CABLES AND CONNECTORS

Introduction

The electrical and mechanical designer spends much of his interference control efforts in the design of components without due regard to interconnecting cables and harnesses. The mechanical engineer designs the case or chassis seams with RF gasketing material, controls the machining and finishes of mating surfaces, covers holes with screening or honeycomb cells, and applies other mechanical controls. The electrical engineer specifies the power line filters, designs the grounding system, adds the transient noise suppressors and protectors, specifies the internal harnessing configuration, selects the connectors, and provides other electrical controls. However, unless the component is designed to operate independently from all other components or equipment, such as T.V., oscilloscope, radio, etc., the harness and cable configuration is delegated to subsystem and system engineers. Thus, the component design engineers only do half of the job.

Cable and harness configurations are critical in the component design to reduce the propagation of electrical noise (EMI) and its effects. The best electronic box, shielded enclosure or shielded room can always be compromised by poorly designed interconnecting cables. Cables provide a convenient path by which electrical noise is conducted out of the cnlosure and then radiates or couples to adjacent wiring and equipment. The reverse process also occurs with external noise pick-up on cables being conducted into a well-shielded container. The filtering of the interconnecting lines does not always solve the problem. Lines which conduct clock pulses, digital signals, video signals, etc., cannot tolerate filters which affect the signals. These signals also appear as noise to other circuits when coupling to other lines occurs.

Systems engineers treat interconnecting harnessing very seriously in respect to noise control and electromagnetic compatibility. They realize that crosstalk is a real everyday problem, and intentional system radiation can have backdoor effects if it is allowed to get into system wiring. This problem is not limited to military applications or systems. It can occur in the home, industrial plant, in office buildings, scientific centers, hospitals, automobiles, aircraft, as well as electronic laboratories. A car radio can be jammed by electrical noise radiation from unsuppressed truck ignition systems. Noise from the fluorescent lights, razor, vacuum cleaner, etc., interferes with T.V. and radio reception. Computers are extremely vulnerable to the coupling of transients generated by air-conditioners or time-clocks. In the hospital, patient monitors are disturbed by the magnetic fields emitted by power lines, heating blankets and other electronic equipment. Electric typewriters and other office machines can make communications nearly impossible. Electronic fly killers have been known to affect aircraft navigational equipment. In all of these examples, the method of radiation and pick-up of the electrical noise is through cables. The primary means of protecting electro-explosive devices is through the design of its cables.

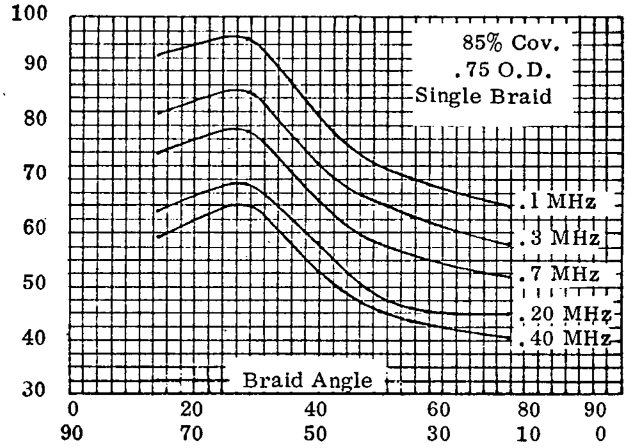

Figure 1

Protected Interconnect Design

When electrical connections are required from one shielded enclosure to another, the protection of these circuits should be as good as that of the enclosures. The exception to this would be where filters provide isolation at the entrance to the enclosure. This applies to circuit shields, electrical connectors, and the method of terminating the shielded cable at each end. The ideal interconnecting system would be a solid conductive conduit, welded to the enclosure at each end so that electrically one enclosure exists. The opposite would be a single conductor routed at random spacing from ground planes, objects and over a longer than necessary distance. Between these two extremes, the number of variations is limitless. Reducing our scope, we will examine only those designs which provide extra protection over and above such interference reduction techniques as twisting, coaxial wire, balanced impedance transmission controlled bundling, etc.

