within the operating band of the analog circuit.](#) If [the interference is](#) large enough, it may also interfere with digital circuit operation.

Broadband sources of interference, such as transients and repetitive sources [are](#) ~~have~~ often ~~been~~ characterized [as](#) ~~by their~~ narrowband [interference for a specific environment.](#) ~~spectral density.~~ This characterization is useful for specifying the interference environment for narrowband analog systems. For digital circuits and systems, ~~the~~ narrowband spectral density is less useful, because it does not define the properties of transients and repetitive interference that are most likely to affect digital circuits— namely peak value, energy ~~or action~~, charge transfer, [or](#) ~~and~~ rate-of-change.

Narrowband spectral density has also been used to characterize broadband noise produced by random processes such as thermal noise and atmospheric noise. These are rather weak sources that are of interest primarily to designers of sensitive communication equipment and high-gain amplifiers, for which the narrowband spectral density is appropriate.

3.5 Sources of electromagnetic interference (EMI)

When electromagnetic energy from sources external or internal to electrical or electronic equipment adversely affects that equipment by creating undesirable responses (degraded performance or malfunctions), the electromagnetic energy is defined as electromagnetic interference or induction (EMI), and the adversely affected equipment is said to be susceptible to EMI.

3.5.1 Natural sources of EMI

The natural sources of electromagnetic interference are the earth's magnetic field, discharges in the atmosphere, such as lightning, and radiation from outside the earth's atmosphere, such as solar flares.

3.5.2 Man-made sources of EMI

For the purpose of completeness, it should be noted that sometimes man-made sources could be broken into two categories defined by the distance to the source of interference.

- *Induction zone:* When the distance to the source is less than the wavelength of the interference. In the induction zone the circuit or system will be affected by transverse or longitudinal fields.

- *Radiation zone*: When the distance to the source is greater than the wavelength of the interference. In the radiation zone the circuit or system will be affected by plane waves.

3.5.2.1 Electrical equipment and wiring

- *Rotating machinery*: The [actions of the](#) brush and commutator ~~action~~ of dc motors or generators and sliding contacts from slip rings in synchronous motors and generators produce repetitive interference.
- ~~Circuit~~ *Switching*: Sudden changes in circuit impedance due to switching cause ~~current and voltage~~ transient interference. The switching on and off of multispeed motors, capacitor banks, transformers, distribution circuitry, and fluorescent lights can be sources for [EMI electromagnetic noise](#).
- [Rectifiers: Silicon-controlled rectifiers produce an especially high levels of repetitive interference.](#)
- *Faults*: Faults interrupted by current limiting fuses, arcing, and restrikes on switching can create transients and electromagnetic noise.
- *Welding and power lines*: Power-frequency electric and magnetic fields can result from resistance welding machines and power lines.
- *High voltage equipment* ~~Transformers~~: Corona or partial discharges (~~pd~~) can occur ~~in the high voltage winding insulation bushings, and voltage tap terminals. The transformer's core and windings have an inherent electromagnetic field.~~ when the electric field on the surface of an object, usually a conductor, exceeds the ionization potential of the surrounding dielectric medium (gas, liquid, solid, or combinations thereof). This causes the immediate surroundings to become ionized, producing interference. This generally occurs at cable splices, terminations, and gaps between live conductors.

- e) ~~Dimmers: Dimmers usually produce high levels of repetitive interference. Silicon-controlled rectifiers produce an especially high level of interference.~~

3.5.2.2 Discharge-type lighting fixtures

Fluorescent lighting fixtures, especially the slim-line type, produce repetitive EMI. The arcing process taking place during the lamp operation produces an electromagnetic field around the lamp and in the surrounding environment. The lamp and ballast feed conducts interference back into the branch circuit and the wiring system supplying the power.

3.5.2.3 Other sources

Some electronic equipment, such as diathermy and microwave ovens, produce considerable narrowband interference. Other miscellaneous sources are ultrasonic devices, ignition systems, and broadcasting transmitters (these include radio, television and airport radar). Other sources may be power and communication systems, industrial radios, and telephone and electronic switching equipment.

