Cabling – Unit 1

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Cabling

- Cables are important because they are usually the longest parts of a system and therefore act as efficient antennas that pick up and/or radiate noise.
- This chapter covers the coupling mechanisms that occur
  - ✔ between fields and cables
  - ✔ between cables (crosstalk),
  - ✔ both unshielded and shielded cables are considered.

<u>In this chapter, we assume the following:</u>

- Shields are made of nonmagnetic materials and have a thickness much less than a skin depth at the frequency of interest.*
- The receptor is not coupled so tightly to the source that it loads down the source.
- Induced currents in the receptor circuit are small enough not to distort the original field. (This does not apply to a shield around the receptor circuit.)
- Cables are short compared with a wavelength. ($L \ll \lambda$.)

Cabling

- Since cables are assumed short compared with a wavelength, the coupling between circuits can be represented in three different ways:

1. **Capacitive or electric coupling**: results from the interaction of electric fields between circuits. Also known as Electrostatic (because the fields are not static)
2. **Inductive or magnetic coupling**: which results from the interaction between the magnetic fields of two circuits.
3. **Electromagnetic coupling or radiation:** Combination of electric and magnetic fields and is appropriately called electromagnetic coupling or radiation.

Capacitive Coupling

- A simple representation of capacitive coupling between two conductors is shown in Fig. 2.1.
  - ✓ Capacitance C12 is the stray capacitance between conductors 1 and 2.
  - ✓ Capacitance C1G is the capacitance between conductor 1 and ground.
  - ✓ C2G is the total capacitance between conductor 2 and ground
  - ✓ R is the resistance of circuit 2 to ground.
- The equivalent circuit of the coupling is also shown in Fig. 2-1.

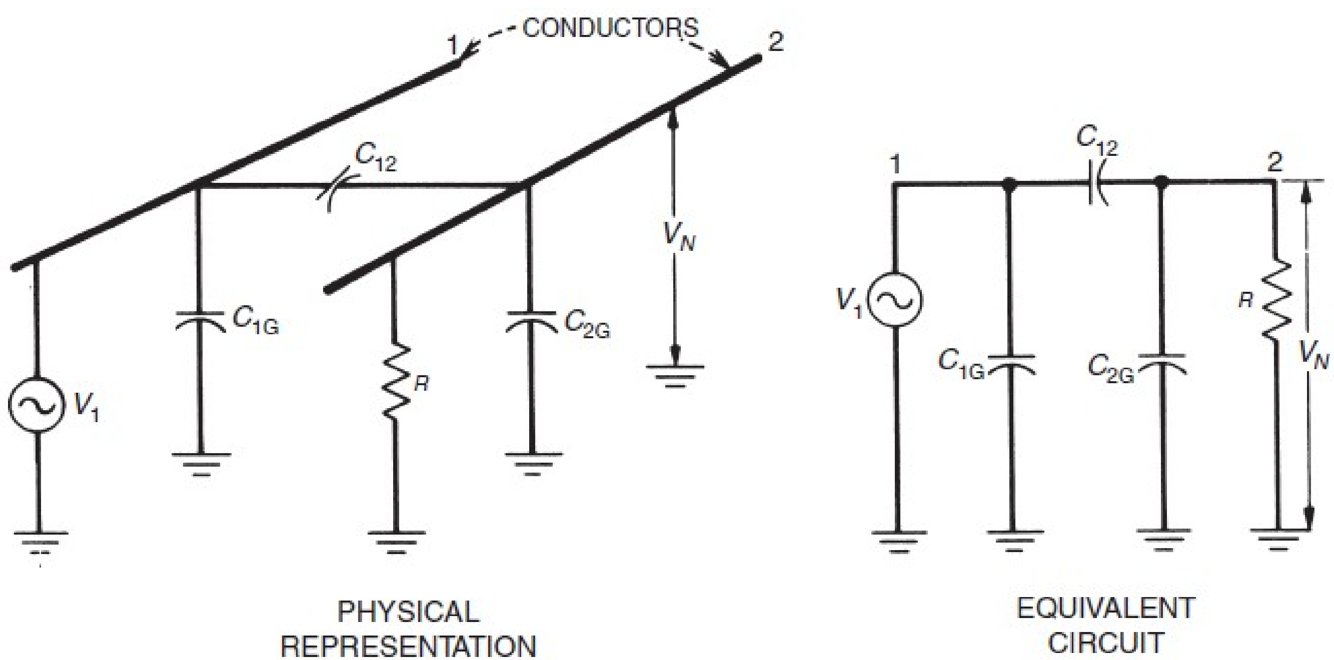


FIGURE 2-1. Capacitive coupling between two conductors.

Capacitive Coupling

- Consider the voltage V1 on conductor 1 as the source of interference and conductor 2 as the affected circuit or receptor.
- Any capacitance connected directly across the source, such as C1G can be neglected because it has no effect on the noise coupling.
- The noise voltage VN produced between conductor 2 and ground can be expressed as follows:

$$V_N = \frac{j\omega[C_{12}/(C_{12}+C_{2G})]}{j\omega + 1/R(C_{12}+C_{2G})} V_1.$$

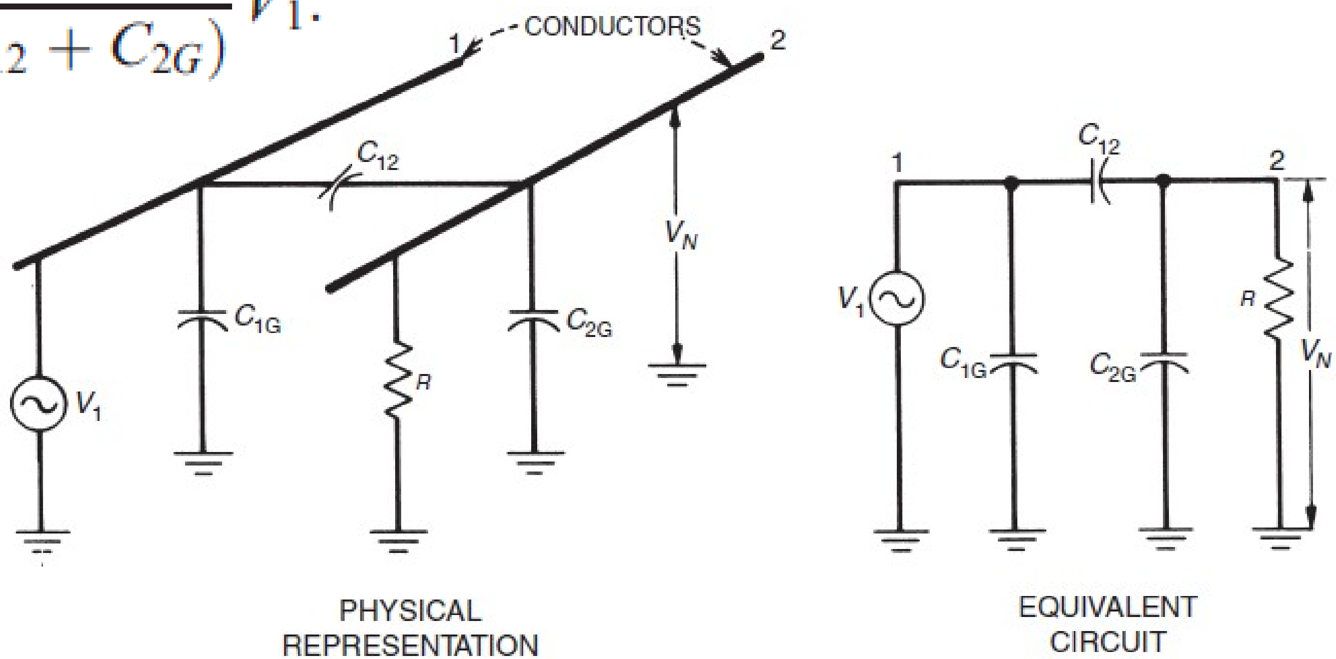


FIGURE 2-1. Capacitive coupling between two conductors.