This is divided into two sections—cable sheath design and the termination of sheath to connectors and enclosures by means of backshells/adapters. The most common EMI protective sheath is metallic braid—it provides a controlled amount of coverages (%) and can be applied in multiple layers. These layers can be separated by an insulator for reduction in conductive and inductive coupling or be applied over each other to increase the percentage coverage and reduce the capacitive coupling. It is important to note that addition to percentage of coverage the braiding angle (conductive path direction) has an influence on the amount of protection the sheath will yield. (See figure 1). Tin or silver plated copper is the most common. However, other metals particularly metals with permeability can provide that extra level of performance desired. But it is important to note that whatever material is selected—a good surface/contact conductivity is needed either through plating or intrinsic.

Metallic mylar with drain wires under but in contact with the shield is a very effective protection against capacitive coupling. The overlap, number of layers determine the level of shielding/screening obtained. Conductive elastomers or elastomeric conductive coating on shrink tubing is another type of reduction. The conductivity and the uniformity are the most important parameters in providing the level of shielding/screening needed. Due to the construction of the conductive path (thin—mostly silver or carbon filled elastomer) it is desirous to include drain conductor(s) under the sheath. (Figures 2 & 3).

A helically convoluted thin metal tubing with the seam soldered or brazed is commonly used as the protective sheath when shielding/screening over a wide portion of the spectrum and/or very high level of attenuation is desired. (Figure 4.)

This sheath construction also allows the use of very high permeable (100,000) metals such as 80/20 nickel iron alloys providing as much as 40 dB of protection against magnetic field at 60 Hz. Usually, an additional braid cover is provided to protect the thin metal convoluted tubing from mechanical damage. The additional shielding/screening is negligible. This protection media is also many times used where extensive flexing is required as long as the mechanical stress remains within the elastic limits of the metal—there will be no degradation. This method of protection also lends itself to being solder/brazed to terminating hardware (backshell/adapters) reducing troublesome terminations on high level protected interconnections.

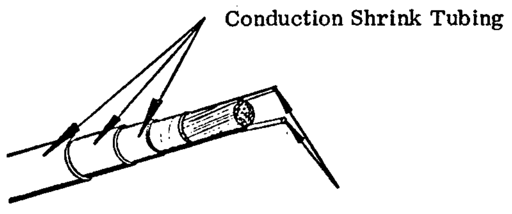

Figure 2

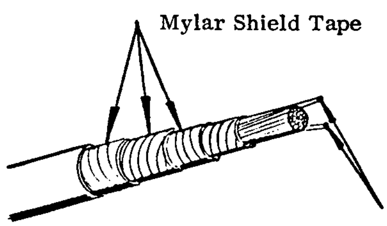

Figure 3

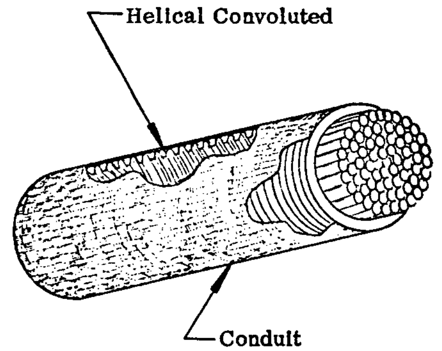

Figure 4
Helically Convoluted Protective Sheath

Sheath Terminations (Backshell Adapters)

A very significant amount of the cost and reliability of the protective system is in the selection/design of the method of termination. For EMI protection, a 360 degree extreme low impedance joint will yield an uncomprised level of shielding/screening. Some of the better known designs are:

Tapered Cone

Most often used with braided sheath. The braid is stretched over a tapered section which is forced into the tapered opening of the backshell/adapter. (Figure 5.)

