Electromagnetic Compatibility (EMC)

Topic 6

Cabling

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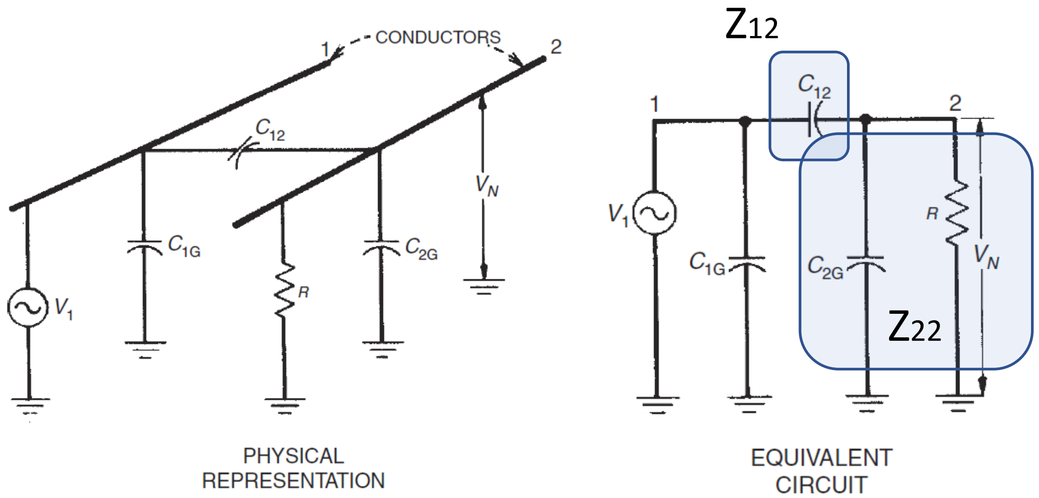
Introduction

- Cables are the longest parts of electrical systems and usually act as efficient antennas to radiate and pick up noise.
- In our analysis to come (to simplify and be able to use circuit models), we assume:
  - Cables are short compared to the wavelength
  - Induced currents in the receptor circuit are smaller than and does not disturb the original fields
  - Shields are made by nonmagnetic material, and have less than a skin depth thickness
  - The receptor is not tightly coupled to the source and does not load it
- Due to such assumptions, we will model coupling by lumped C and L elements
- We will discuss 3 coupling types:
  - Capacitive (electric field)
  - Inductive (magnetic field)
  - Combined E and H field couplings

Capacitive coupling



- A simplified representation of capacitive coupling is shown
- C_{12} is stray capacitance (between conductors), C_{xG} is the capacitance between conductor and ground
- The developed noise voltage on conductor 2 due to coupling from conductor 1 is:

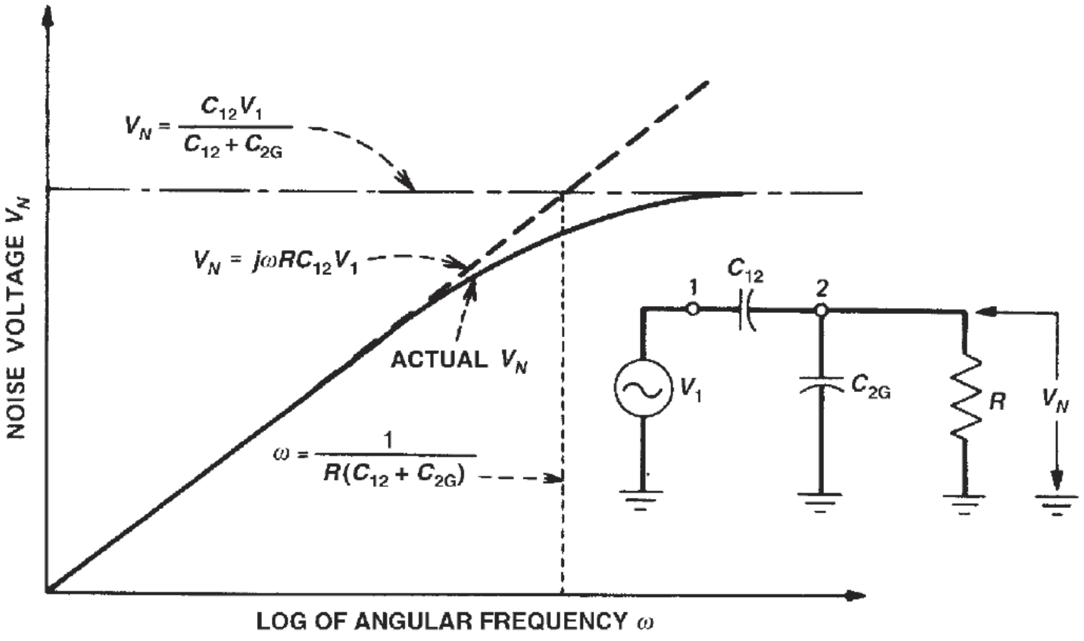
$$V_N = V_1 \frac{Z_{22}}{Z_{12}+Z_{22}} = V_1 \frac{j\omega\left[\frac{C_{12}}{C_{12}+C_{2G}}\right]}{j\omega + \frac{1}{R(C_{12}+C_{2G})}}$$

- If, $R << \frac{1}{j\omega(C_{12}+C_{2G})}$
- Then $\boxed{V_N = j\omega R C_{12} V_1}$
- Thus, to reduce capacitive coupling, we can reduce the impedance of the receiver, or reduce the coupling capacitance value (C12).
- Capacitance can be reduced via (1) orientation of conductors
  (2) separation of conductors
  (3) shielding of conductors

- If resistance of conductor 2 is large, such that, $R >> \frac{1}{j\omega\left(C_{12}+C_{2G}\right)}$
- Then we have, $$\boxed{V_N = \left[\frac{C_{12}}{C_{12}+C_{2G}}\right]V_1}$$
- In this case, the noise is independent of frequency and of larger magnitude than if R is small.
- A plot showing this behavior of the noise voltage versus frequency is shown
- Note that at the frequency of $\omega = \frac{1}{R\left(C_{12}+C_{2G}\right)}$

The approximate formula give a V_N that is 1.4 times the actual one, but usually the frequency is less than this and so the approximation is valid. But always pay attention.

- Also note that the maximum noise voltage is achieved when assuming R is very large and a voltage divider between the capacitors is achieved



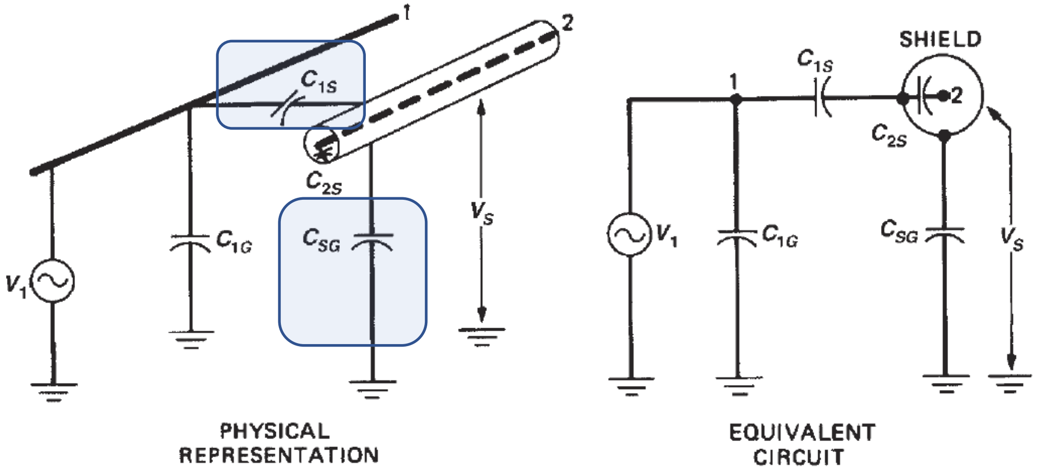
- Consider an ideal shielded conductor as shown in figure
- The shield is solid (no holes), and not terminated (high impedance) while completely enclosing conductor 2
- The shield is exposed to coupling from conductor 1 (C_{1S})
- Then, the noise voltage on the shield is given by

$$V_N = \left[\frac{C_{1S}}{C_{1S} + C_{SG}} \right] V_1$$

- Since no current passes through C2S (no other connected impedances), then noise voltage on conductor 2 will be

$$V_N = V_S$$

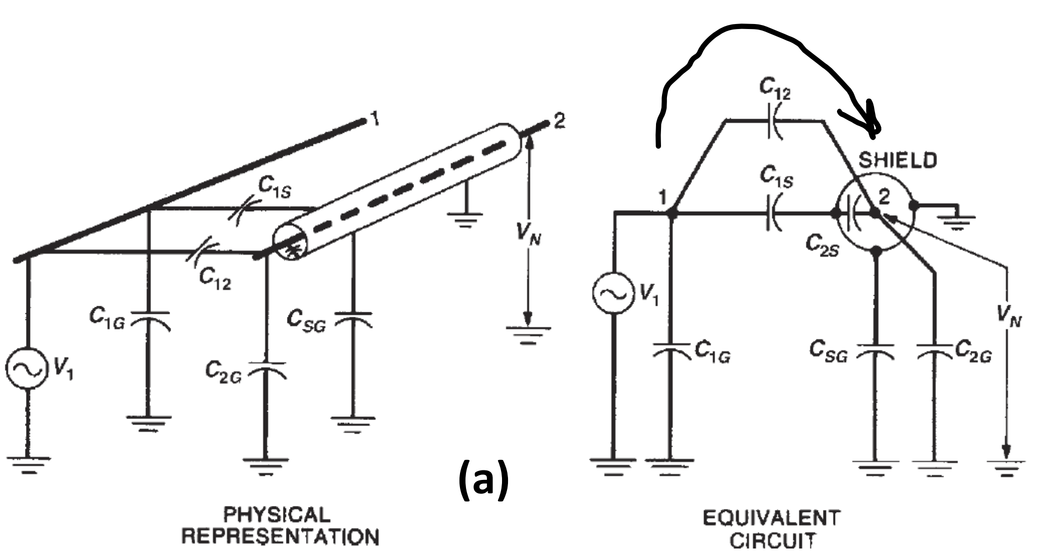
- This means that the shield did not do its job! (i.e. reduce noise voltage on conductor 2)
- We can conclude that the shield is not effective unless it is properly terminated