Capacitive Coupling

$$V_N = \frac{j\omega[C_{12}/(C_{12}+C_{2G})]}{j\omega + 1/R(C_{12}+C_{2G})} V_1.$$

- when R is a lower impedance than the impedance of the stray capacitance C12 plus C2G.

$$R \ll \frac{1}{j\omega(C_{12}+C_{2G})},$$

Eq. 2-1 can be reduced to the following:

$$\boxed{V_N = j\omega R C_{12} V_1.} \quad (2\text{-}1)$$

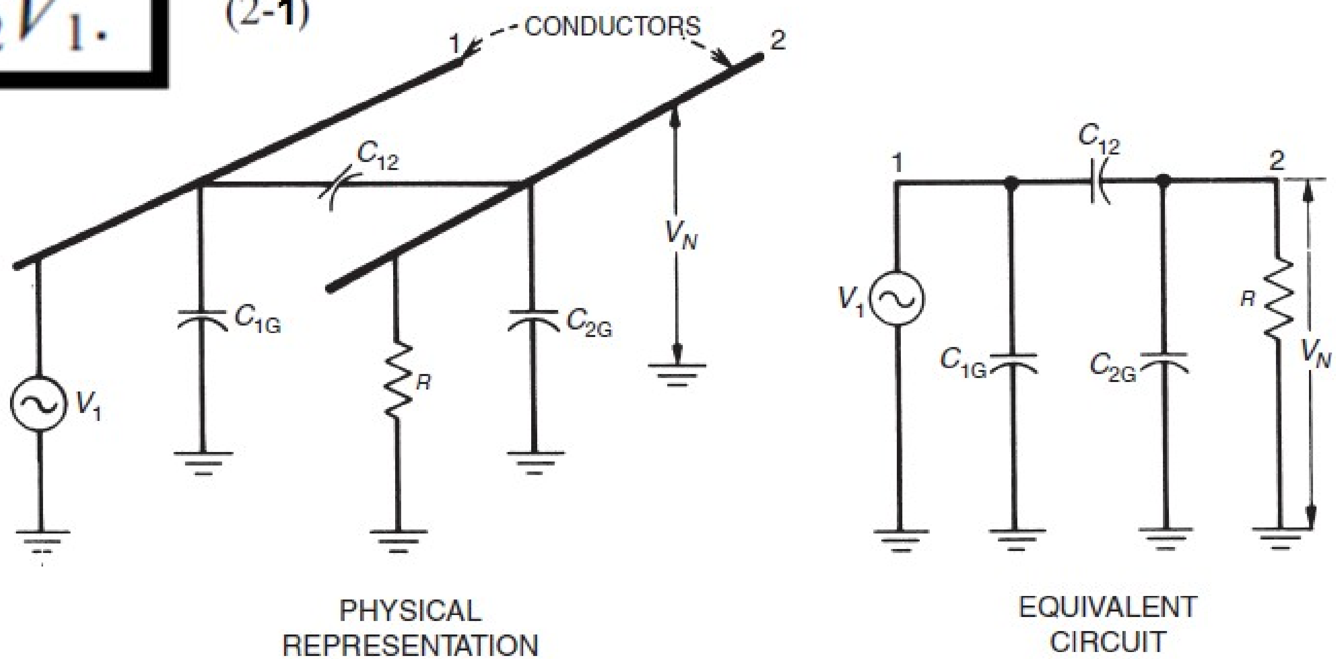
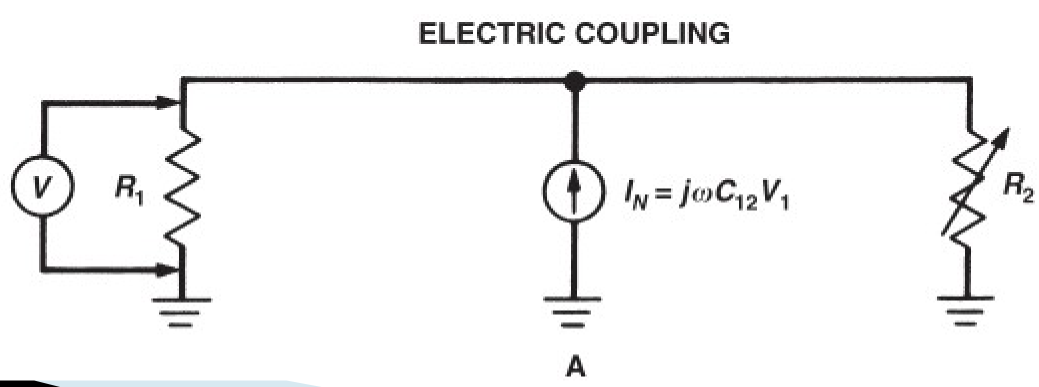


FIGURE 2-1. Capacitive coupling between two conductors.

Capacitive Coupling

- Electric field (capacitive) coupling can be modeled as a current generator, connected between the receptor circuit and ground, with a magnitude of $j\omega C12V1$. This is shown in Fig. 2-9A.
- Equation 2-2 shows that the noise voltage is directly proportional to
  - ✔ the frequency ($\omega = 2\pi f$) of the noise source,
  - ✔ the resistance R of the affected circuit to ground,
  - ✔ the mutual capacitance C12 between conductors 1 and 2,
  - ✔ and the magnitude of the voltage V1.

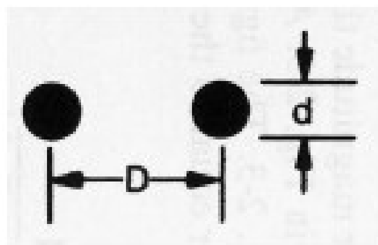
$$V_N = j\omega R C_{12} V_1. \tag{2-2}$$



Capacitive Coupling

- Assuming that the voltage (V1) and frequency (ω) of the noise source cannot be changed, this leaves only two remaining parameters for reducing capacitive coupling.
- The receiver circuit can be operated at a lower resistance (R) level, or the mutual capacitance C12 can be decreased.
- Capacitance C12 can be decreased by proper orientation of the conductors, by shielding or by physically separating the conductors.
- If the conductors are moved farther apart, C12 decreases, thus decreasing the induced voltage on conductor 2.
- As a reference, 0 dB is the coupling when the conductors are separated by three times the conductor diameter.

$$V_N = j\omega R C_{12} V_1. \qquad (2\text{-}2)$$



$D/d > 3$

Capacitive Coupling

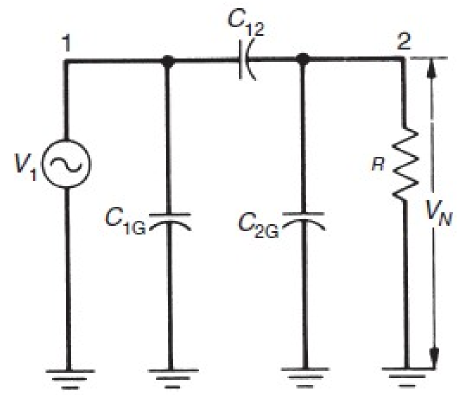
- If the resistance from conductor 2 to ground is large, such that

$$R \gg \frac{1}{j\omega(C_{12} + C_{2G})}$$

- then Eq. 2-1 reduces to

$$V_N = \left(\frac{C_{12}}{C_{12} + C_{2G}}\right) V_1 \qquad (2\text{-}3)$$

- Under this condition, the noise voltage produced between conductor 2 and ground is the result of the capacitive voltage divider C12 and C2G. The <u>noise voltage is independent of frequency</u> and is of a <u>larger magnitude</u> than when R is small.



EQUIVALENT
CIRCUIT

Capacitive Coupling

- A plot of Eq. 2-1 versus ω is shown in Fig. 2-3.
- As can be observed, the maximum noise coupling is given by Eq. 2-3.
- The figure also shows that the actual noise voltage is always less than or equal to the value given by Eq. 2-2.
- At a frequency $\omega = \dfrac{1}{R(C_{12} + C_{2G})}$ Eq. 2-2 gives a value of noise that is 1.41 times the actual value.
- In almost all practical cases, the frequency is much less than this, and Eq. 2-2 applies.

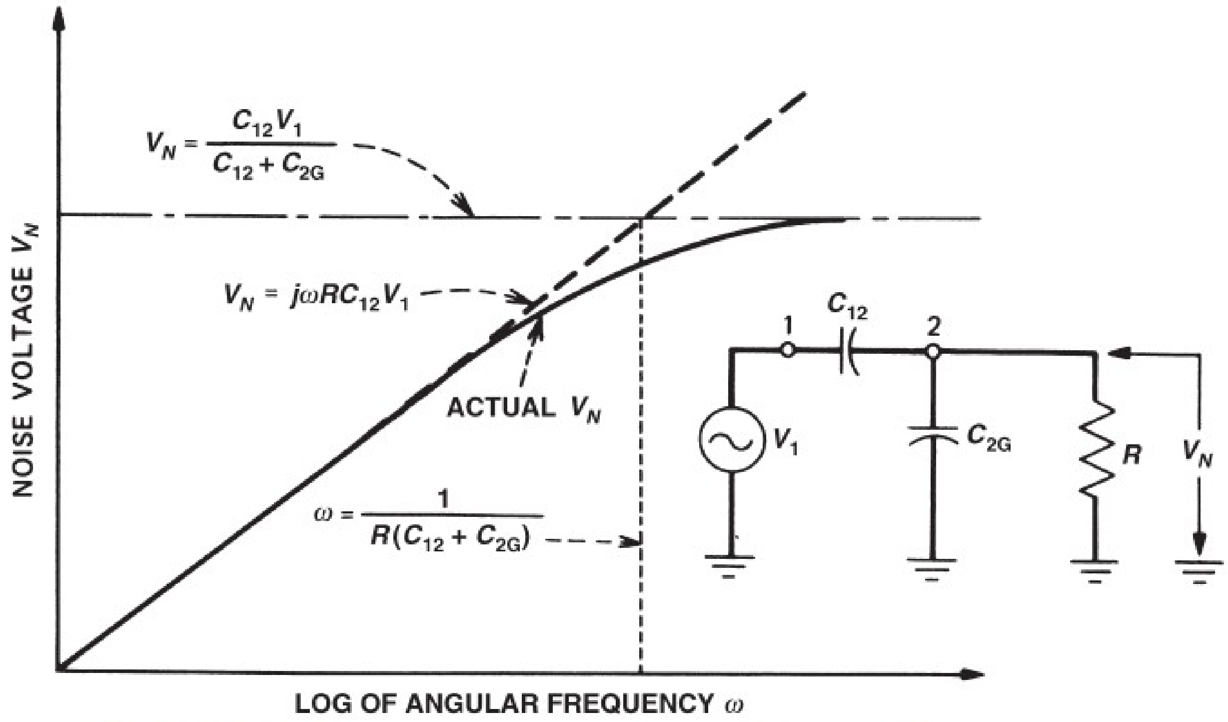


FIGURE 2-3. Frequency response of capacitive coupled noise voltage.