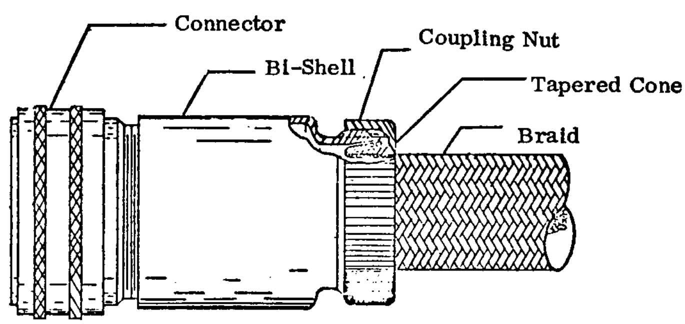

Figure 5
Braided Sheath With Tapered Cone Termination

Magna-forming is a metal forming process that utilizes an electromagnetic pulse to create two opposing fields. One on the surface of the to be formed part, the other on a metallic field shaper, resulting in the movement of metal without physically touching the material. This technique results into being able to bond (electrical) metallic components in an absolute continuous peripheral continuous manner. The continuity of a peripheral bond being one of the key termination criteria, this technique is rapidly becoming a preferred technique, (Figure 6).

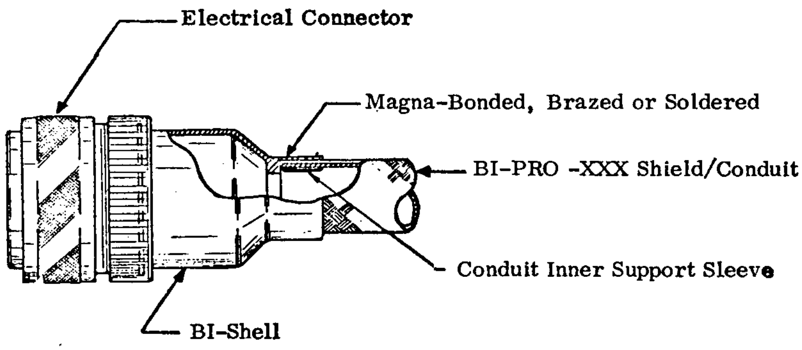

Figure 6
Magna Formed Termination

Direct Bond or Ring Termination

With this design, the sheath is applied over a supporting ring or directly onto an extended section of the backshell/adapter. The shield screening is then secured to the backshell/adapter through one of the following; soldering, brazing, swaging/crimping, magna-forming, (Figure 7).

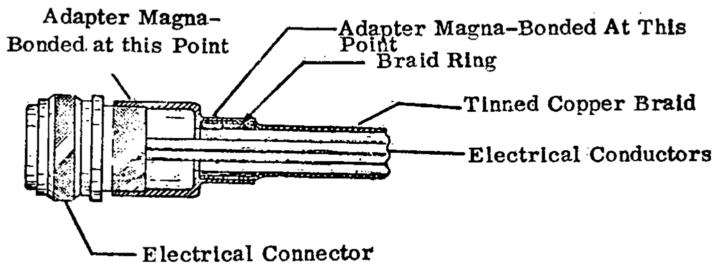

Figure 7
Direct Bond Termination

Compression Media Terminations

This technique employs the principal of wedging a compressible element such as a metal coil spring, conductive elastomer, or other compressive and conductive media in contact with the sheath, while maintaining in contact with the backshell/adapter. The chief benefit is terminating the protective sheath without disturbing it and having effective control over how many contacts there will be around the periphery, (Figure 8).