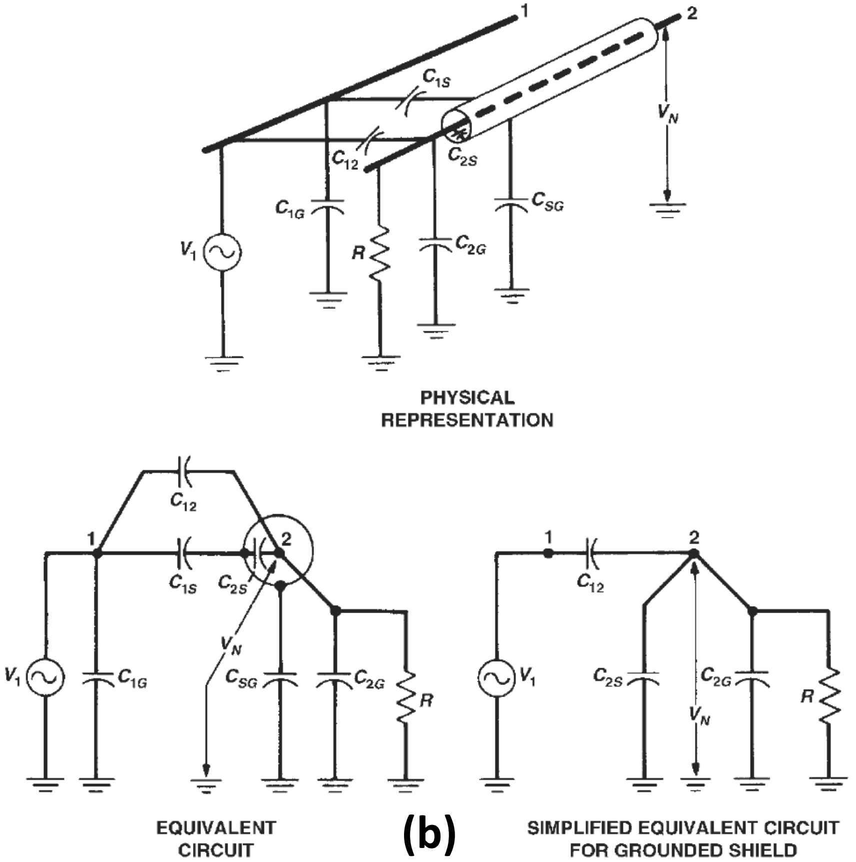
- In real situations, the center conductor does extend beyond the shield, thus we have C_{12} and C_{2G} as in Figure (a)
- Now, the noise voltage is the one across C_{2G} and C_{2S} (in parallel) connected to C12 in series (note that the shield is GND)
- We get, $$V_N = \frac{C_{12}}{C_{12} + C_{2G} + C_{2S}} V_1$$
- To minimize the coupling (noise) we can

  (1) minimize the length of the extended conductor from shield

  (2) provide a good ground connection to shield
- If the receptor resistance is finite (small), then we have the configuration in Figure (b)
- If we have the practical condition $R << \frac{1}{j\omega\left(C_{12} + C_{2S} + C_{2G}\right)}$
- Then, $$\boxed{V_N = j\omega R C_{12} V_1}$$
- this is smaller because C_{12} is smaller due to shield (extended portion of conductor 2 is much shorter)



(a)



(b)

Inductive coupling

- When current flows in a conductor, it generates magnetic flux, and constant of proportionality is the inductance

$$\phi_T = LI$$

- Inductance depends on the circuit geometry and the magnetic properties of the medium
- When current flows in one circuit (1), the flux it produces affects adjacent circuits (2) via mutual inductance between them, such that

$$M_{12} = \frac{\phi_{12}}{I_1}$$

- Using Faraday's Law, we can find the induced voltage in a closed loop due to an external magnetic flux density via

$$V_N = -\frac{d}{dt}\int_A \vec{B} \bullet d\vec{A}$$

- For a stationary loop and sinusoidally varying flux density, we can write

$$V_N = j\omega BA\cos(\theta)$$

- Since BA cos(θ) represents the total flux (ϕ12), then we can write

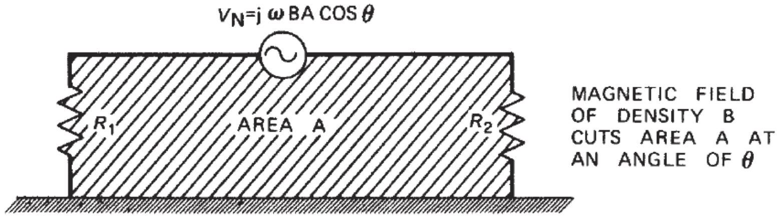
$$V_N = j\omega MI_1 = M\frac{dI_1}{dt}$$

- Thus, to reduce the noise, we need to reduce

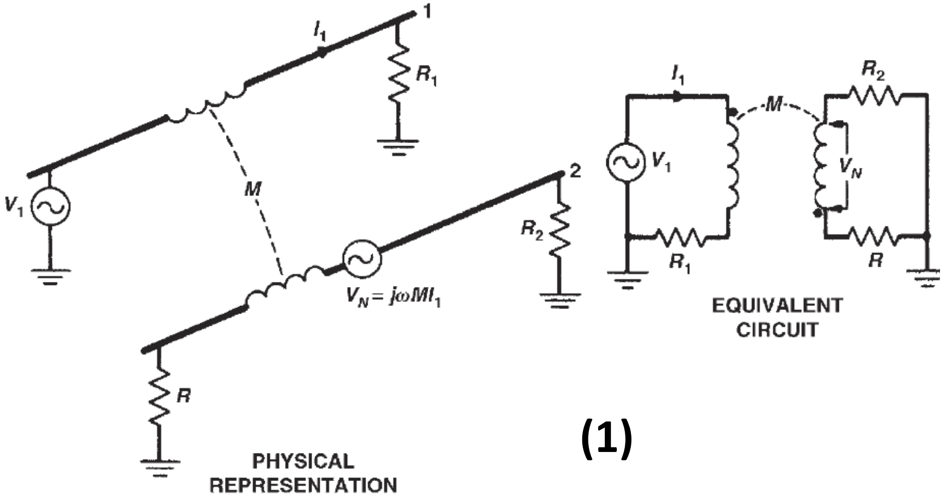
(1) **B**, via increasing physical separation between circuits or using twisted pair wires

(2) **A,** can be reduced by placing conductor closer to its return path (GND), or using twisted pair wires

(3) **cos(θ)**, can be reduced by proper orientation



- The physical representation of magnetic field coupling and its equivalent circuit representation are shown in Figure (1)

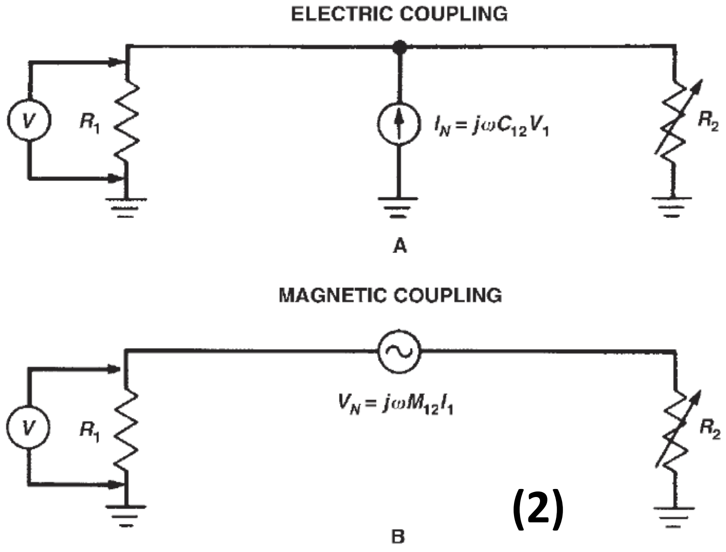


(1)

- For magnetic field coupling, the noise voltage is produced in series with the receptor conductor (voltage source), whereas for electric field coupling, a noise current (current source) is produced between the receptor conductor and the ground (Figure (2))
- In measurements, we can distinguish between electric and magnetic coupling as follows:

measure the noise voltage across the impedance at one end of the cable while decreasing the impedance at the opposite end. If the measured noise voltage decreases, the pick up is electric, and if it increases, the pick up is magnetic

(check the circuits →)

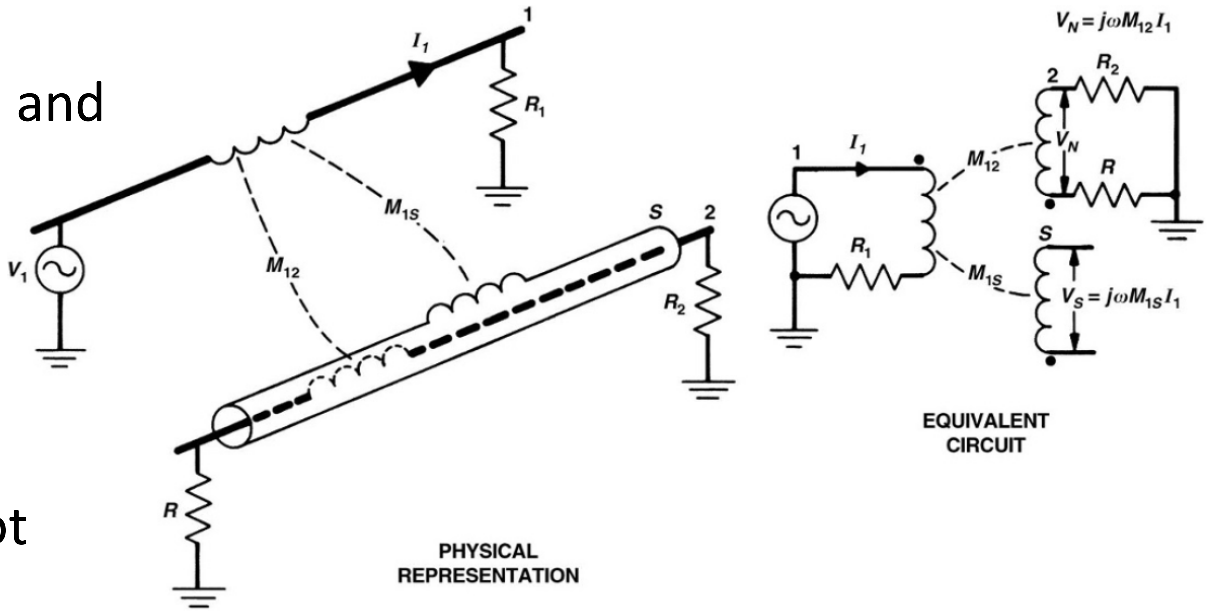


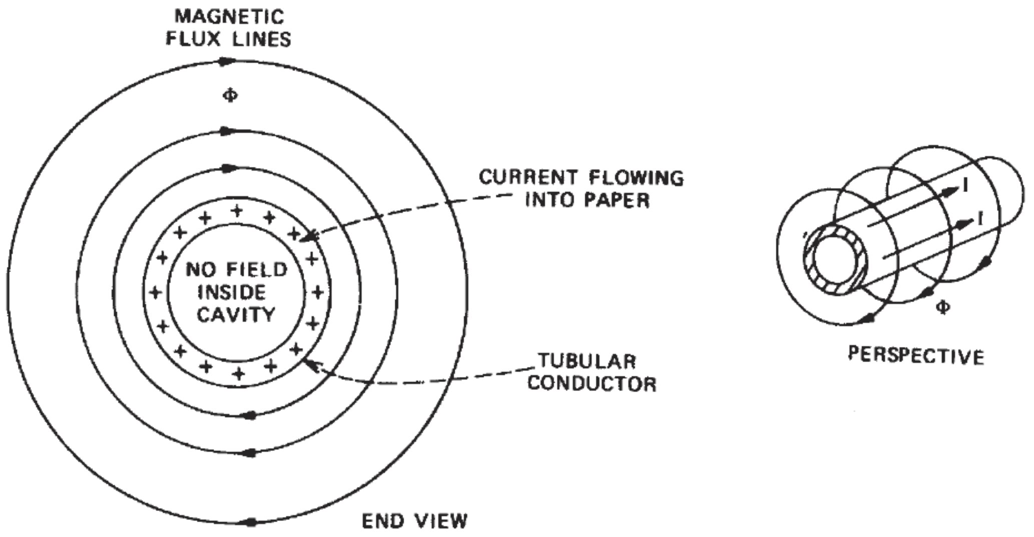
(2)

- If an ungrounded and nonmagnetic shield is placed around conductor 2, M_{1S} exists between conductor 1 and the shield.
- The shield has no effect on the induced on 2
- The shield will pick up a voltage (V_S), as

$$V_s = j\omega M_{1S} I_1$$

- If we ground the shield on one end only, this does not change the situation and cannot affect conductor 2
- If, the shield is grounded at both ends, this will allow a current to flow on it. This current, will generate another magnetic flux that can affect conductor 2, and thus needs to be accounted for. To do this calculation, we need to estimate the magnetic coupling between the shield (hollow conducting tube) and the conductor inside it.
- Consider the magnetic field from a tubular conductor carrying a uniform current as shown. The magnetic field is outside the cavity as there is nothing inside it.