Problems

- 2.1 In Fig. P2-1 the stray capacitance between conductors 1 and 2 is 50 pF. Each conductor has a capacitance to ground of 150 pF. Conductor 1 has a 10-V alternating current (ac) signal at a frequency of 100 kHz on it. What is the noise voltage picked up by conductor 2 if its termination R_T is:
- a. An infinite resistance?
- b. A 1000Ω resistance?
- c. A 50Ω resistance?

- a. An infinite resistance?

$$R \gg \frac{1}{j\omega(C_{12}+C_{2G})}$$

$$V_N = \left(\frac{C_{12}}{C_{12}+C_{2G}}\right)V_1$$

$$V_N = \left(\frac{50}{50+150}\right) x10$$

$$V_N = 2.5V$$

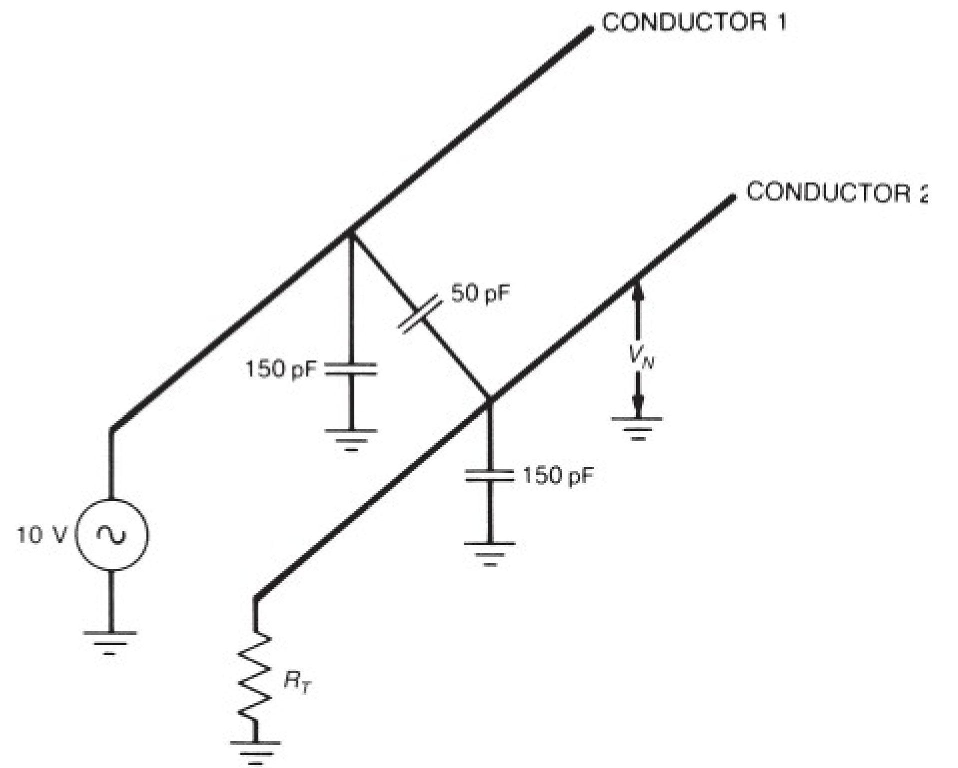


FIGURE P2-1.

Problems

- b. A 1000Ω resistance?

When $R \ll \dfrac{1}{j\omega(C_{12} + C_{2G})}$

$$V_N = j\omega R C_{12} V_1$$

$$V_N = j(2\pi 100K) x 1000 x 50 x 10^{-12} x 10$$

$$V_N = 314mV$$

- c. A 50Ω resistance?

When $R \ll \dfrac{1}{j\omega(C_{12} + C_{2G})}$

$$V_N = j\omega R C_{12} V_1$$

$$V_N = j(2\pi 100K) x 50 x 50 x 10^{-12} x 10$$

$$V_N = 15.7mV$$

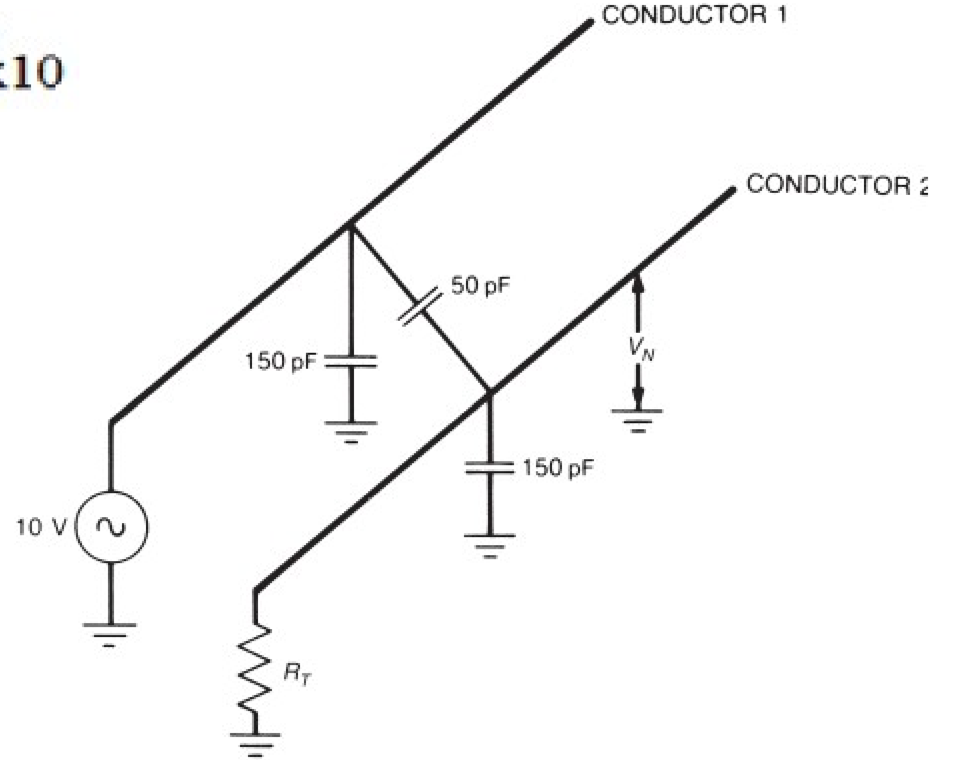


FIGURE P2-1.

EFFECT OF SHIELD ON CAPACITIVE COUPLING

- First, consider the case of an ideal shielded conductor as shown in Fig. 2-4.
- An equivalent circuit of the capacitive coupling is also shown in the figure.
- This is an <u>ideal case</u> because of the following:
  1. The shield completely encloses conductor 2, none of conductor 2 extends beyond the shield.
  2. The shield is solid—there are no holes in the shield such as would be the case of a braided shield.
  3. The shield is not terminated, and there is no terminating impedance on conductor 2.

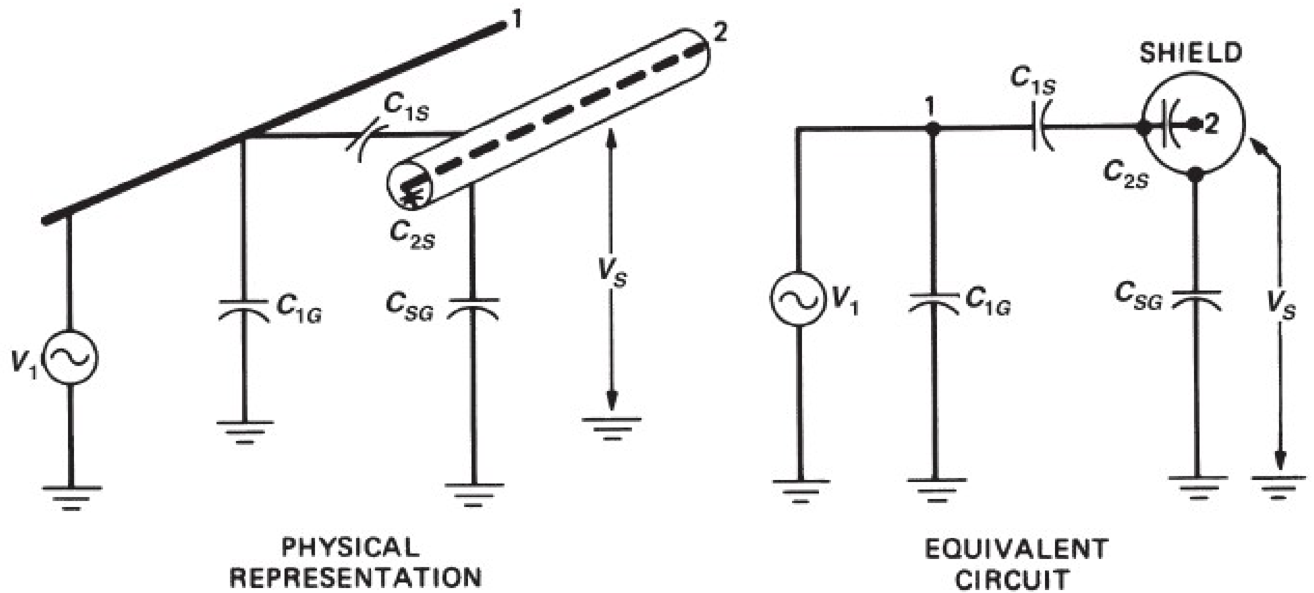


FIGURE 2-4. Capacitive coupling with shield placed around receptor conductor.