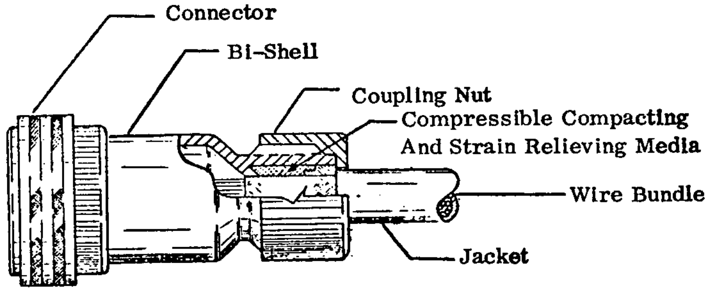

Figure 8
Compression Media Termination

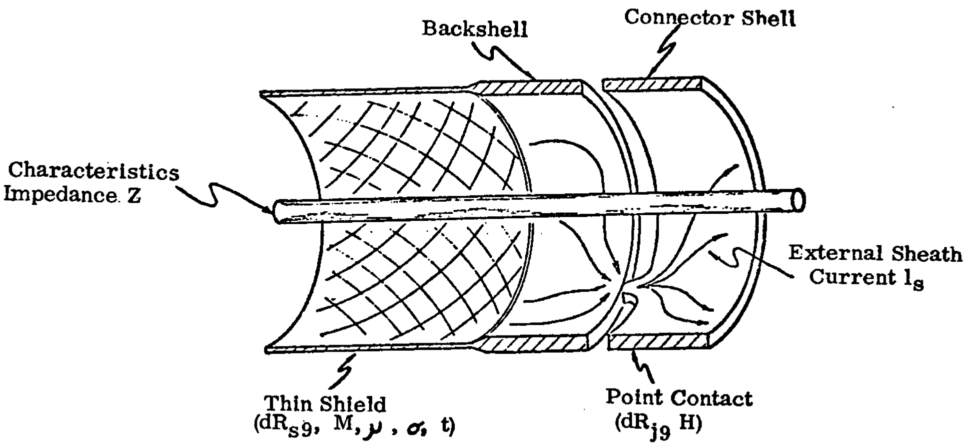

Figure 9
Thin Sheath Joined To Backshell

EVALUATION

Leakage Models

Figure 9 shows a thin sheath joined to a backshell which is in partial contact with a connector shell. Figure 10 uses the approach of Taylor and Harrison to model the resulting leakages with lumped voltage and current generators for the thin sheath and separately for the shell joint. For well-shielded connectors, the electric field coupling is always unimportant and is hereafter ignored. The Transfer Impedance A_{tr} is defined as:

$$Z_{tr} = V_c / I_s$$

Where I_s is the external shield current: V_c is the voltage induced in series with the center conductors by diffusion or magnetically coupled leakage energy.

Method

There are many possible configurations in which a shield current I_s can be made to flow over the exterior of a sheath while the integral of the leakage signals induced in a conductor located concentrically inside the shield is monitored.

Open Wire Configuration

Figure 11 shows a configuration in which the requirement that:

$$R_{exterior} = R_{interior} = Z_{exterior} = Z_{interior}$$

Can only be met at low frequencies. The "matching resistor" $R_{external}$ is connected in series with inductance $L_{external}$ and consequently the total source impedance, can only be matched at low frequencies when the impedance $L_{external}$ is vanishingly small.

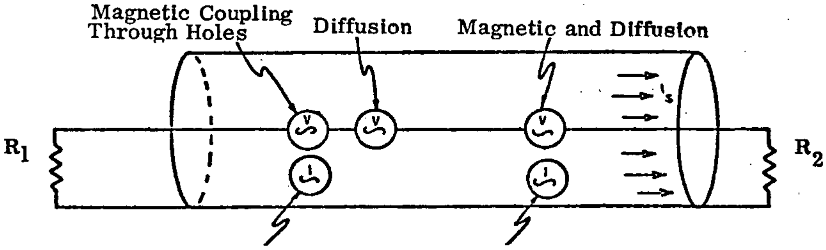

Figure 10
Electric Coupling Through Holes

The inverted Triaxial Configuration shown in Figure 11 makes use of an adjustable "Outer Tube" length. At high frequencies the total load imposed on the signal generator can be made to be $R_{external}$ by adjusting the position of the shorting ring such that $Z_{exterior}$ is a quarter-wave tuned stub. Under these conditions, however, the current along the interconnect assembly under test will vary coinusoidally with length reaching a maximum at the position of the shorting ring. The magnitude of this current will always be greater than the current flowing through $R_{external}$, thus assuming this be used as a reference, the measured shielding value will be in error by an amount dependent upon the Q of the resonant stub and the position along the interconnection of the dominant leakage sources.