~~4.6 Electrical noise produced by power processing and control~~

3.5.2.4 Arcs or sparks

Current chopping in electrical contacts causes discharges known as arcs or sparks. During circuit interruption, current will suddenly cease. This step change in current creates an electrical noise transient. Peak voltages of the arc are a function of the contact gap. The breakdown discharge within the gap depends upon number and size of the contact gaps, contact material, and surrounding atmosphere. Sliding contacts in ac motors and dc motor commutators also create showering arcs and repetitive interference.

3.5.2.5 Solid-state switching devices

Power line voltage transients can be initiated by switching power loads. For example, closing a switch to a resistive load when the voltage is not zero allows the current to rise to the normal value as rapidly as the circuit constants will permit, thereby producing a voltage transient.

Solid-state switching devices switch faster than mechanical contacts. Because of the speed at which solid state switching systems operate, a common use is to control power by repeated switching operations (every half-cycle is common). The results in repetitive electrical interference are as follows:

~~4.6.2.1 Resistive loads~~

- a) Phase control devices for resistive loads: Phase control devices for incandescent lamps ~~dimmers~~ or heaters may be ~~controls are~~ solid-state switching devices that ~~and~~ can be a source of electromagnetic noise.

~~4.6.2.2 Inductive loads~~

- b) Adjustable speed drives (ASD) for inductive loads: ASDs for inductive ~~Silicone-controlled rectifier (SCR) drives~~ loads are solid-state switching devices and can be a source of electromagnetic noise. The noise is produced when the current in one line is suddenly stopped and then established in another line.

3.6 Radiated interference

Radio frequency interference (RFI) or radiated noise requires a transmission source and a reception antenna that is at least 1720th the length of the wavelength of the radiated noise, i.e., wavelength divided by 20. At 10 MHz, the wavelength is 30 m, so 1720th of a wavelength is 1.5 m. At 300 MHz, the wavelength is 1 m, so 1720 of a wavelength is 5 cm (2 in). So, for signals at 300 MHz, exposure of less than 5 cm (2 in) of cable is all that is required to accept radiated interference. The reception antenna should be at least one-half a wavelength away from the radiating source, but this may be an unlikely source of trouble.