- Place a conductor inside the tubular shield. All the flux from the shield encircles the inner conductor
- The shield inductance is $L_s = \frac{\phi}{I_s}$
- The mutual inductance between the shield and the center conductor is $M = \frac{\phi}{I_s}$
- Because all the flux encircles the inner conductor, the mutual inductance between the two is the same as the self inductance of the shield, thus $\boxed{M = L_s}$
- This is valid if we have multiple conductors within the shield, each M is the same and equal to L_s
- Now to find V_N due to I_s, $V_N = j\omega M I_S$
- Also,

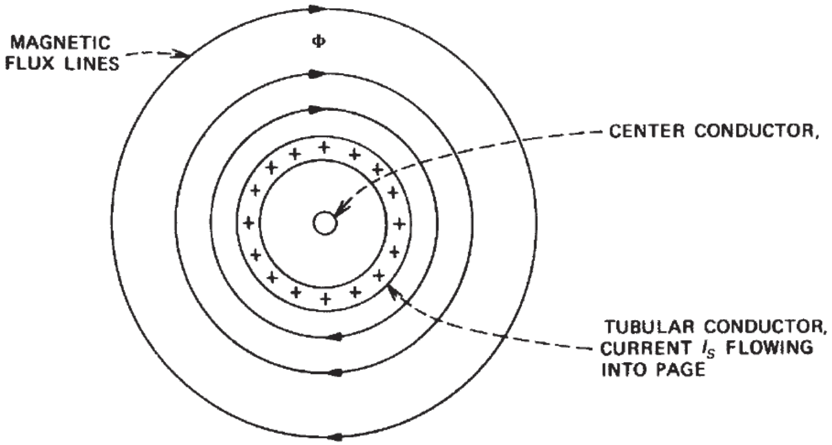
$$I_S = \frac{V_S}{L_S}\left(\frac{1}{j\omega + (R_S / L_S)}\right)$$

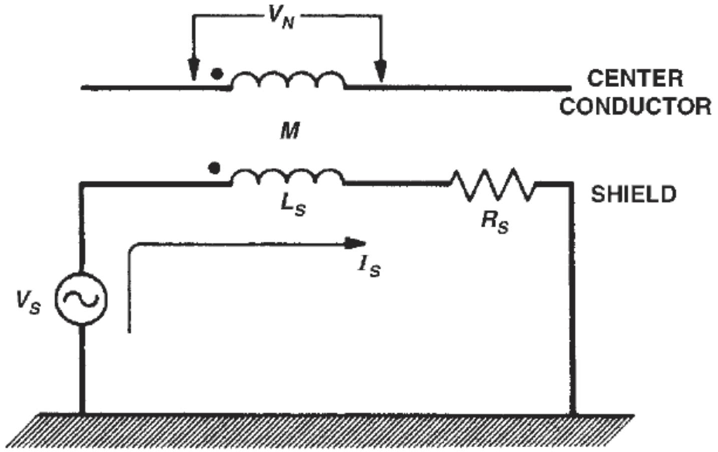
- Therefore,

$$V_N = \left(\frac{j\omega M V_S}{L_S}\right)\left(\frac{1}{j\omega + (R_S / L_S)}\right)$$

- Since, $M=L_s \rightarrow$

$$\boxed{V_N = V_S\left(\frac{j\omega}{j\omega + (R_S / L_S)}\right)}$$





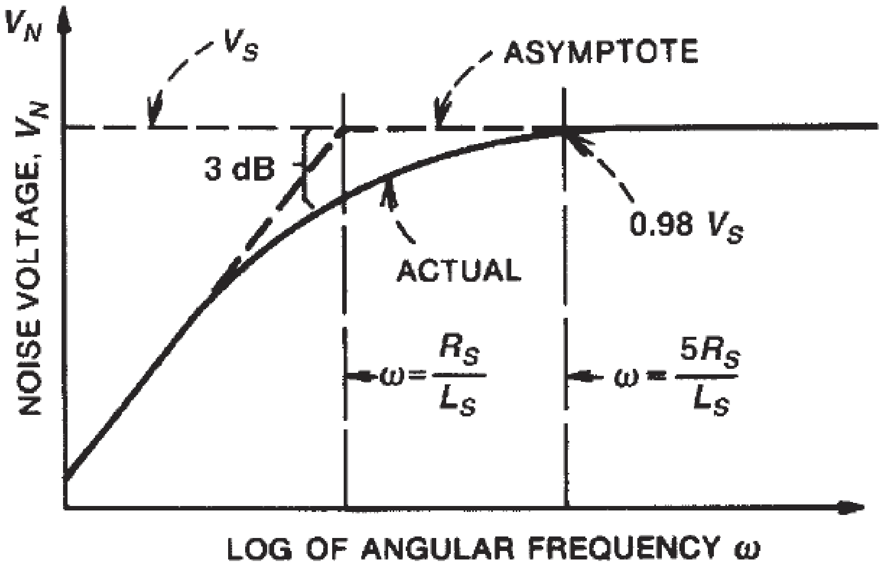
- If we plot the last equation for V_N, we can identify the shield cutoff frequency (ω_c) as

$$\boxed{\omega_c = \frac{R_S}{L_S} \quad , \quad f_c = \frac{R_S}{2\pi L_S}}$$

- The noise voltage induced on the inner conductor vanishes at DC and very low frequencies, and increases to reach Vs at a frequency of 5 times the cutoff.

$$\boxed{\omega = 5\omega_c = \frac{5R_S}{L_S}}$$

- If the shield current is allowed to flow, then a noticeable amount of voltage can be observed on the inner conductor that can equal that induced on the shield when we cross the 5 times the shield cutoff frequency (ω_c)
- Shield cutoff frequencies are important to know…



Cable	Impedance (Ω)	Cutoff Frequency (kHz)	Five Times Cutoff Frequency (kHz)	Remarks
Coaxial cable				
RG-6A	75	0.6	3.0	Double shielded
RG-213	50	0.7	3.5	
RG-214	50	0.7	3.5	Double shielded
RG-62A	93	1.5	7.5	
RG-59C	75	1.6	8.0	
RG-58C	50	2.0	10.0	
Shielded twisted pair				
754E	125	0.8	4.0	Double shielded
24 Ga.	–	2.2	11.0	
22 Ga.[a]	–	7.0	35.0	Aluminum-foil shield
Shielded single				
24 Ga.	–	4.0	20.0	

[a] One pair out of an 11-pair cable (Belden, 8775).

- Consider the figure shown for the situation of a grounded shield at both ends that has an inner conductor (2). The source conductor (1) couples to the shield and to the inner conductor. Also, the shield couples to the inner conductor.
- Note that the voltages on (2) from the shield (V_c) and the source (V_2) have opposite polarities due to the orientation of the fluxes (current directions), thus we have,

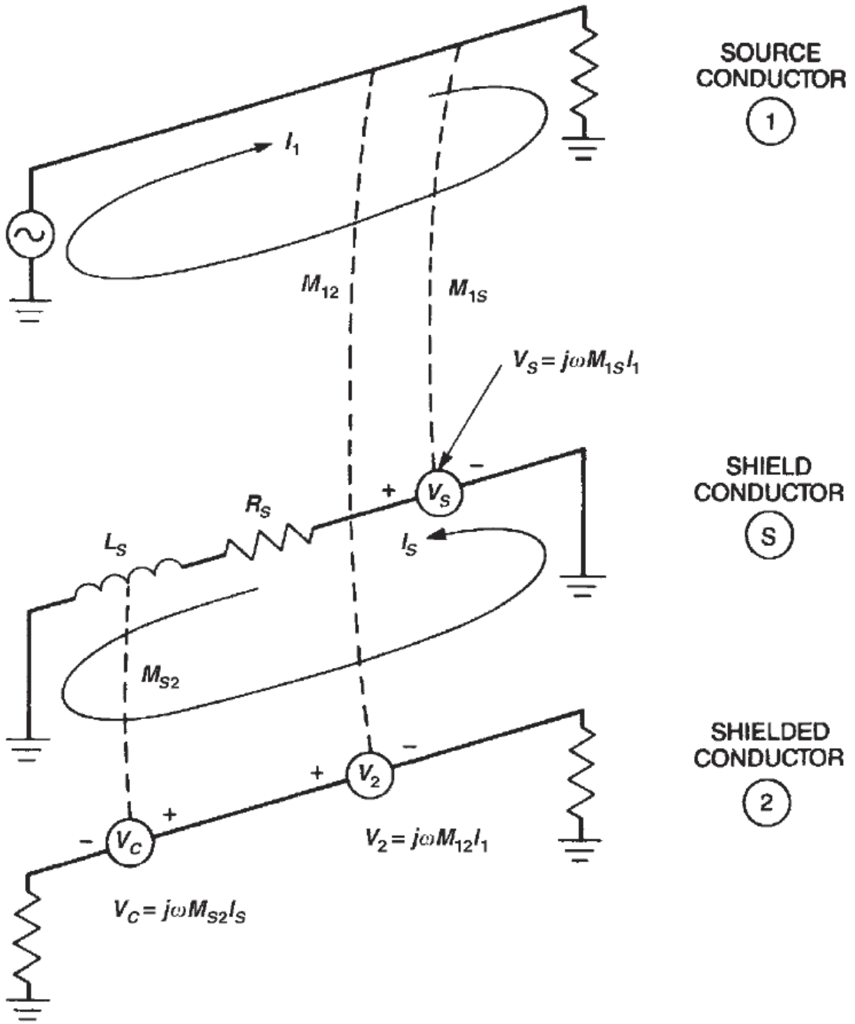
$$V_N = V_2 - V_c$$

- Since M_{1S}= M_{12} (both are in the same distance from source somehow), and M=Ls, we can write,