Triaxial Configuration

The familiar Triaxial configuration, used by many organizations and required by U.S. Military specifications, is obtained by interchanging the signal generator and the detector and by omitting the resistor $R_{external}$ shown in Figure 12. In this Triaxial configuration the load imposed on the signal generator can be constant and matched over a wide band of frequencies, thus allowing a uniform current to flow through or past all leakage sources. However, the coaxial path which integrates the leakage energy and feeds the detector cannot be matched. This path includes the "sliding shorting ring" which is positioned for maximum detector signal for each test frequency. The signal reaching the detector is then the sum of the energy leaking through the assembly under test, and propagating in the direction of the detector with the energy leaking through the interconnection and propagating in the opposite direction towards the source. This latter energy being reflected by the shorting ring and adding, in-phase, with the former. The lowest useful frequency is limited by the length of the sliding path provided for the shorting ring. The Triaxial configuration can be used at high frequencies subject to the limitations concerning TEM modes stated in page 25 of the appendix to MIL-C-39012B.

Quadraxial Configuration

Figures 13 & 14 show a Quadraxial configuration which allows both the signal generator, or driven path, and the leakage integrating, or detector path, to be matched at all frequencies for which TEM modes predominate thus eliminating the need for an adjustable shorting ring. The usable frequency range extends from zero frequency to the limit at which TEM Modes no longer predominates. Since this frequency range can be achieved without mechanical adjustment, a swept frequency source and an automatically tracked or self-tuned detector can be used resulting in a considerable reduction in test time and eliminating the possibility of a frequency dependent leak escaping notice between the chosen or specified discrete measurement frequencies.

The Quadraxial method in addition lends itself to measuring complex interconnection cable assemblies through the design of a 3 sided (trough) transmission line into which the assembly under test is placed. A current probe is used to measure the level of current induced in the sheath under evaluation. The SAE-AE4 subcomittee on EMT connector evaluation is preparing an ARP using a modified quadraxial test fixture to evaluate connectors and other interconnection systems components such as backshells, adapters, etc.

SUMMARIZING THE OPTIONS FOR TEST CONFIGURATIONS

Options	Frequency Range	Data Format	Relative Complexity
Open Wire	DC to Very Low	X-Y Plotter	Simple
Coaxial	DC to Low	X-Y Plotter	Simple
Inverted Triaxial	100 MHz to High	Discrete, tabular	Not Simple
Triaxial	100 MHz to Very High	Discrete, tabular	Complex
Quadraxial	DC to Very High	X-Y Plotter	Complex