4. Types of cable shielding

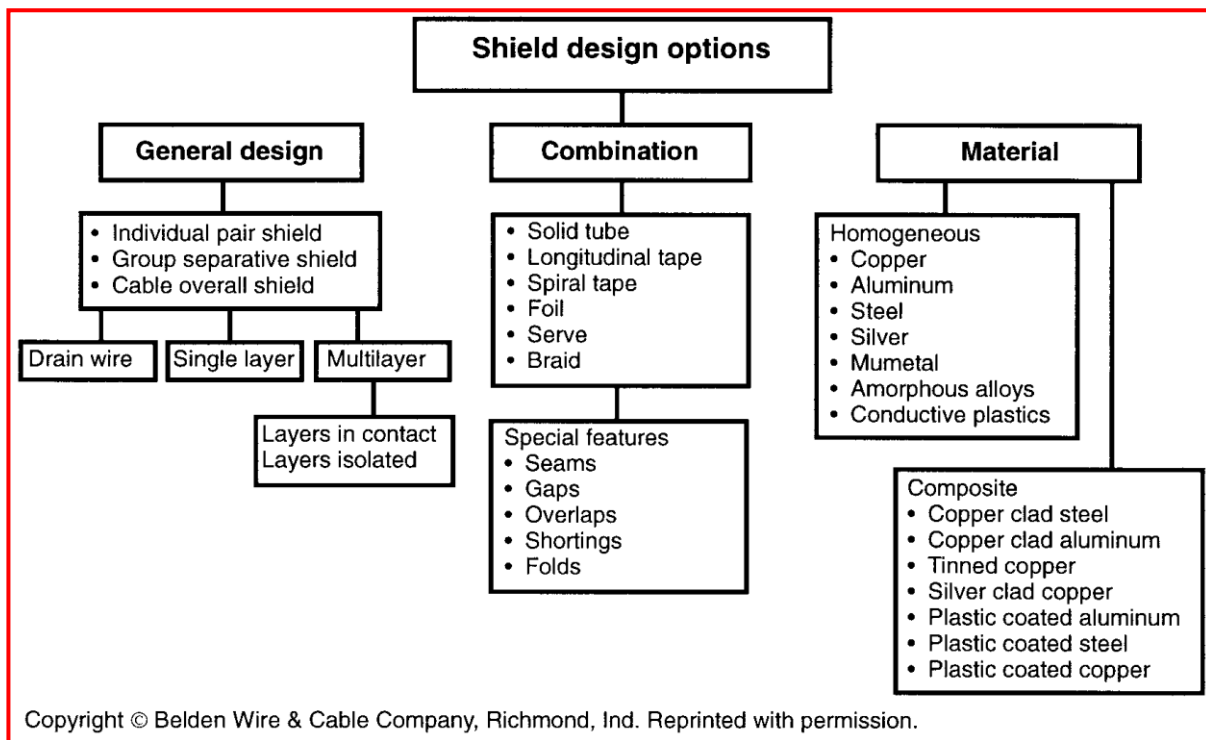
4.1 Introduction

Table 1 shows the many types of shields used for cables. These differ in design and material composition and therefore have different shielding properties. [Also see Chapter 10 of IEEE Std 1100-2005 \[B58\].](#)

Table1— Shield design options

General design			Construction Choices	Material Choices
Foil Shield over an individual pair Foil Shield over groups of conductors or shielded pairs Overall shield about equal in resistance to a conductor over groups of conductors, foil shield and/or shielded pairs			Solid tube Longitudinal tape Helical tape Foil Serve Braid	Homogeneous Copper Aluminum Steel Silver High magnetic permeability nickel iron alloy Conductive plastics
Drain wire	Single layer	Multilayer Layers in contact Layers isolated	Special Construction Features: Seams Gaps Overlaps Folds	Composite Copper clad steel Copper clad aluminum Tinned copper Silver clad copper Plastic coated aluminum Plastic coated steel Plastic coated copper

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Figure 1—~~Electrical cable~~ shield design options

4.1.1 Foil shield

A foil shield should be chosen for protection against capacitive (electric field) coupling where shield coverage is more important than low dc resistance. A foil shield should be considered when possible sources of interference include TV signals, crosstalk from other circuits, radio transmitters, fluorescent lights, or computing equipment. Also, a foil shield should be considered for [master antenna metropolitan-area](#) television (MATV), community antenna television (CATV), video, local area networks (LANs), [and](#) computer cables in office industrial or commercial environments where ambient EMI levels are low or where [emission](#) ~~FCC~~ requirements need to be met ~~[B7]~~.

The types of foil shields used in low voltage cables are quite extensive. The thickness of the aluminum foil varies from 9.0 μm (0.35 mil) to 25 μm (1.0 mil) to 51 μm (2.0 mil). The aluminum foil is laminated with a polyester tape or other polymer for tensile strength. The polyester can vary in thickness from 12 μm (0.48 mil) to 76 μm (3.0 mil). There can be shields with 2 layers of aluminum. Copper foils are used when additional corrosion resistance is required (frequently used in military cables). Certain types of polyolefin layers can replace the polyester when reduced smoke is a requirement such as when category, fire alarm, or power-limited cables are used in plenum applications. Colors can be yellow (gold), blue, white, violet or another color. There is also a class of foil shields with an adhesive layer on the foil to bond the shield to a PVC or polyethylene cable component. Table 2 provides a summary of the various types of foil shields and their application in various types of cables.