EFFECT OF SHIELD ON CAPACITIVE COUPLING

- The shield is an unshielded conductor exposed to conductor 1, and because there is no termination on the shield it has a <u>high terminating impedance.</u>
- Therefore Eq. 2-3 can be used to determine the voltage picked up by the shield.
- The noise voltage on the shield will be

$$V_S = \left(\frac{C_{1S}}{C_{1S} + C_{SG}}\right) V_1.$$

- From the equivalent circuit shown in Fig. 2-4, we recognize, that for this ideal case, the <u>only impedance</u> connected to conductor 2 is capacitance <u>C2S.</u>
- Because no other impedances are connected to conductor 2, <u>no current can flow through C2S.</u> As a result, there can be <u>no voltage drop across C2S</u>, and voltage picked up by the conductor 2 will be

$$\boxed{V_N = V_S}$$

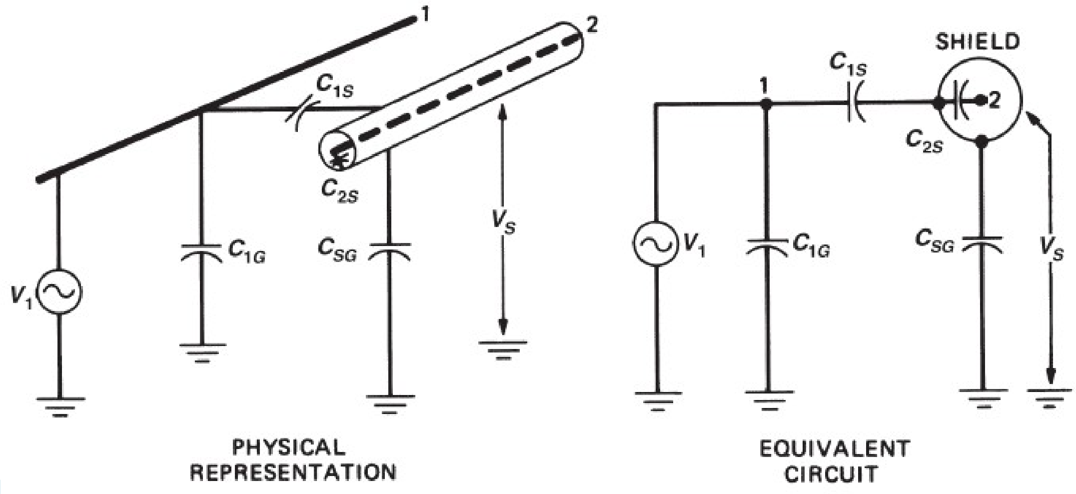


FIGURE 2-4. Capacitive coupling with shield placed around receptor conductor.

EFFECT OF SHIELD ON CAPACITIVE COUPLING

- The shield therefore did not reduce the noise voltage picked up by conductor 2.
- If, however, the shield is grounded, the voltage $V_S = 0$, and therefore the noise voltage $V_N = 0$
- Therefore, we can conclude that the shield is not effective unless it is properly terminated (grounded).

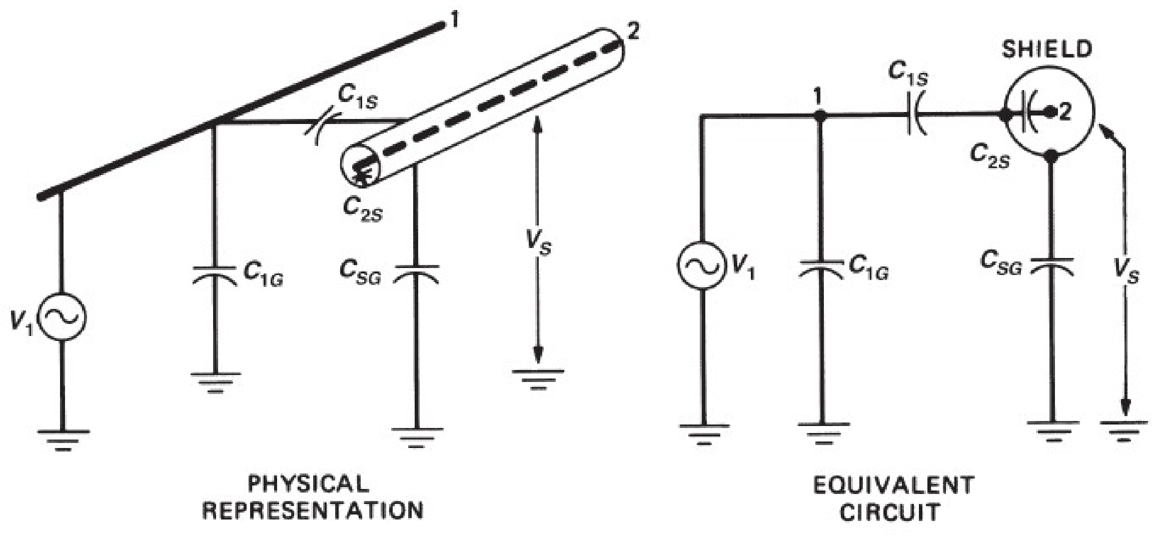


FIGURE 2-4. Capacitive coupling with shield placed around receptor conductor.

EFFECT OF SHIELD ON CAPACITIVE COUPLING

- In many practical cases, the center conductor does extend beyond the shield, and the situation becomes that of Fig. 2-5. Here
  - ✔ C12 is the capacitance between conductor 1 and the shielded conductor 2
  - ✔ C2G is the capacitance between conductor 2 and ground.
- Both of these capacitances exist because the ends of conductor 2 extend beyond the shield and as the result of any holes in the shield.
- Even if the shield is grounded, there is now a noise voltage coupled to conductor 2. Its magnitude is expressed as follows:

$$V_N = \frac{C_{12}}{C_{12} + C_{2G} + C_{2S}} V_1.$$

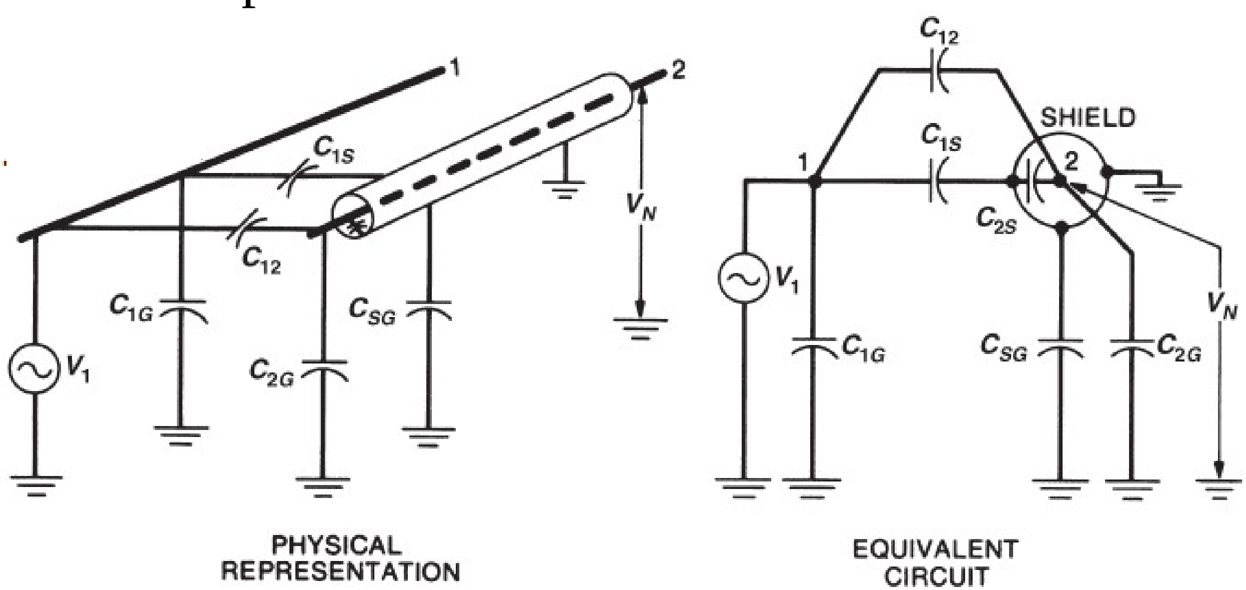


FIGURE 2-5. Capacitive coupling when center conductor extends beyond shield; shield grounded at one point.

EFFECT OF SHIELD ON CAPACITIVE COUPLING

$$V_N = \frac{C_{12}}{C_{12} + C_{2G} + C_{2S}} V_1.$$

- The value of C12, and hence V_N, depends primarily on the length of conductor 2 that extends beyond the shield and to a lesser extent on any holes present in the shield.
- **For good electric field shielding**, it is therefore necessary (1) to minimize the length of the center conductor that extends beyond the shield and (2) to provide a good ground on the shield.
- On longer cables, multiple grounds may be necessary.