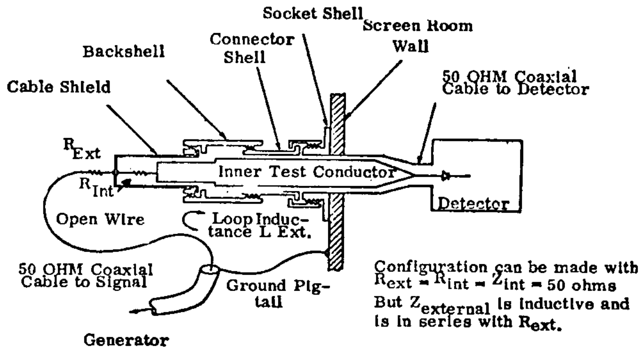

Figure 11
Open Wire Configuration

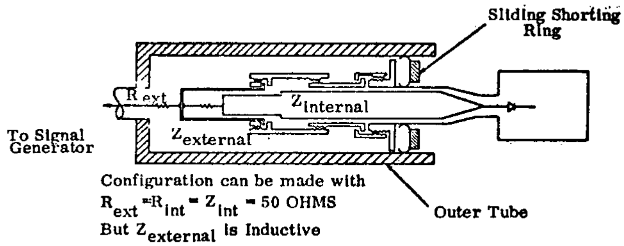

Figure 12
Inverted Triaxial Configuration

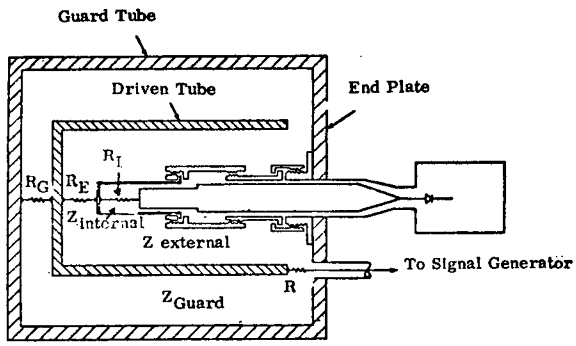

Figure 13
Quadraxial Configuration

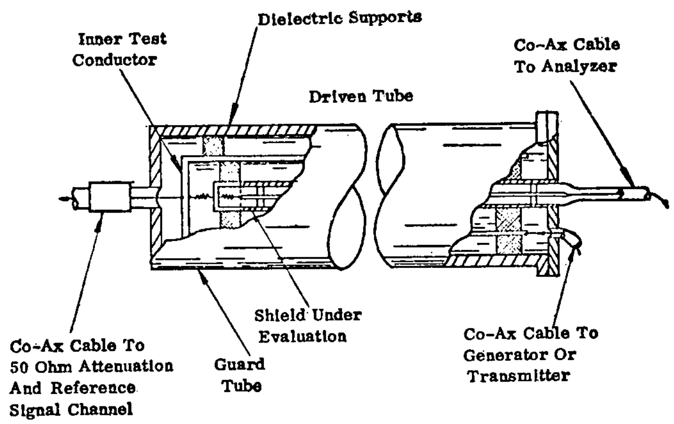

Figure 14

CABLE SEPARATION

The coupling of signals and noise between wires and cables is a function of the distance between cables. Thus, it is most advantageous to categorize the various types of cable signals and to provide maximum separation between them. This is not always easy to accomplish, especially on space vehicles, or in complex electronic facilities where there are numerous cables and harness restrained by limited cable troughs. It also becomes a problem when wires of different categories share the same cable connector. However, an attempt should be made to provide whatever separation is practical. The following categories are illustrative only, and are usually modified to match the partial line voltages, signal levels and frequencies:

a. Category P, Power:

1. 115 volts and 240 volts single phase and three phase to motors, transformers, blowers, etc.
2. Control wiring which includes relay logic, stepping switches, indicator light circuits (incandescent), etc.
3. RF power, primarily transmitter outputs.

b. Category S, Sensitive Wiring:

This category includes moderately susceptible circuitry which is easily protected such as limited bandwidth audio amplifiers, input medium-level wide bandwidth video lines, properly designed digital computer input circuitry, clean dc power, etc.

c. Category VS, Susceptible Wiring:

This includes very sensitive circuitry such as a servo null circuit working to a null level of less than 100 microvolts, electro-explosive devices, high-impedance, low-level high-accuracy sensor circuitry (such as 10 millivolt, 10,000 ohm, and 0.5 percent accuracy), and antenna input circuitry.

As an aid, these three categories of wires might have an identifying color for ease in wiring and identification. The three categories should be run separately via different routing and should cross at right angles.

COUPLING MECHANISM

The physical model for analyzing the coupling between cables is that two or more cables run parallel. The coupling may be expressed in terms of the transfer impedance. The transfer impedance can be defined as the ratio of the voltage appearing between the conductors of the second cable to the current applied at the first. At low frequencies, i.e., those frequencies for which the total length of one is short compared to the wavelength (these are defined as those cables shorter than one-sixteenth wavelength), the current and voltage along the cable may be considered to be constant; therefore, it does not matter at which end of the cable the current or voltage is measured. At higher frequencies, standing waves on the cables must be taken into account if the cables are not terminated in their characteristic impedances.