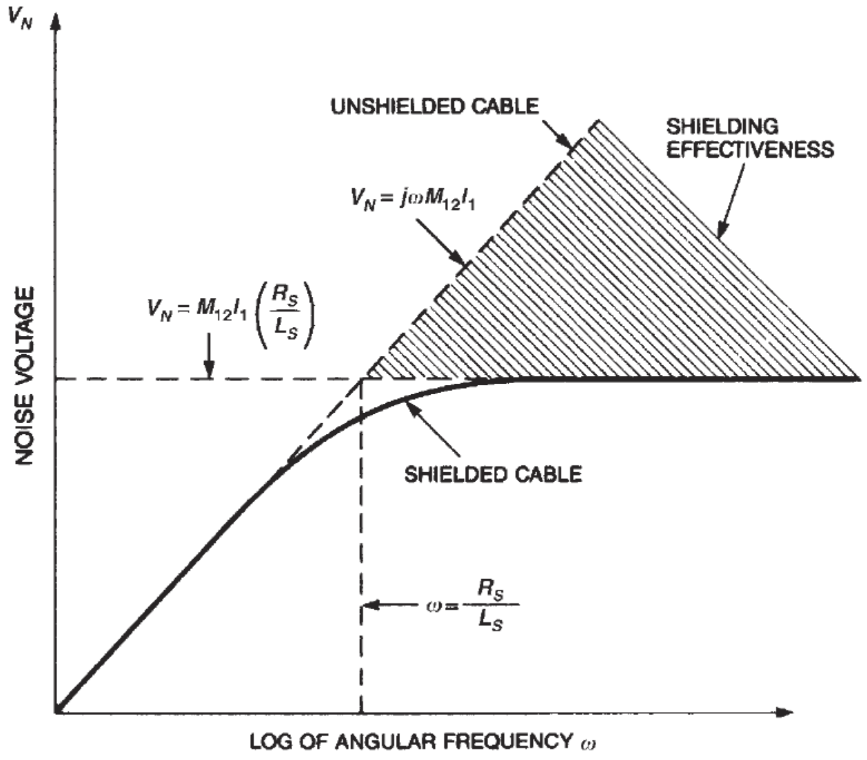
$$\boxed{V_N = j\omega M_{12} I_1 \left(\frac{(R_S / L_S)}{j\omega + (R_S / L_S)} \right)}$$

- At low frequencies, the noise pickup of the shielded cable is the same as the unshielded one (terms in brackets = 1 above).
- At higher frequencies,

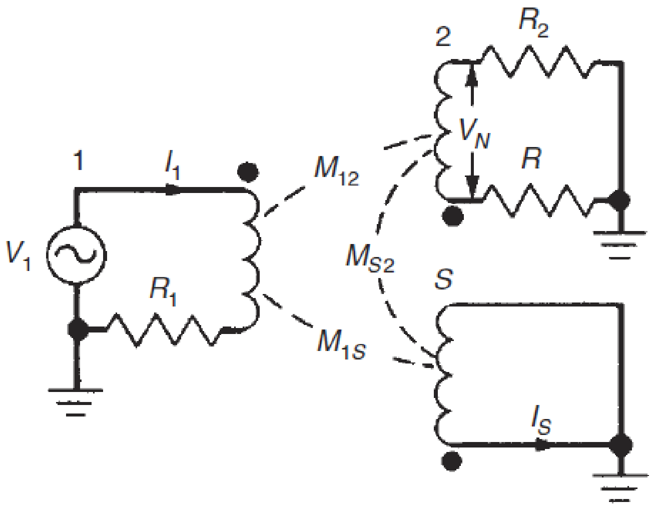
$$V_N = M_{12} I_1 \left(\frac{R_S}{L_S} \right)$$



- Plotting the general expression of V_N (in the box from previous slide), we get the figure shown.
- At low frequencies, noise pick up is same as unshielded cable
- At frequencies above ωc, the pick up voltage stops increasing and remains constant.
- Thus we can define the **Shielding Effectiveness** as the difference between the Noise level we get from an unshielded cable to that of a shielded one at that specific frequency (shaded region).
- To minimize the coupled noise voltage, we need to reduce the shield resistance (Rs). This resistance includes the shield resistance, and any shield connected termination or ground resistance (the total resistance in the shield loop), All these resistances should be minimized for maximum shielding effectiveness



$V_N = j\omega M_{12} I_1 - j\omega M_{12} I_1$



Shielding to prevent magnetic radiation

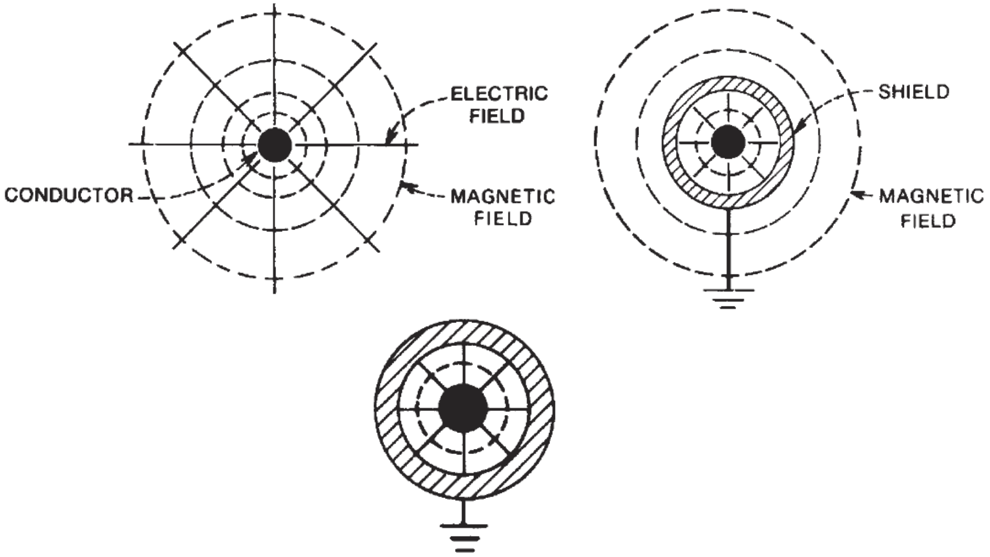
- To prevent radiation, shield the source of interference
- If the shield current is equal to and opposite to the inner conductor current, it will generate and equal and opposite magnetic field, thus cancelling the center conductor field and eliminating radiation/interference
- Consider the circuit shown, to eliminate radiation, the return current should flow through the shield (Is) and should equal to and oppose in direction (I1)
- Consider the loop (A-Rs-Ls-B-A), we have

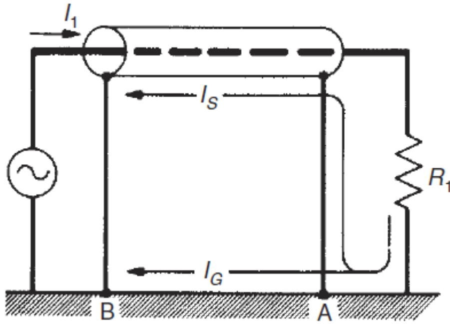
$$0 = I_S\left(j\omega L_S + R_S\right) - I_1\left(j\omega M\right)$$

- consider M=Ls,

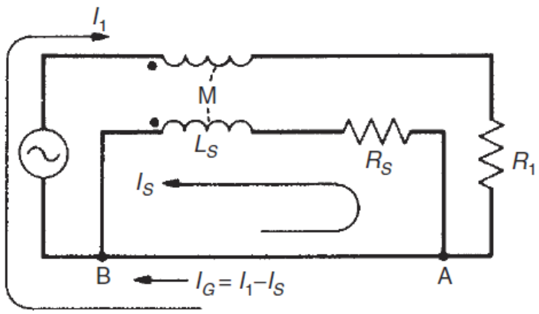
$$I_S = I_1\left(\frac{j\omega}{j\omega + \left(R_S / L_S\right)}\right) = I_1\left(\frac{j\omega}{j\omega + \omega_c}\right)$$

- **If $\omega \gg \omega c$ then $I_S = I_1$**
- **For frequencies lower than cutoff, do not GND other end**

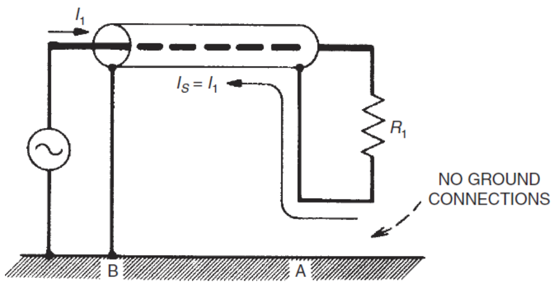




PHYSICAL REPRESENTATION

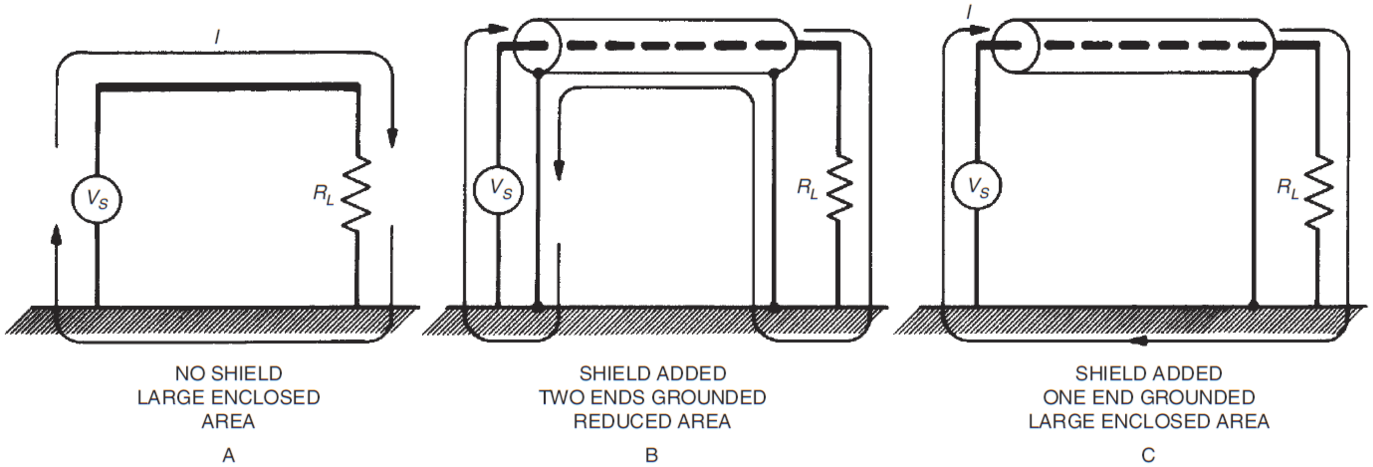


EQUIVALENT CIRCUIT

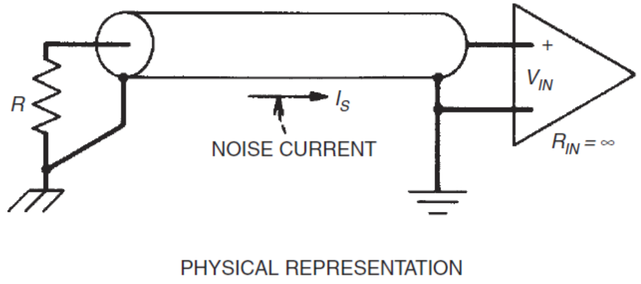


Shielding a receptor against magnetic fields

- The most effective way to reduce effects of magnetic fields at the receptor is to **decrease the area of the receptor loop**. This is the total area enclosed by the current flow in the receptor circuit
- Figure (A) shows the regular unshielded scenario, where a large loop is obtained (large coupled noise)
- Figure (B) is very effective and reduces the loop area at the receptor if the operating frequency is 5ωc of the shield. For lower frequencies than the cutoff, the current will not return through the shield and thus a larger loop current is obtained.
- Figure (c) shows one ended grounding, which is not effective in reducing the loop area.