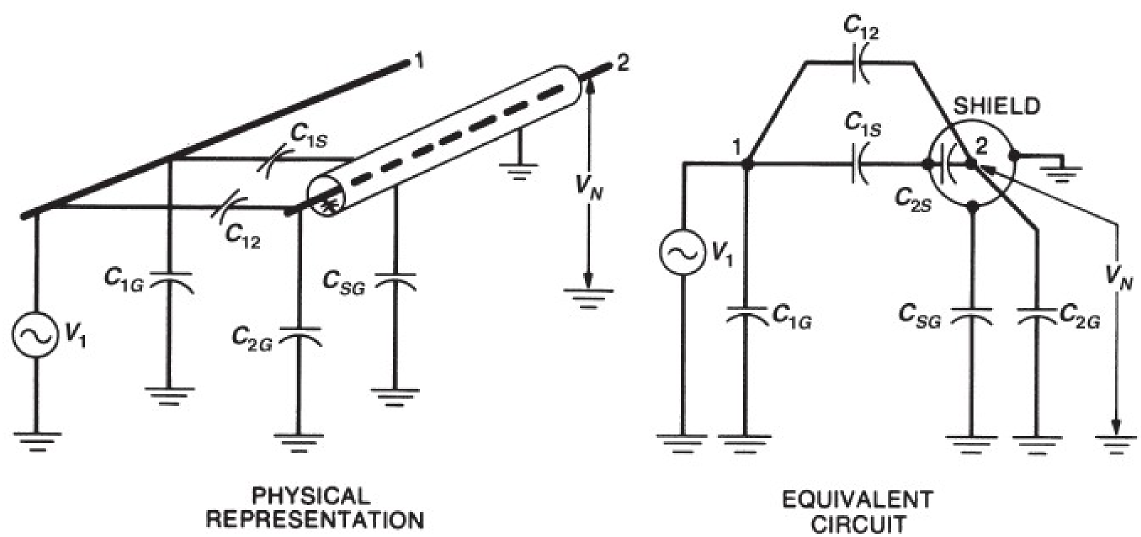


FIGURE 2-5. Capacitive coupling when center conductor extends beyond shield; shield grounded at one point.

EFFECT OF SHIELD ON CAPACITIVE COUPLING

- When the receptor conductor has finite resistance to ground,
- The arrangement is that shown in Fig. 2.6. If the shield is grounded, the equivalent circuit can be simplified as shown in the figure.
- Any capacitance directly across the source can be neglected because it has no effect on the noise coupling.
- The simplified equivalent circuit can be recognized as the same circuit analyzed in Fig. 2.1, provided C2G is replaced by the sum of C2G and C2S. Therefore, if $R \ll \frac{1}{j\omega(C_{12} + C_{2G} + C_{2S})}$, then Noise Voltage is $V_N = j\omega R C_{12} V_1.$

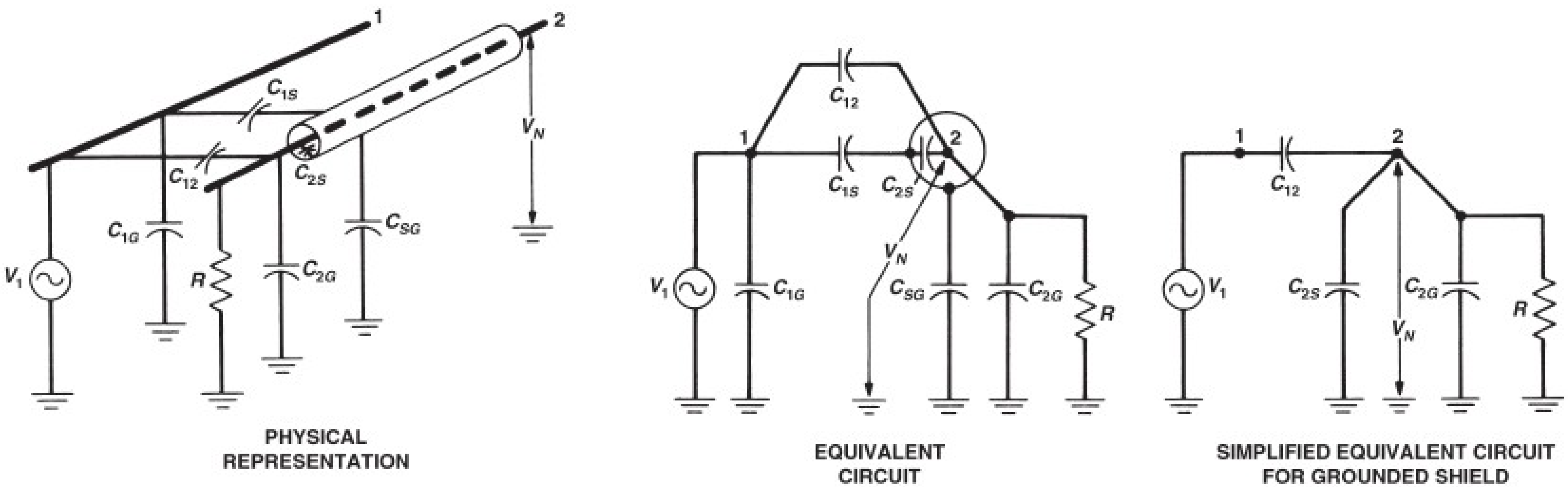


FIGURE 2-6. Capacitive coupling when receptor conductor has resistance to ground.

EFFECT OF SHIELD ON CAPACITIVE COUPLING

- Therefore, if $R \ll \dfrac{1}{j\omega(C_{12} + C_{2G} + C_{2S})}$, then Noise Voltage is

$$V_N = j\omega R C_{12} V_1.$$

- This is the same as Eq. 2-2, which is for an unshielded cable, except that C12 is greatly reduced by the presence of the shield.
- Capacitance C12 now consists primarily of the capacitance between conductor 1 and the unshielded portions of conductor 2.
- If the shield is braided, any capacitance that exists from conductor 1 to 2 through the holes in the braid must also be included in C12.

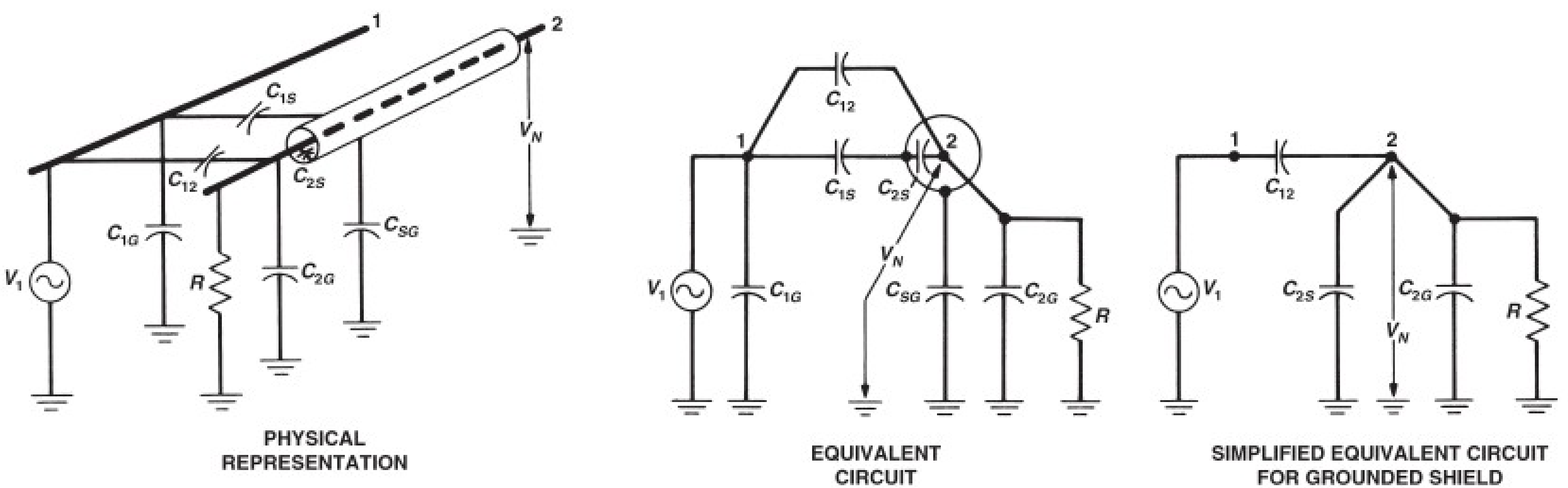


FIGURE 2-6. Capacitive coupling when receptor conductor has resistance to ground.