Table 2—Typical Foil Shield Constructions and Their Use in Cable

<u>Thickness, μm</u>			<u>Application</u>	<u>Cable Type</u>
<u>Al</u>	<u>PET</u>	<u>Al</u>		
9	12	—	<u>Individual Pairs</u>	<u>Electronic, CAT</u>
9	23	—	<u>Outer or Individual Pairs</u>	<u>Electronic, CAT</u>
9	23	9	<u>Outer Shield</u>	<u>CATV, LAN</u>
9	23	51	<u>Outer, Contact Drain Wire</u>	<u>LAN, Coaxial</u>
9	43	—	<u>Foil Free Edge</u>	<u>Process Control</u>
9	51	—	<u>Outer Shield, Binder</u>	<u>Multi-pair</u>
25	23	—	<u>Outer Shield, Binder</u>	<u>Multi-pair</u>
25	23	25	<u>Second Shield</u>	<u>LAN, Coaxial</u>
25	51	—	<u>Outer Shield</u>	<u>Telecom</u>
38	12	—	<u>ANSI/IEEE 802.5</u>	<u>Network Type I, II</u>
38	23	—	<u>ANSI/IEEE 802.5</u>	<u>Network Type I, II</u>
51	12	—	<u>Twisted Pair</u>	<u>CAT</u>
51	76	—	<u>ANSI/IEEE 802.5</u>	<u>Network, Type I, II</u>
<u>PET = Polyester, Al = Aluminum, 1 μm = 0.00004 in = 0.04 mil</u>				

As to the choice of a particular foil shield, many factors are involved besides the electrical properties. One important factor is the mechanical properties of the foil shield. Minimum thickness is often determined by the ability of the shield winding equipment to apply the shield without damage to the foil shield. Electrical properties may be secondary when compared to cost, production output and equipment capabilities. Also, the longevity of the shield when flexed may be a requirement that may impact the choice of minimum thickness of the foil.

Foil shields are used most often to reduce high-frequency, capacitive coupled noise. A foil shield is not an effective shield for magnetically coupled noise. This is because the energy in magnetically induced interference can easily saturate the relatively thin layer of metallic foil and couple into the signal conductors in the cable. Foil can be effective against high frequencies because it provides 100% coverage. Overall shields with metal thicknesses approaching the resistance of a conductor can control magnetically induced noise when grounded at both ends (See 6.3).

4.1.2 Braid shield

A braid shield may ~~should~~ be chosen for increased ~~superior~~ resistance to EMI ~~diffusion-coupling~~ at low frequencies where low dc resistance is important, and to a lesser extent, when capacitive and inductive coupling is present. A braid shield may be ~~is~~ effective in the following circumstances:

- a) When possible sources of interference exhibit low impedance characteristics, such as motor control circuits and switches that operate inductive loads
- b) For computer to terminal interconnects for process, instrumentation, or control applications

Braided shields offer protection against magnetically induced interference in the 30 MHz to 100 MHz ranges, and with 85% or more coverage, braid shields can reduce RFI interference significantly below 500 MHz. The braided wire works because the surface area of the braid is significantly greater than solid wire or stranded wire. Since the skin effect applies to high-frequency interference, the greater surface area of the braid can facilitate in reducing the effect of high frequency EMI. Braids are effective for controlling both immunity and emissions. When the interference is less than 100 MHz within the shield, the braid will represent a large inductive path preventing the coupling into an unintended circuit. When frequencies much higher than 100 MHz need to be guarded than 85% will need to be used.

4.1.3 Helical/Spiral shield

A helical/spiral shield may ~~should~~ be chosen for ~~functional~~ shielding against inductive ~~diffusion~~ coupling at low frequencies and capacitive coupling at audio frequencies ~~only~~, under the following circumstances:

- a) When possible sources of interference are power lines and fluorescent lights
- b) For applications when flexibility and flex life are major concerns, such as microphone and audio cables and retractile cords

4.1.4 Combination shield

A combination shield may ~~should~~ be chosen for shielding against high-frequency radiated emissions, capacitive coupling, and electrostatic discharge (ESD). This type of shield combines the low resistance of braid with the ~~and~~ 100% coverage of foil shields. The combination shield is effective for the following:

- a) When possible sources of interference include radio transmitters, TV stations, motor control circuits, and computing equipment
- b) For video, CATV, MATV, FCC, LANs, computer cables, and computer-aided manufacturing applications