Transfer Impedance

The transfer impedance is clearly dependent upon the impedances terminating between the source and the susceptible cable. It will depend upon both magnetic and capacitive coupling effects. At low frequencies capacitive coupling is easily prevented by placing one or both of the cables in metallic shields. If the concern is with individual sensors in a cable, this shielding will not be possible, and both magnetic and capacitive coupling will be significant.

Magnetic Coupling

Magnetic coupling is most noticeable as a contributor to interference when the cables are terminated with low impedances at each end. Interference voltages are induced into a wire by flux linkages. The source of interference will be a generator of magnetic flux which may be a relay coil, transformer, solenoid, or just another current-carrying wire. The voltage induced in a loop by an adjacent wire of infinite length carrying current as illustrated in Figure 15 will be

$$E = (3.19 \times 10^{-8})\, fLI \ln \frac{r_2}{r_1}$$

where

f = frequency, Hertz
L = length, inches
I = current, amperes
E = induced voltage, volts
r_1 and r_2 = loop distance, inches

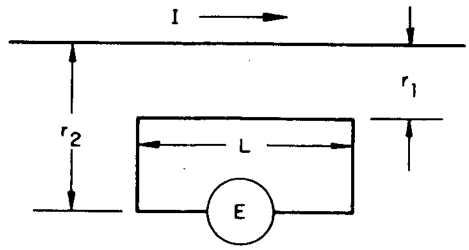

Figure 15
Voltage Induced In A Loop

If the susceptible loop is at an angle to the interference source, the following holds true. Figure 16 illustrates a source loop coupled to a sensitive wire loop.

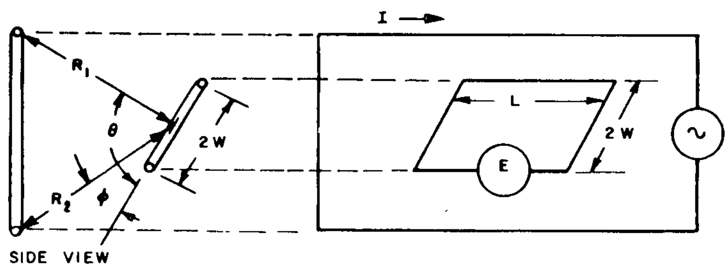

Figure 16
Susceptible Loop At An Angle

$$E = (1.595 \times 10^{-8})\, fLI \left[\ln - \left(\frac{R_1^2 + W^2 + 2R_1 W \cos\Theta}{R_1^2 + W^2 - 2R_1 W \cos\Theta}\right) - \ln\left(\frac{R_2^2 + W^2 + 2R_2 \cos\phi}{R_2^2 + W^2 - 2R_2 \cos\phi}\right)\right]$$

The induced voltage increases with an increase in frequency, source current, and length of closed loop. The induced voltage also increases with effective area enclosed by the pick-up loop and will affect circuits by driving current through the impedances in the pick-up loop and its loads. For low frequencies, the impedance of the pick-up loop will consist primarily of wire resistance, and maximum power will be delivered to a load of low resistance. It should be assumed that the source circuit is a low impedance circuit since the most significant interference will result from a high current. The voltage delivered to the circuits attached to the pick-up loops will rise to half the induced voltage as the load impedance in the pick-up loops rises to match the driving impedance due to the coupling. As the load impedance rises from this point, the voltage at the circuit loads will rise to the full induced voltage as a maximum.