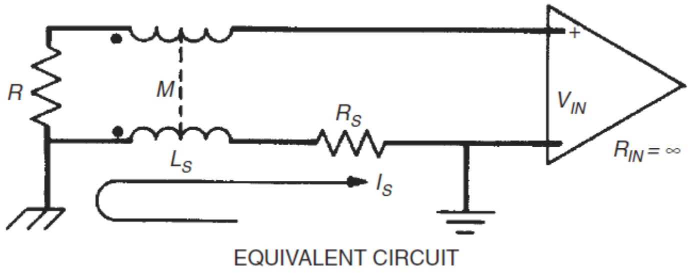


Common impedance shield coupling



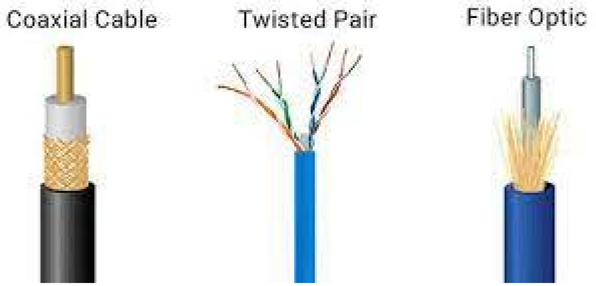
- If a noise current is induced (due to a ground differential or any external fields) on the shield that is grounded at both ends, this will create a noise voltage at the receiver input, as

$$V_{in} = -j\omega M I_S + j\omega L_S I_S + R_S I_S$$



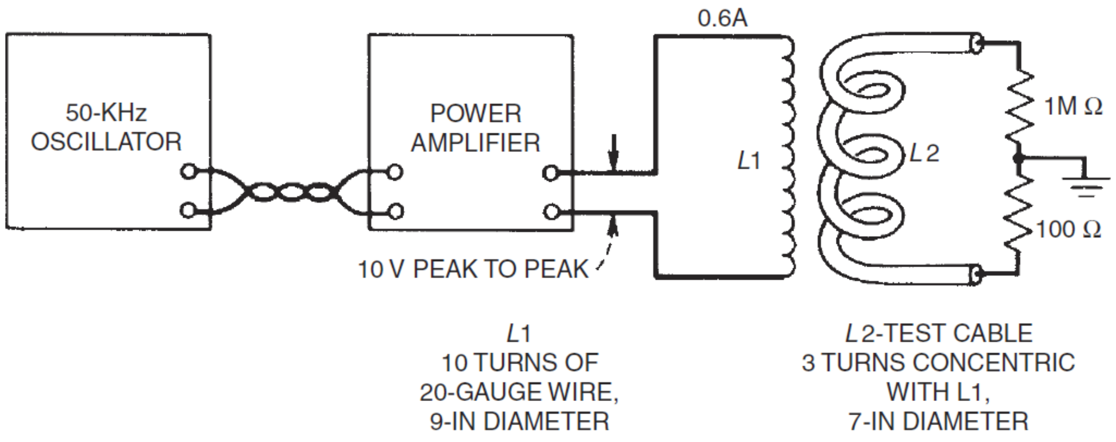
- Since we showed that M = LS, then $V_{in} = R_S I_S$
- This is called **common impedance coupling**
- This is due to the two functions the shield is doing: (1) **carrying the return current**
  (2) **carrying induced noise**
- This can be reduced via the use of a 3-conductor cable; a twisted pair for the signal, and the shield for the noise
- Reducing the resistance of the cable and using a balanced interconnections minimizes this issue
- Noise induced on the shield is often called shield current induced noise (SCIN)
- **At higher frequencies and due to skin effect, the SCIN is not an issue as noise currents flow on the outer shield surface while return currents on the inside**

Coaxial Cable vs. Twisted Pair

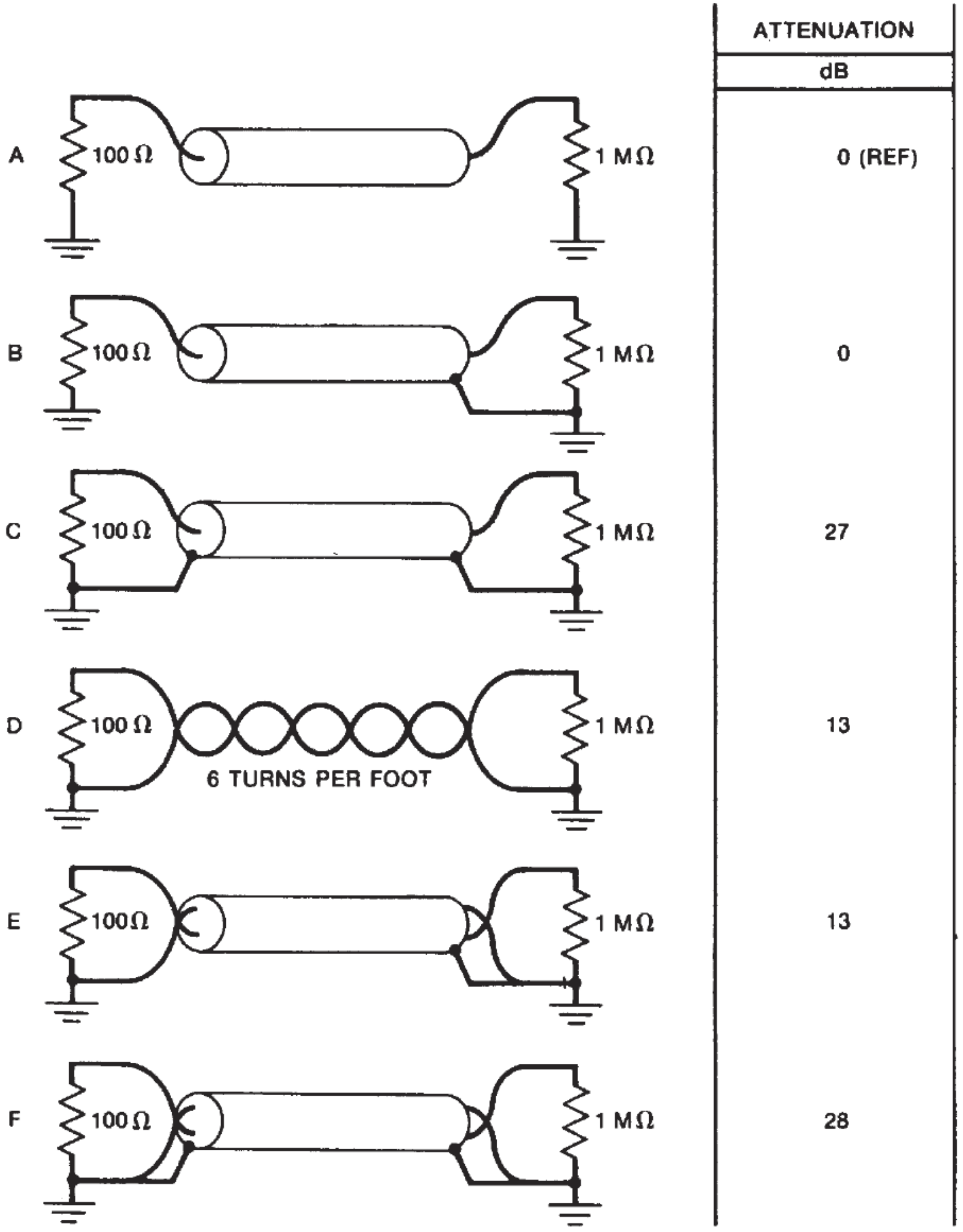


- Twisted cables do not have as uniform Z_0 as coaxial ones, due to the fact that the two conductors do not maintain a constant position relative to one another, specially when the cable is bent or flexed
- Twisted pairs can support up to 2GHz frequencies, while coaxial cable can extend much more beyond 40GHz
- Twisted pairs are inherently balanced structures that effectively reject noise
- Unshielded twisted pairs (UTP) are widely used in ethernet and other digital interconnects and are given categories based on their frequency of operation, impedance, etc. CAT 8 can cover up to 2GHz.
- Coaxial cables can cover wider bandwidths and widely used in high power as well as high frequency applications.
- Do not confuse twisted pair wiring with balancing, they are two different things, although they are often used together.
- Do not separate the twisted pair wires when terminating them, as this will reduce noise immunity