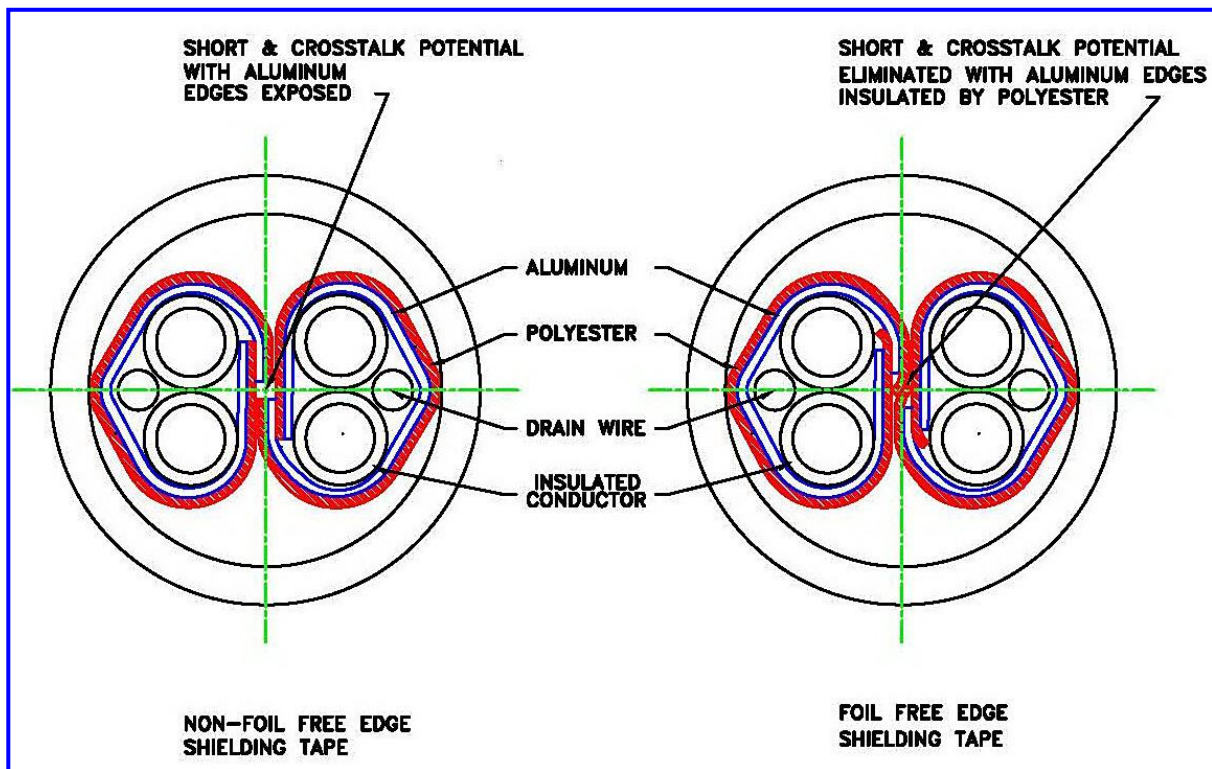
4.1.5 Overall shield

An overall shield ~~may should~~ be chosen ~~when for~~ power surges or other transients ~~may be present~~ and for protection against ~~both capacitive and~~ magnetic field (inductive) coupling, see Casey, [B10]. The overall shield is relatively thick, typically a minimum of 0.125 mm (5 mil) thick. The shield is effective against both power frequency and high frequency electrostatic and electromagnetic interference when grounded at both ends. By grounding at both ends the shield generates a counter current that cancels out the interference current interacting with the protected current. The overall shield avoids the saturation problem that limits the performance of foil shields (See 6.4).

4.1.6 Foil free edge shield

Multi-paired or multi-triad instrumentation cable cores are individually shielded to prevent crosstalk. This is commonly done with aluminum foil/polyester film shielding tape and drain wire. With a conventional tape (non-foil free edge), the possibility of crosstalk is greater since the edges are not insulated and direct shorts can occur between the individual cable core shields. Additional clear polyester films can be added over the individual shields as a preventative measure but would be at an additional cost.

Another method is to utilize a foil free edge shielding tape. A foil free edge shielding tape is typically used in multi-paired or multi-triad instrumentation cable to reduce crosstalk. Laminating an aluminum foil to a wider polyester film makes this type of tape, creating a non-conductive foil free edge tape. Since the polyester film insulates the edge of the aluminum foil, the possibility of shorts is eliminated and crosstalk between the individual cable cores is greatly reduced.