Problems

- 2.2 In Fig. P2-2, a grounded shield is placed around conductor 2. The capacitance from conductor 2 to the shield is 100 pF, The capacitance between conductors 2 and 1 is 2 pF, and the capacitance between conductor 2 and ground is 5 pF. Conductor 1 has a 10-V ac signal at a frequency of 100 kHz on it. For this configuration, what is the noise voltage picked up by conductor 2 if its termination R_T is:
- a. An infinite resistance?
- b. A 1000Ω resistance?
- c. A 50Ω resistance?

$$V_N = \frac{C_{12}}{C_{12} + C_{2G} + C_{2S}} V_1$$

$$V_N = \left(\frac{2}{2+5+100}\right) \text{x} 10$$

$$= 187 \text{mV}$$

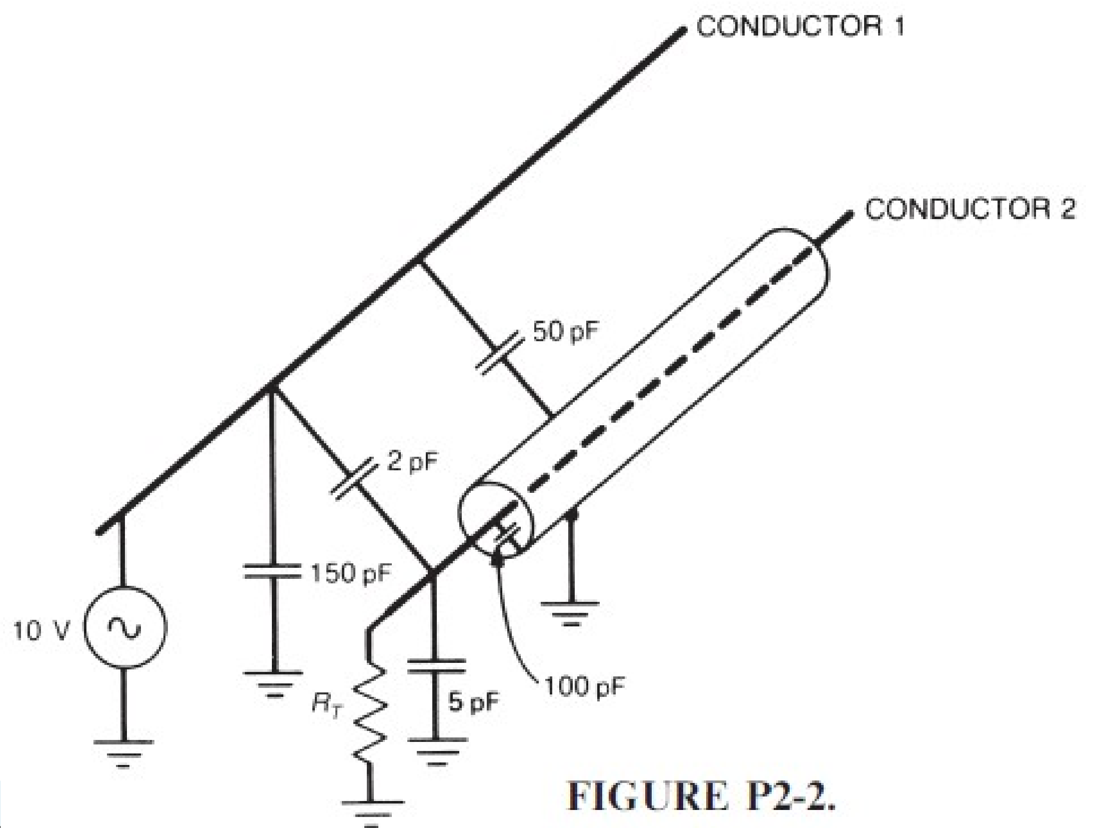


FIGURE P2-2.

Problems

- b. A 1000Ω resistance

$$V_N = j\omega R C_{12} V_1$$

$$= j\,(2\pi x100K)1000x2x10^{-12}x10$$

$$= 12.56mV$$

- c. A 50Ω resistance?

$$V_N = j\omega R C_{12} V_1$$

$$= j\,(2\pi x100K)\,50\,x2x10^{-12}x10$$

$$= 0.628mV$$

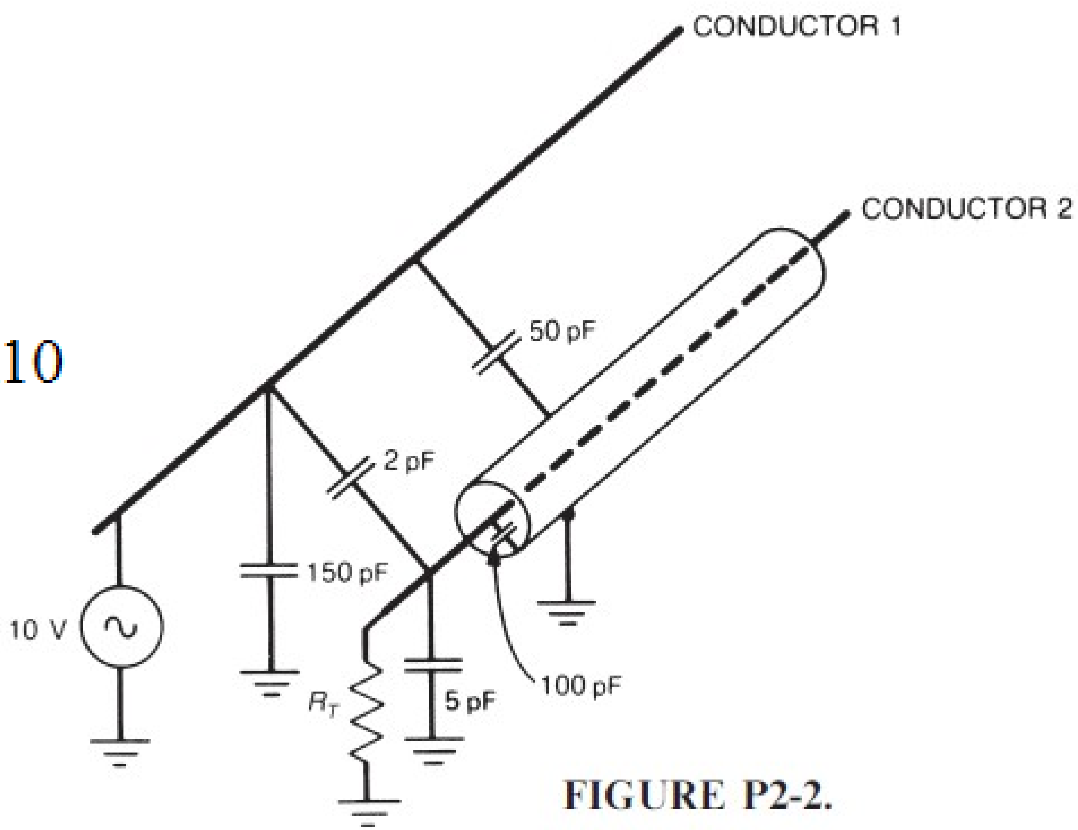


FIGURE P2-2.

INDUCTIVE COUPLING

- When a current I flows through a conductor, it produces a magnetic flux Φ, which is proportional to the current.
- The constant of proportionality is the inductance L; hence, we can write:

$$\phi_T = LI$$

- where Φ_T is the total magnetic flux and I is the current producing the flux.
- Rewriting Eq. we get for the self-inductance of a conductor

$$L = \frac{\phi_T}{I}$$

- The inductance depends on the geometry of the circuit and the magnetic properties of the media containing the field.
- When current flow in one circuit produces a flux in a second circuit, there is a mutual inductance M_{12} between circuits 1 and 2 defined as:

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

Where symbol Φ_{12} represents the flux in circuit 2 because of the current I1 in circuit 1

INDUCTIVE COUPLING

- The voltage V_N induced in a closed loop of area A resulting from a magnetic field of flux density B can be derived from Faraday's law and is:

$$V_N = -\frac{d}{dt}\int_A \overline{B}\cdot d\overline{A}$$

where B and A are vectors is the flux density and area of the closed loop, resp.

- If the closed loop is stationary and the flux density is sinusoidally varying with time but constant over the area of the loop, Eq. reduces to

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

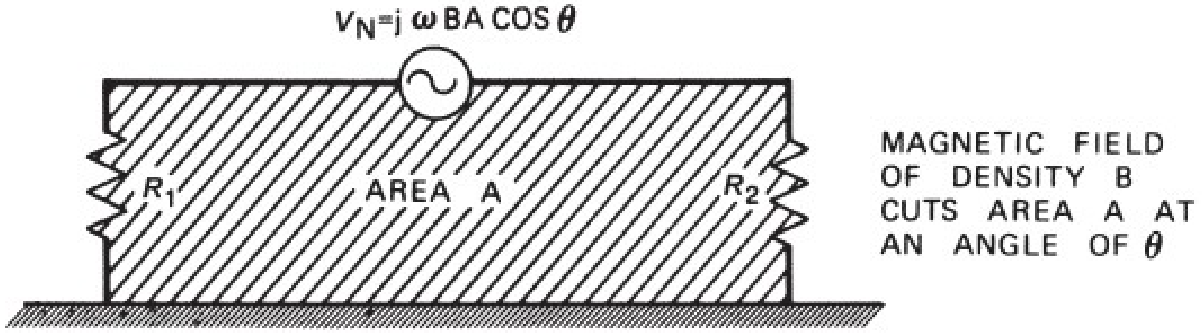


FIGURE 2-7. Induced noise depends on the area enclosed by the disturbed circuit.

INDUCTIVE COUPLING

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

�Because BA cosΘ represents the total magnetic flux (Θ_{12}) coupled to the receptor circuit, the <u>induced voltage in terms of the mutual inductance</u> M can be written as:

$$\boxed{V_N = j\omega M I_1 = M\frac{di_1}{dl}}$$

basic equations describing inductive coupling between two circuits.