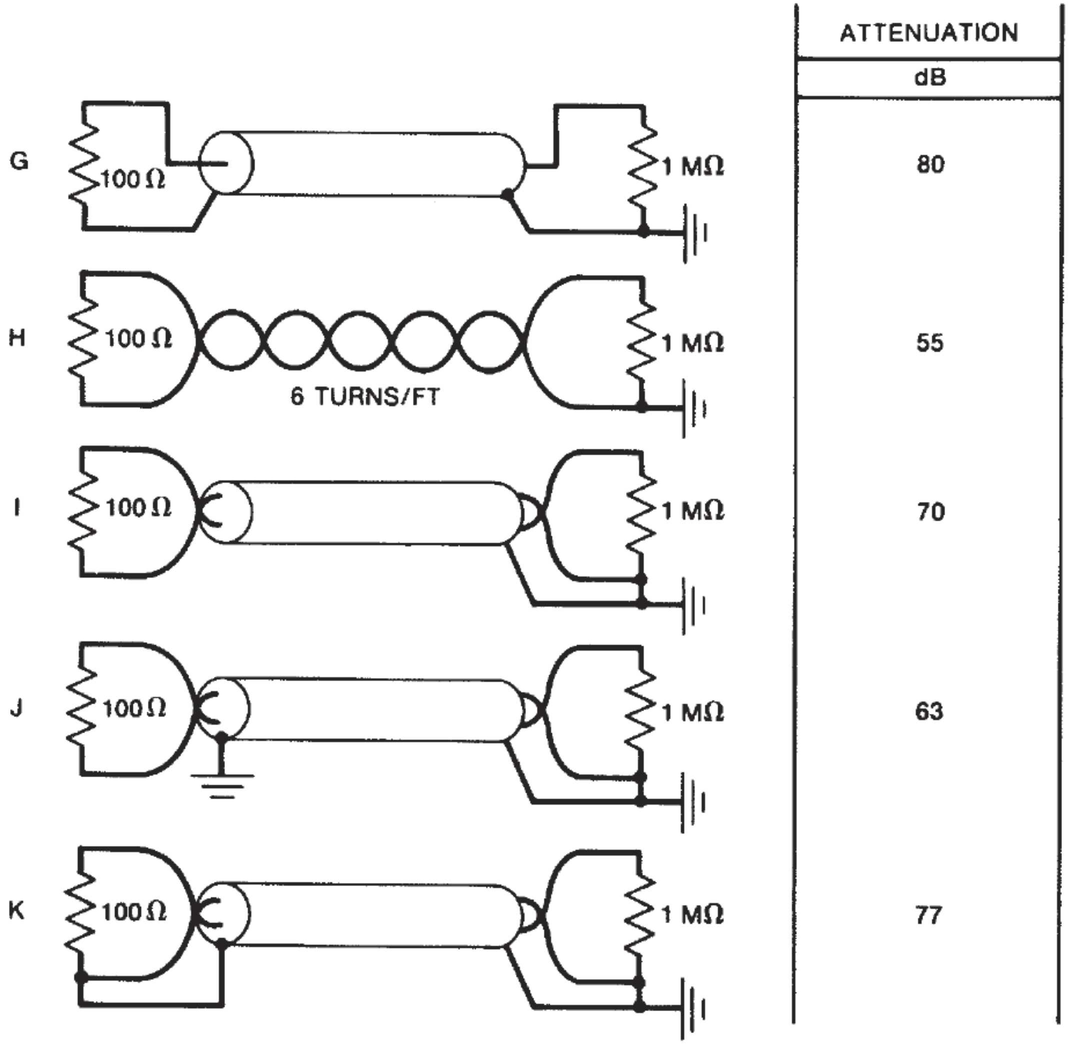
Experimental Data



- Magnetic field shielding capabilities were measured using the setup shown.
- 50KHz is greater than 5 X the shield cutoff frequency of all the cables tested (next slide)
- Coaxial cables and twisted pairs are examined
- Circuits A-F have both ends grounded (not necessarily the shield, pay attention), but provide less shielding compared to G-K (except J) which are single ended grounded.
- Case A is the reference with 0dB, as it provides no shielding. The measured voltage on the 1MΩ resistor was 0.8V.
- Case C shows some advantage of improved shielding via the grounding of the shield at both ends (27dB improvement/H-field rejection relative to case A). The ground loop formed by the shield and two grounding points degrades the shielding performance, i.e. we would get more shielding if the ground loop was smaller!
- Case D shows some immunity, but is degraded by the ground loop as well.
- Cases E and H show that adding a shield to the case D will only improve if it is grounded at both ends



FREQUENCY = 50 KHz FOR ALL TESTS



FREQUENCY = 50 KHz FOR ALL TESTS

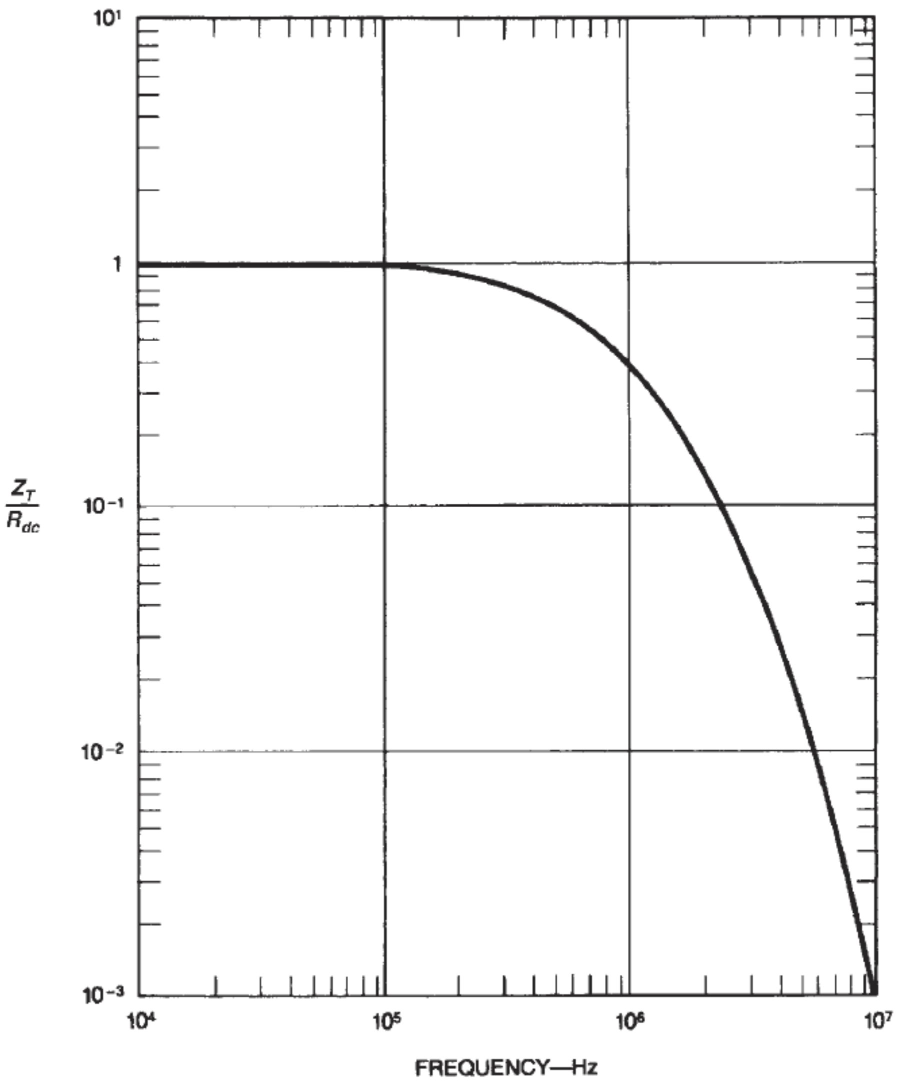
- If grounding at both ends is used, Cases C (coax) and F (twisted) provide the maximum immunity, but still they both suffer from ground loop degradation
- Case G shows super immunity and shielding capability due to the minimization of the ground loop where only one side is grounded. Levels as high as 80 dB are obtained.
- Case H shows improved twisted pair immunity to magnetic fields with levels around 55dB (as compared to D and F), but now the levels might be degraded due to E-field coupling because the twisted pair is not shielded and is not balanced.
- Adding a shield to case H gives us case I, where improved rejection of the magnetic fields is observed (around 70dB now).
- Comparing the coax in G and shielded twisted pair (STP) in I shows that the coax still has higher performance than the STP due to the smaller loop area within the coax compared to the STP. But this is not necessarily true in general, as we prefer to use I over G at lower frequencies, since the shield in I is not one of the signal conductors (i.e. current return path)
- Grounding both ends of the shield of a STP as in J degrades the performance, due to the higher shield current in the ground loop that causes unequal voltages on the two center conductors
- Case K combines the coax and STP features and thus gives higher attenuation to the magnetic fields. But this configuration is not desirable, because any noise that gets into the shield, will be passed to the signal conductors! It is better to connect the shield to the conductor at one end only.

Shield transfer impedance

- Is a means of measuring the shielding effectiveness of cable shields
- Relates the open circuit voltage developed between the center conductor and the shield to the shield current, and is given by,

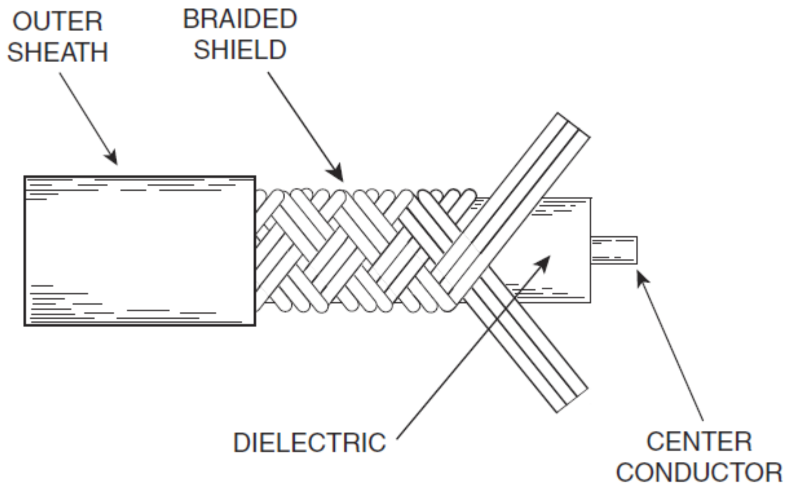
$$Z_T = \frac{1}{I_S}\left(\frac{dV}{dl}\right)$$

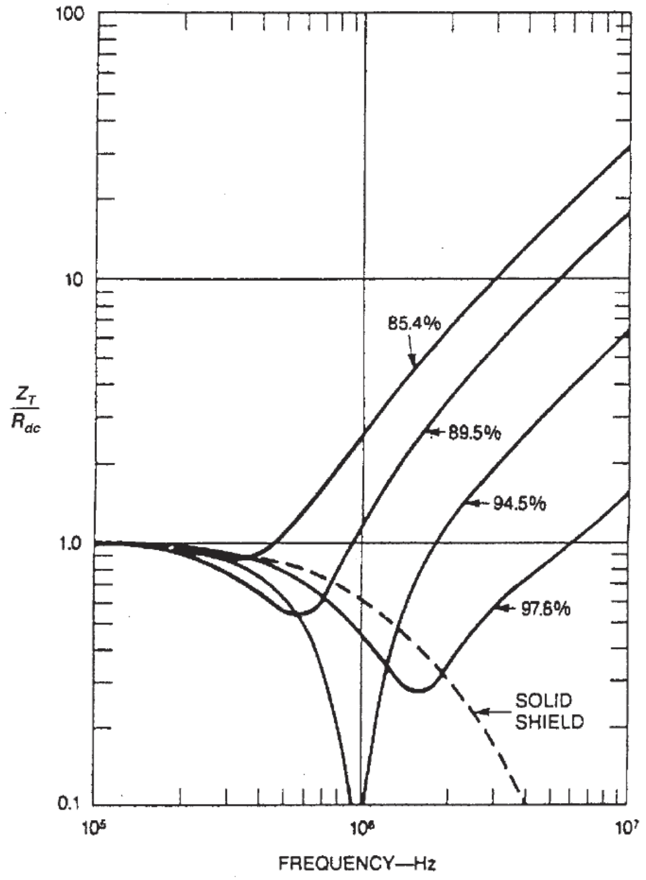
- The smaller the transfer impedance the more effective the shielding
- At low frequencies, it is equal to the DC resistance of the shield
- At higher frequencies, it decreases due to the skin effect (in solid shields) and thus the shielding effectiveness increases. Skin effect causes the noise current to remain on the outer surface of the shield and the signal return current on the inside surface, thus eliminating common impedance coupling between the two