(New)

Figure 1—Non-Foil Free Edge and Foil Free Edge Shielding Tape

4.1.7 Metalized plastic shields

A metalized plastic film can be made by vacuum depositing 2 μm to 5 μm (0.08 mil to 0.20 mil) of metal on a plastic film, to allow the metalized film to be used as a shield. This metalized plastic film is useful where only low-frequency electric field protection is needed, and where the cable is not subject to flexing or corrosive environments.

~~Such~~ a thin metal coating cannot carry much current and does not provide much protection against induced longitudinal currents. The resistance of a shield with a metalized coating is about 0.1 Q/m (0.03 Q/ft) and its cutoff frequency is on the order of 300 MHz. Because the metal film is very thin, it has little mechanical strength, and it is easily cracked, scratched, or torn during mechanical flexing. It is also easily damaged in a corrosive environment.

4.1.8 Comparison of various shield types

The cable shield is a part of an electromagnetic barrier that separates the shielded circuits from the external sources of EMI (or confines EMI effects to the shielded volume). An electromagnetic barrier is a closed surface made up of shields and other elements to exclude (or confine) electromagnetic waves propagating in space or guided along conductors. The barrier may be made up of metal or conductively coated equipment cases, interconnecting cable shields, filters or surge arresters on wires that penetrate the shield, and mesh or waveguides (below cutoff frequency) at ventilation openings. In a protected system, the barrier is everywhere sufficiently impervious to guide and space waves so that EMI sources outside the barrier do not degrade the performance of the protected system.

A perfectly conducting cylindrical tube or shell that is grounded at both ends would allow virtually no external electromagnetic fields to affect circuits inside the shell. Since it is a closed shell, there are no apertures or conductors through which electromagnetic fields can penetrate and interact with the internal conductors. Because the cylindrical shell is a perfect conductor, no fields diffuse through the shell.

Practical cable shields are made of braided wires and tapes that have apertures through which electromagnetic fields may penetrate. See "Cable Shield Performance and Selection Guide" [B9]. Currents in braided wire shields shuttle between the outer surface and the inner surface in the woven braid. Current induced at the outer surface is carried to the inside of the shield where it can interact with internal circuits. Helical-wound tape shields may behave as solenoids when the turn-to-turn contact is poor. Tape shields are wrapped with an overlap that may act as an aperture. Practical shields are made from finitely conducting materials that may allow some fields to leak through the shield material.

Cable material characteristics and cable construction techniques affect EMI shielding effectiveness and frequency dependence. For instance, with a braided shield, the braid weave angle and optical coverage affect the amount of leakage. Tape shields allow leakage at the tape overlaps. Foil shields with interlocking slots may also exhibit leakage at very high frequencies. Apertures are also a factor in shielding effectiveness.

4.2 Coupling through apertures

The coupling into the interior of a coaxial cable through an isolated aperture in the shield is shown in Figure 2. Both electric and magnetic fields can couple through the aperture; thus the presence of shield apertures leads to capacitive and inductive coupling between the exterior and the interior of the cable.

[Where \(Figure 2a\):](#)

[\$I_s\$ = current in the shield due to EMI](#)

[\$H\(I\)\$ = Magnetic field generated by the interference](#)

$H(I_s)$ = Magnetic field generated by the shield current [180 degrees out of phase, in turn canceling $H(I)$]

Where (Figure 2b):

V_o = Electrical Voltage on Conductor:

$E(V_o)$ = Shield Cancelling Voltage on Conductor

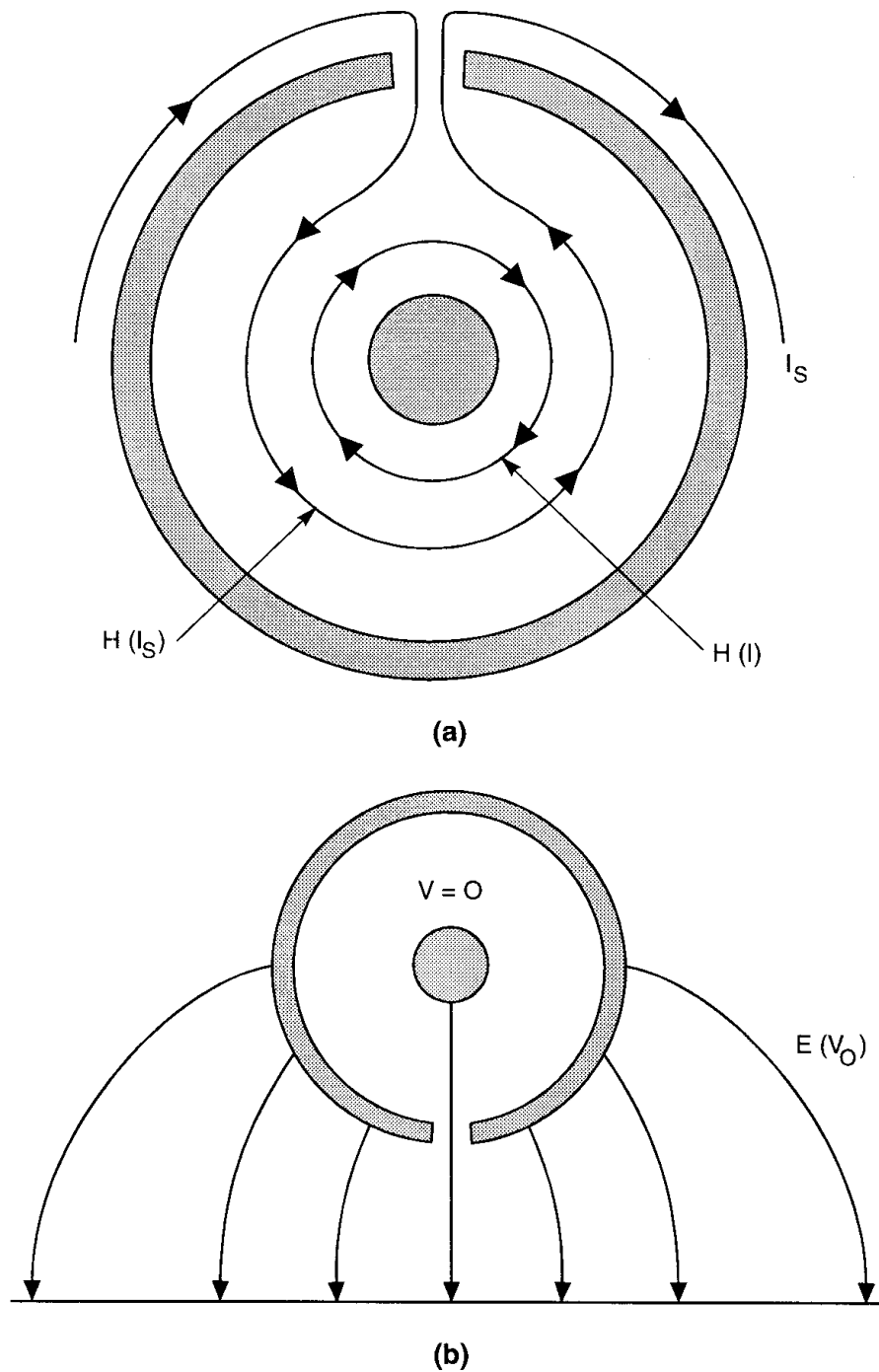


Figure 2—Electrical and magnetic field coupling through aperture in coaxial cable shield