�Figure below shows the inductive (magnetic) coupling between two circuits as described by the above (

�The presence of ω in Eq. indicates that the <u>coupling is directly proportional to frequency.</u>

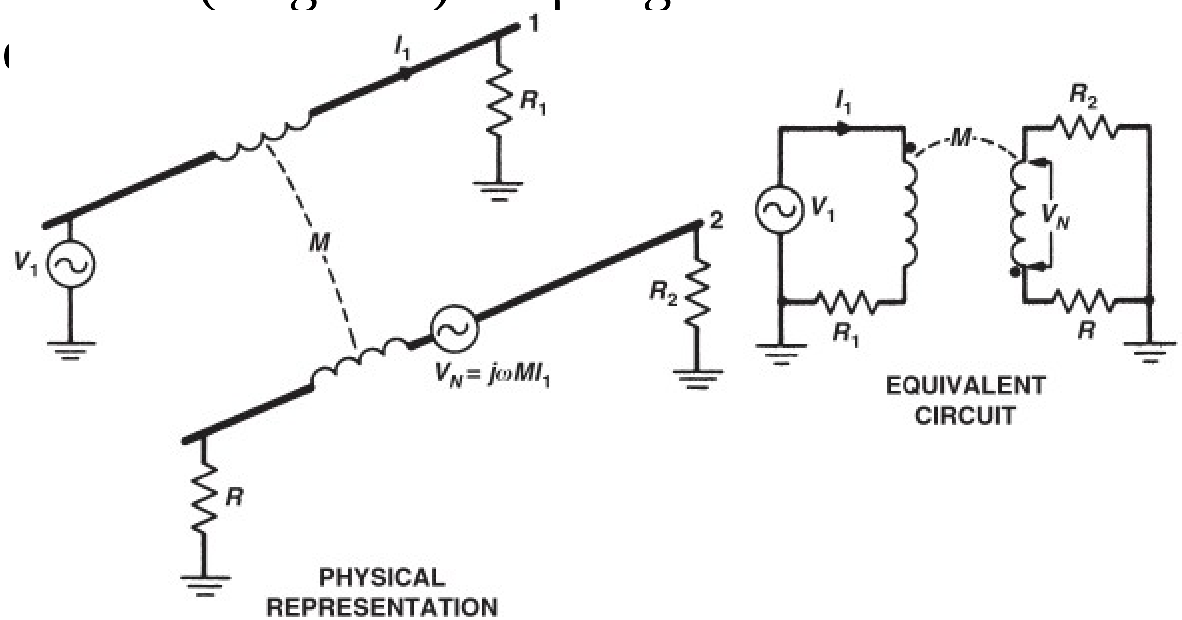


FIGURE 2-8. Magnetic coupling between two circuits.

INDUCTIVE COUPLING

- To reduce the noise voltage, B, A, or cos Θ must be reduced.
- The **B term** can be reduced by physical separation of the circuits or by twisting the source wires. Under these conditions, twisting causes the B fields from each of the wires to cancel.
- The **area (A)** of the receiver circuit can be reduced by placing the conductor closer to the ground plane (if the return current is through the ground plane) or by using two conductors twisted together (if the return current is on one of the pair instead of the ground plane).
- The **cosΘ** term can be reduced by proper orientation of the source and receiver circuits.

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

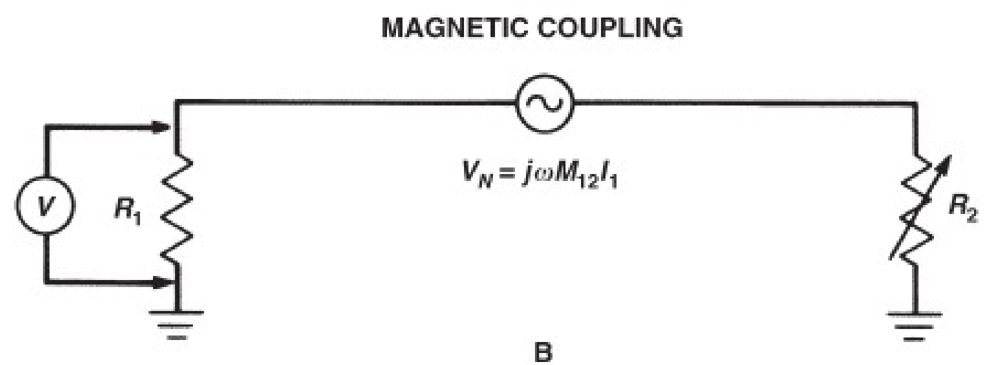


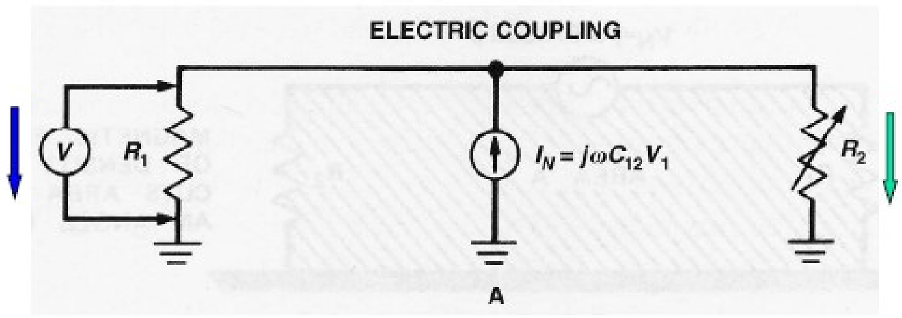
FIGURE 2-9. (B) equivalent circuit for magnetic field coupling.

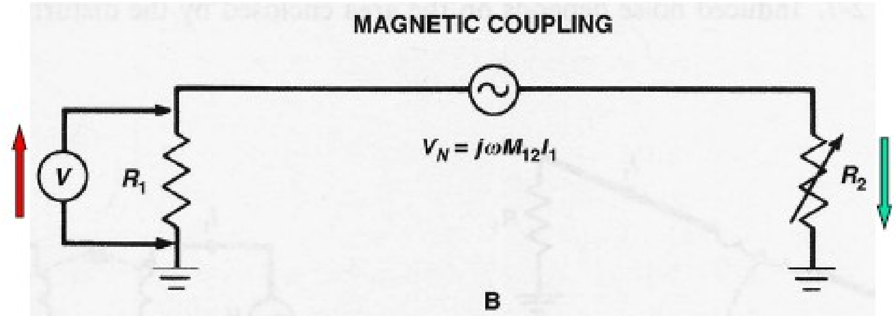
INDUCTIVE COUPLING

Differences between magnetic and electric field coupling.

- For magnetic field coupling, a noise voltage is produced in series with the receptor conductor (Fig. B), whereas for electric field coupling, a noise current is produced between the receptor conductor and ground (Fig. A).
- This difference can be used in the following test to distinguish between electric and magnetic coupling. Measure the noise voltage across the impedance at one end of the cable while decreasing the impedance at the opposite end of the cable.
- If the measured noise voltage decreases, the pickup is electric, and if the measured noise voltage increases, the pickup is magnetic.

Test to distinguish the electric and magnetic coupling



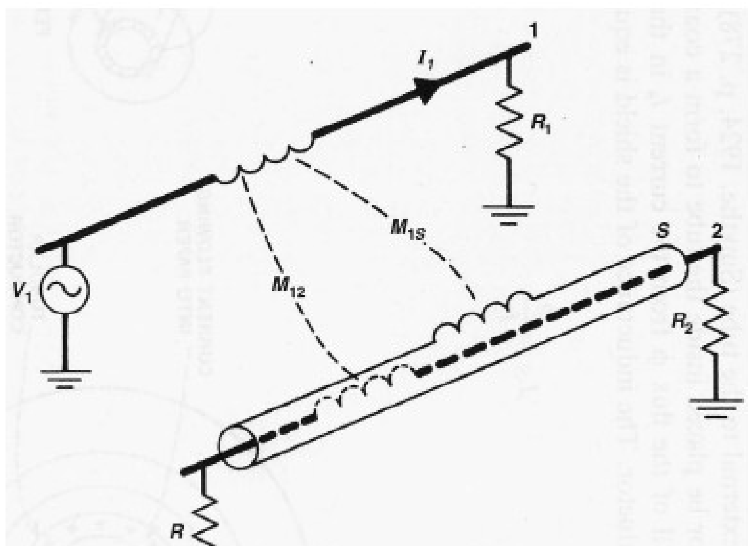


EFFECT OF SHIELD ON MAGNETIC COUPLING

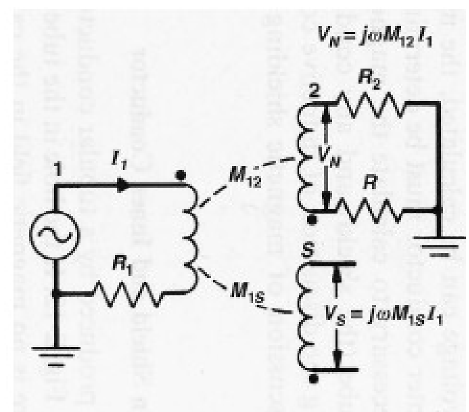
- If an ungrounded and nonmagnetic shield is now placed around conductor 2, the circuit becomes that shown below, where M1s is the mutual inductance between conductor 1 and the shield.
- The shield picks up a voltage because of the current in conductor 1:

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

- A ground connection on one end of the shield does not change the situation. Therefore shield placed around a conductor and <u>grounded at one end has no effect on the magnetically induced voltage in that conductor.</u>