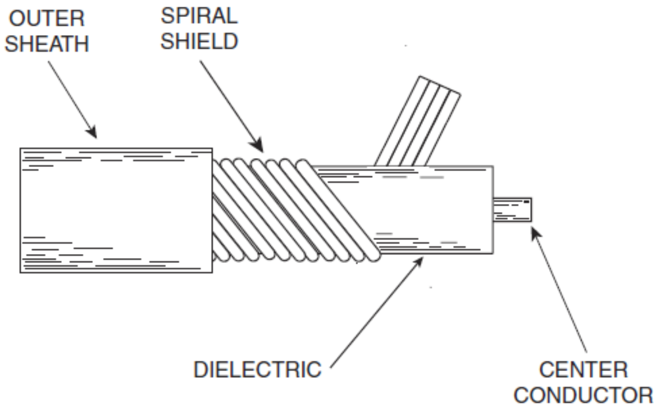
Shield Types

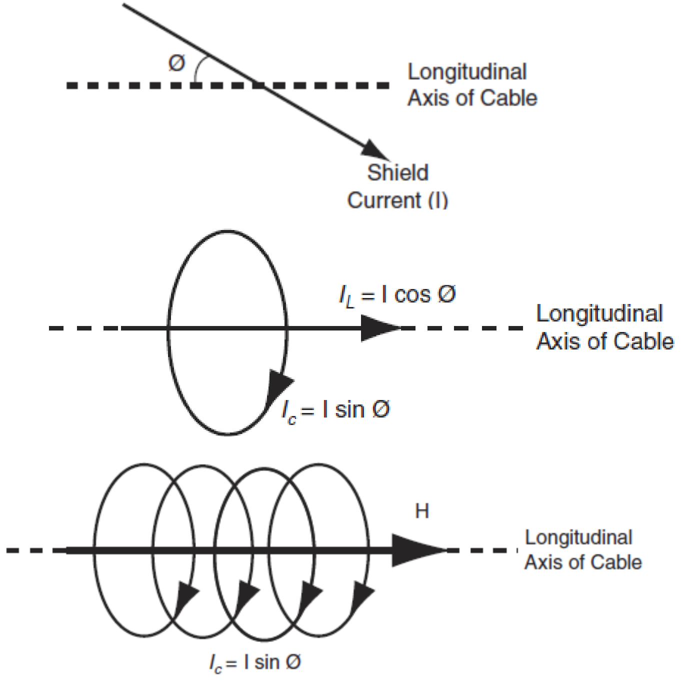
- **Braided Shields:**
  - Most cable shields are not solid conductors but rather braided ones.
  - Braided shields are flexible, strong, durable and long flex life
  - They cover 60%-98% of the surrounding of the center conductor, and thus are less effective as shields compared to solid counterparts (5-30dB less effective than solid ones)
  - They are best for magnetic field shielding
  - At higher frequencies, the shielding effectiveness degrades due to the air gaps within the braid
  - The decrease in the transfer impedance of the shield around 1MHz is due to the skin effect of the shield
  - The increase of the transfer impedance beyond 1MHz is due to the air holes within the braid

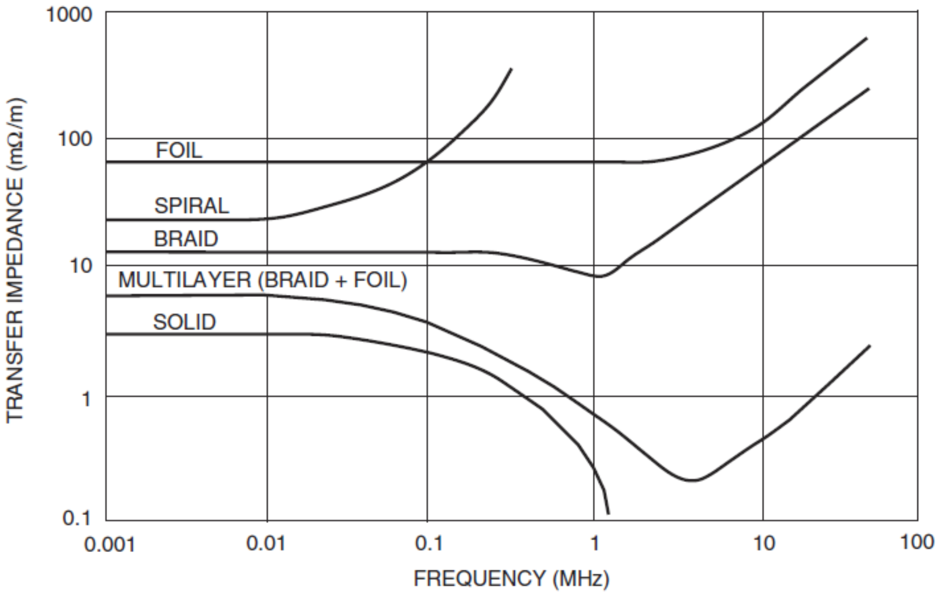




- **Spiral Shields:**
    - Spiral shields are used because of:
    - (1) Ease of manufacturing
    - (2) Ease of termination
    - (3) Increased flexibility
    - In solid homogeneous shield cables, the shield current is longitudinal along the axis of the cable, and the magnetic field produced is circular
    - In a spiral shield cable, the shield current flows in the spiral and has an angle (ϕ) with respect to the longitudinal axis. This creates two components for the current, thus creating two magnetic fields.
    - While the longitudinal component of the current creates a magnetic field circulating outside and around of the shield (Faraday's Law) similar to a solid shield, the circular current that is perpendicular to the cable axis acts as a solenoid and produces a magnetic field inside the shield and no magnetic field outside, this will increase the shield inductance.
    - The larger the angle (ϕ) the lower the shield effectiveness (larger transfer impedance)
    - Since a braided shield has two interwoven spiral ones, the circular currents from one cancels the other, and thus does not suffer from such increased shield inductance as a simple spiral one.







Shield Terminations

- Most shielded cable problems are due to improper shield terminations.
- The maximum benefit from shielding will be observed only when it is properly terminated
- To properly terminate the shield, you need to:

  (1) terminate at the proper end(s), and to the proper point or points

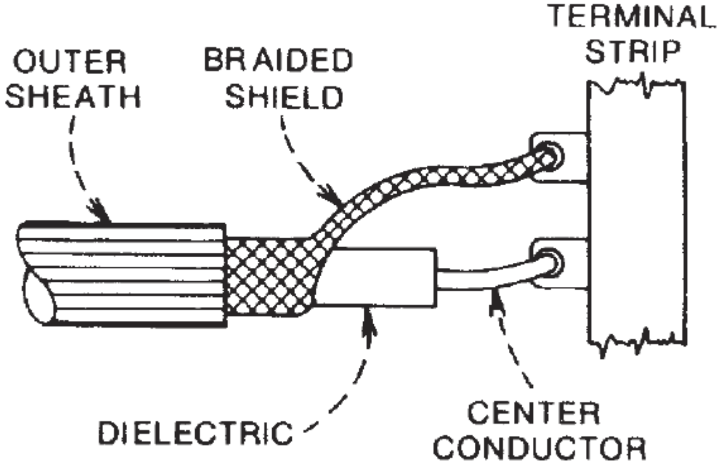
  (2) provide a very low impedance termination connection

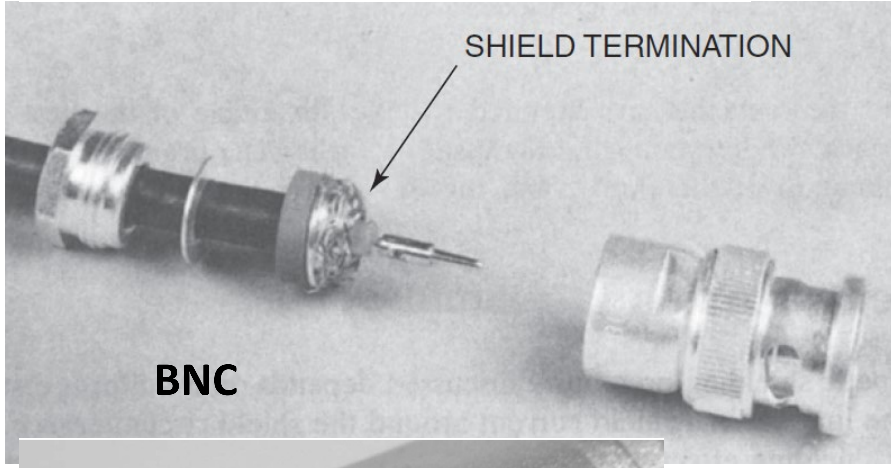
  (3) 360 degree contact with the shield (covering it all around)

- We will consider
  - Pigtails
  - Low frequency grounding
  - High frequency grounding
  - Hybrid Cable shield grounding