Capacitive Coupling

In long cable runs, an appreciable capacitance will most likely exist between adjacent wires and from each wire to ground or shield and capacitance will exist at connectors and associated wiring. The voltage induced into one wire from an adjacent wire is a function of these capacities. Figure 17 illustrates one model for the capacitive coupling in a cable. The interfering voltage, (E_o) couples through stray capacity (C_c) to produce a voltage (E_x) on the adjacent cable. The interfering cable and the adjacent cable have stray capacities to ground (C_a and C_b). Each cable has its system loads (Z_1, Z_2, Z_3, and Z_4) across which the stray capacities appear. If cable load impedances are high, the frequency spectra of voltages (E_o) and (E_x) may be affected by (C_a) and (C_b). The voltage division ratio will be

$$\frac{E_x}{E_o} = \frac{Z_x Z_b/(Z_x + Z_b)}{Z_c + Z_x Z_b/(Z_x + A_b)}$$

If Z_x is a high resistance load

$$\frac{E_x}{E_o} = \frac{C_c}{C_c + C_b}\sqrt{\frac{R_x^2}{R_x^2 + [\frac{1}{2}\pi f (C_c + C_b)]^2}}$$

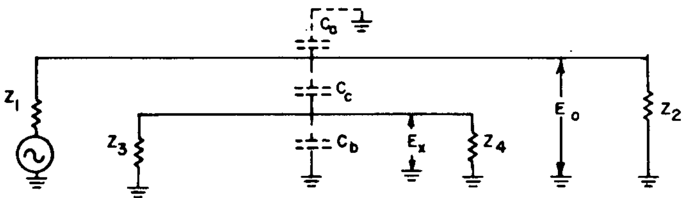

Figure 17
Capacitance Coupling In A Cable

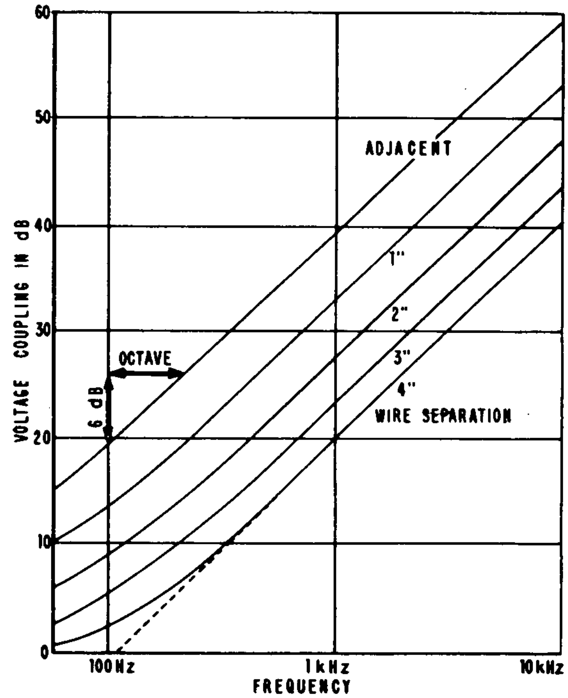

Figure 18
Frequency Versus Voltage Coupling In Wires

At high frequencies (rf), any open-ended wire should be given careful attention to determine if it is a pick-up point for high frequency excitation. Since small stray capacities provide effective coupling to a high impedance point, wires can frequently be excited when they are attached to vacant connector pins or open switch contacts. At a quarter wavelength distance, such open wires will be carrying maximum current and can readily couple into other wiring or circuits by the fields generated. An open wire will represent an effective antenna in the presence of electromagnetic fields. High radio frequencies are readily coupled into power wiring either magnetically or electrically, depending upon the standing wave which may be excited in the power wiring at the coupling point.

Figure 18 illustrates the frequency versus voltage coupling in adjacent wires and the function of their separation.

Not all connectors are designed to preclude the entry of RF energy. Each connector surface represents an impedance discontinuity of the cable shield. Even though there is mechanical contact with the shield through the outer mating section of the connector, a good RF connection is not assured. Radio frequency energy could enter at this point and cause a hazardous situation. A good connector is one in which the shielding effectiveness of the mated connector equals or exceeds that of an equal length of the cable utilized in the circuit. If the effectiveness of cable shields is to be maintained, the cable shield must be properly terminated. In an otherwise adequately shielded enclosure, RF currents that are conducted along the shields will be coupled to the system wiring from the point of improper cable termination.

Portions of the above article were provided by William F. Bakker, Breeze, Illinois.