(a) Magnetic coupling, (b) Electrical coupling

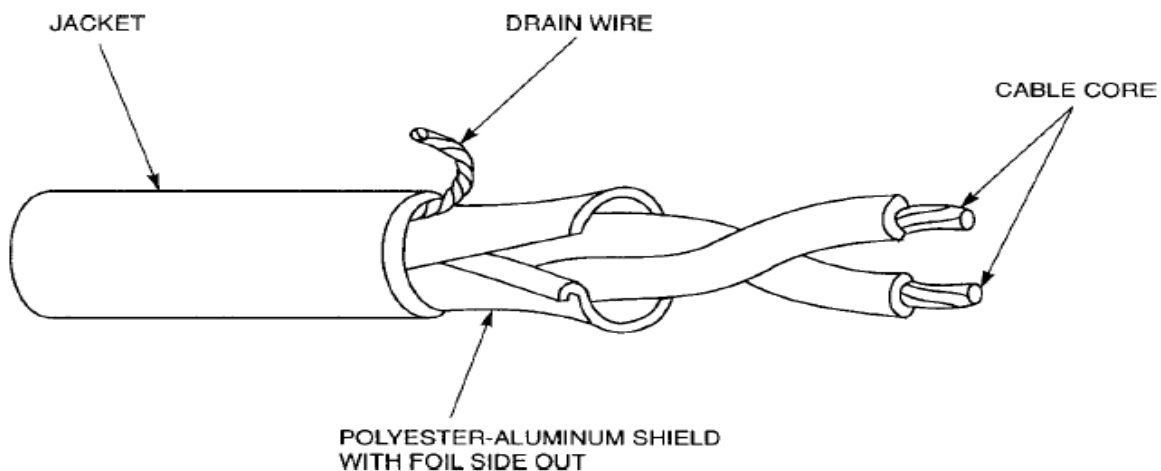
4.3 Solid tube shield

A solid wall tube shield displays the most favorable high-frequency shielding properties. Its performance is a direct function of skin effect and the diffusion transfer processes. The shielding properties improve with higher levels of shield conductivity, magnetic permeability, and thickness.

Despite their excellent shielding characteristics, tubular shields have limited use where flexibility is a requirement. They are normally used in permanent installations.

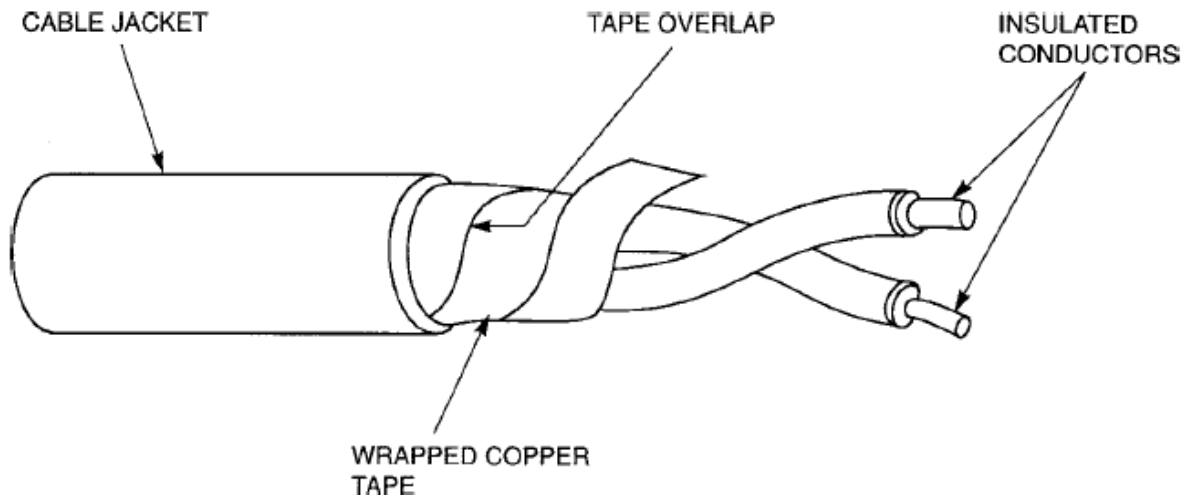
4.4 Single layer foil shield with drain wire

A foil shield is a thin, self-supported metallic tape, wrapped longitudinally (Figure 3) or helically (Figure 4) around the cable core. Usually, aluminum foil is used, although some cables use copper, magnetic alloys, or conductive plastics. Occasionally, metalized film has been used.



Reprinted with permission from Belden Inc., "Cable Shield Performance and Selection Guide" [B9].

Figure 3—Longitudinally applied foil shield



Reprinted with permission from Belden Inc., "Cable Shield Performance and Selection Guide" [B9].

Figure 4—Helically applied foil shield

4.5 Multilayer Shield with Drain Wire

To provide the necessary mechanical strength, the foil is usually bonded to the cable insulation or laminated to polyester or other plastic layer. Figure 5 shows the use of a drain wire inside or outside the shield. Since the dc resistance of the foil is large, a drain wire is used to facilitate shield termination.