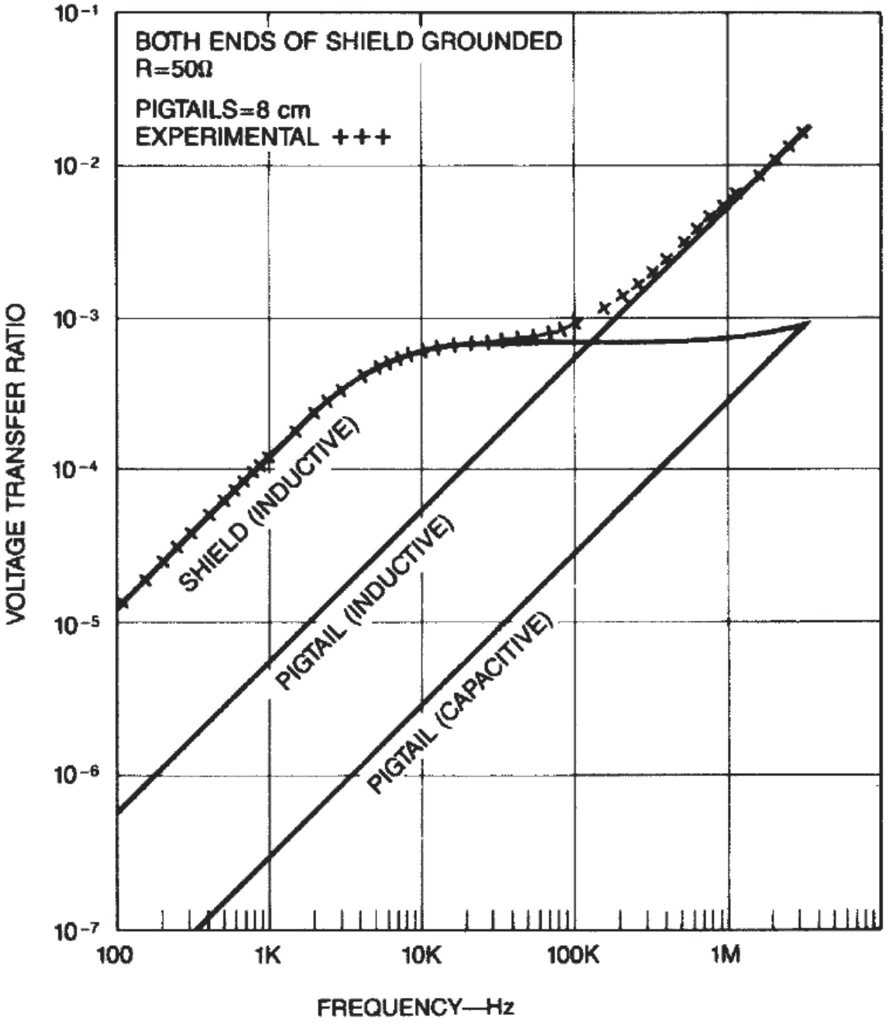
Pigtails

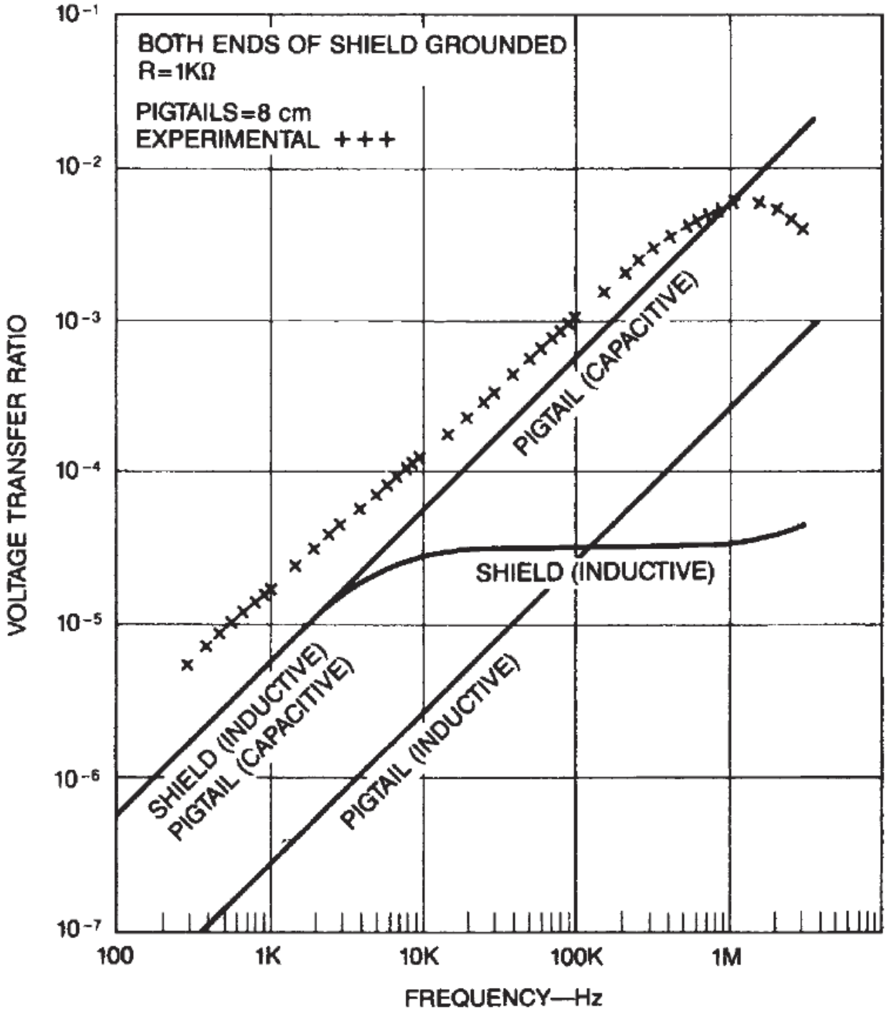
- A pigtail connection makes the shield current to be concentrated on one side of the shield as shown in figure
- The shield should be terminated uniformly around its circumference to provide 360 degree electrical contact. This complete circular contact is also important between all mating halves of cables.
- The complete electrical connection is also found in audio XLR cables via spring figures as shown
- even a small length portion of the total cable length used for a pigtail connection can significantly affect the noise performance and coupling to the cable at frequencies above 100KHz. Thus care should be taken to **have as short as possible pigtails** as possible **at low frequencies**, but at **high frequencies**, they are problematic and should be **avoided**.
- Check the curves that follow.





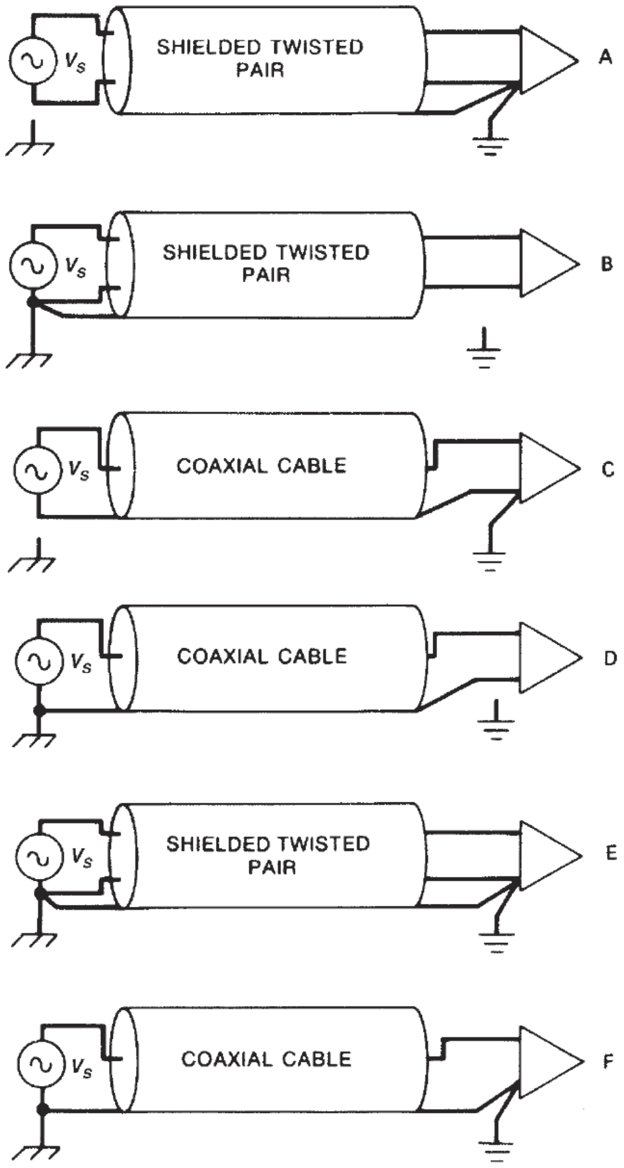
- 3.7m shielded cable with 8cm pigtail connections with two terminating impedances
- Note that for 50 ohm, beyond 100KHz, the pigtail inductance starts dominating (increasing the noise levels)
- For the 1K ohm termination, capacitive effects dominate beyond 100KHz, and also, degraded noise levels are obtained





Low frequency shield cable grounding

- The main reason behind shielding cables at low frequencies (LF) is to protect them from E-field coupling from 50/60 Hz power lines.
- It was pointed out that shields do not protect against H-field coupling at LF.
- The shield in the STP protects against E-field coupling, while the twisted pair construction by nature protects against H-field coupling.
- LF cable shielding is important because many LF circuits have high impedances (thus very susceptible to LF coupling).
- At LF, shields on multiconductor cables where the shield is not acting as the return current path are often grounded at one end. It is recommended to ground at the source end because it is the reference to the signal voltage. If the signal source is floating, then ground at load end.
- When the signal circuit is grounded at both ends (cases E and F), the noise reduction is limited by the difference in ground potential and by the susceptibility of the ground loop to magnetic fields.



- Reducing the shield resistance can reduce the amount of coupled noise (as seen before)
- If additional noise immunity is required, the ground loop must be broken via the use of transformers, optical couplers, or common-mode chokes.
- Note that grounding the cable shield at one end to eliminate power line noise coupling, make the cable act as a high frequency antenna (radiator) and will be capable of picking up RF noise.

→Proper way to terminate the cable shield is to the equipment’s shielded enclosure, not to the circuit ground. This connection should have the lowest impedance possible and should be made to the outside of the enclosure.

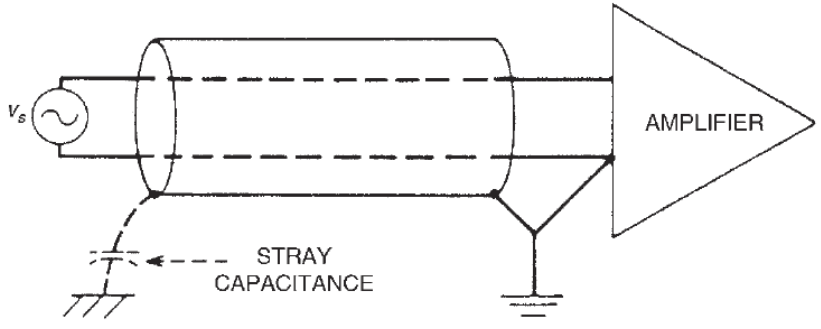
- In audio world, the noise issue that happens due to the cable shield connection to circuit ground and not chassis ground, is called the “Pin 1 Problem” ☺
- This is documented and mentioned explicitly in the Audio Engineering Society standards, AES48, 2005.

High frequency shield cable grounding

- At frequencies above 100KHz, or when the cable length is more than 1/20 wavelengths, it becomes necessary to ground the shield at both ends.
- At high frequencies (HF), stray capacitances tends to complete the ground loop, which makes it almost impossible to maintain ground isolation at the unterminated end of the shield.
- At HF, with digital circuits, ground both ends of the cable shield.
- Any small noise voltage caused by the difference in ground potential will not affect digital circuits and will be filtered out for RF/analog ones
- Skin effect will cause the noise currents to flow on the outer surface of the shield and the signal return current on the inside.

Hybrid Cable Shield Grounding

- Many applications (video) contains both LF and HF contents. And thus we need a combination of the two techniques for grounding the cable shield (one ended and double ended).
- This can be done using the circuit shown, were we intentionally insert a capacitor of 47nF forming a hybrid ground. At LF, the capacitor is open circuit, thus we have a single point ground, while at HF it becomes a low impedance, thus providing ground at both ends.
- Ideally, the capacitor should be built into the connector to avoid any inductive effect due to such connections. One example of such an implementation is shown for audio XLR cables, where the capacitors are implemented inside the connector as shown in the picture to the right.
- Double shielded cable grounding is used to increase HF shielding effectiveness, and when you have both LF and HF signals on the same cable. The two shields are isolated from one another and different terminations can be devised.



Next time …

- Grounding …