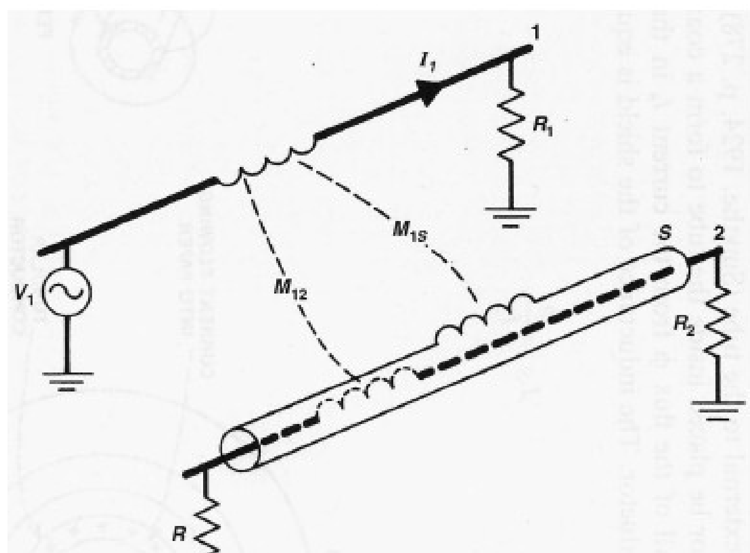
PHYSICAL REPRESENTATION



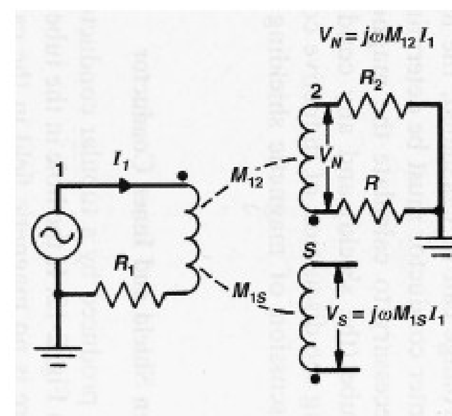
EQUIVALENT CIRCUIT

EFFECT OF SHIELD ON MAGNETIC COUPLING

- If, however, the shield is grounded at both ends, the voltage induced into the shield from M_{1S}, will cause shield current to flow.
- The shield current will induce a second noise voltage into conductor 2.
- Before this voltage can be calculated, the mutual inductance between a shield and its center conductor must be determined.
- For this reason, it will be necessary to **calculate** the magnetic coupling between the shield and any conductor placed inside the tube.



PHYSICAL REPRESENTATION



EQUIVALENT CIRCUIT

Magnetic Coupling Between Shield and Inner Conductor

- First, consider the magnetic field produced by a tubular conductor carrying a uniform axial current, as shown in fig. 2-12
- If the hole in the tube is concentric with the outside of the tube, there is no magnetic field in the cavity, and the total magnetic field is external to the tube.
- Now, let a conductor be placed inside the tube to form a coaxial cable, as shown in Fig. 2-13.
- All of the flux Φ from the current Is in the shield tube encircles the inner conductor. The inductance of the shield is equal to: $L_S = \frac{\phi}{I_S}$

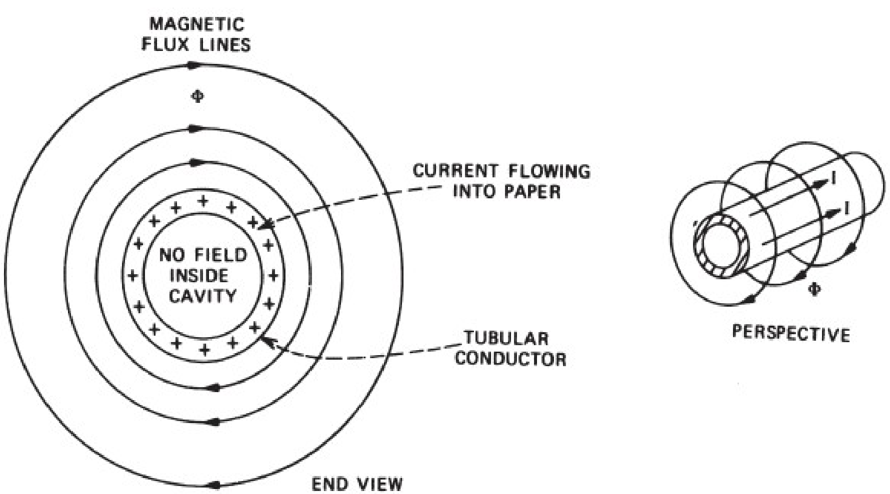


FIGURE 2-12. Magnetic field produced by current in a tubular conductor.

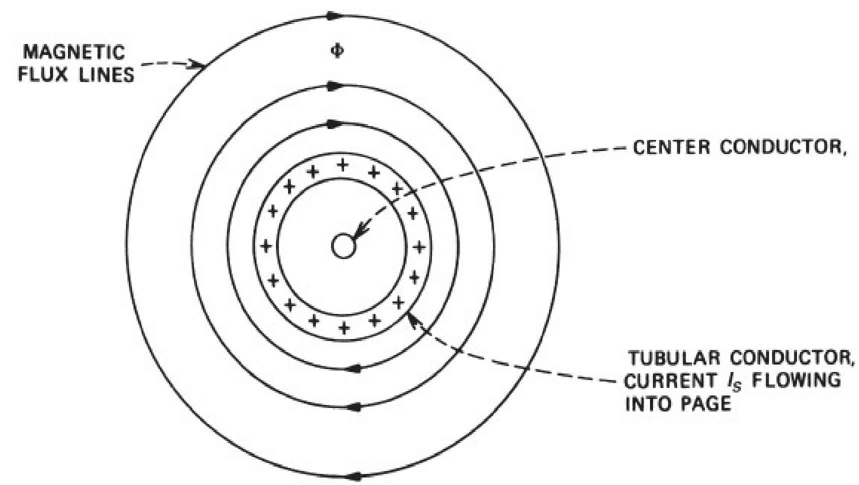


FIGURE 2-13. Coaxial cable with shield current flowing uniformally around the circumference of the shield.

Magnetic Coupling Between Shield and Inner Conductor

- The mutual inductance between the shield and the inner conductor is equal to:

$$M = \frac{\phi}{I_S}$$

- Because all the flux produced by the shield current encircles the center conductor, the flux Φ in both equations is the same.
- The mutual inductance between the shield and center conductor is therefore equal to the self inductance of the shield:

$$M = L_S$$

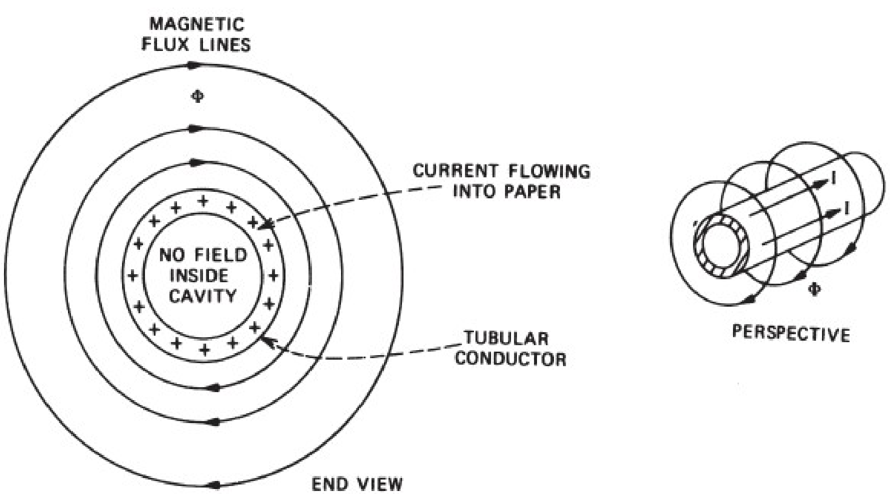


FIGURE 2-12. Magnetic field produced by current in a tubular conductor.

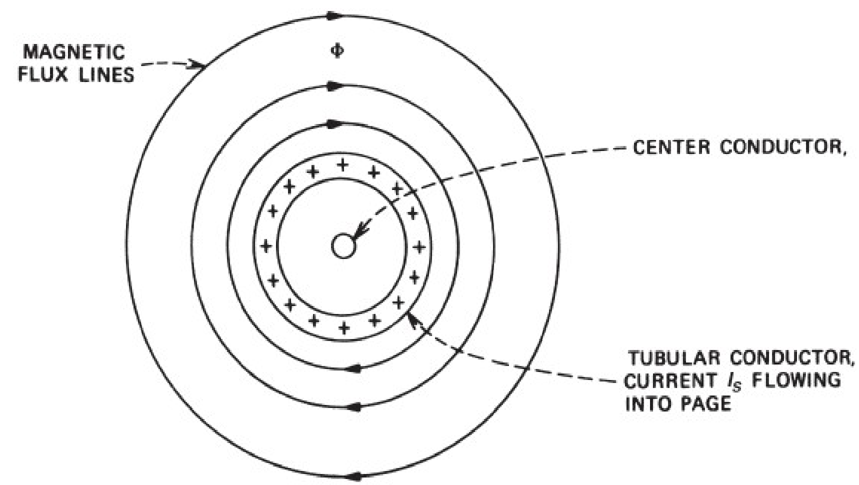


FIGURE 2-13. Coaxial cable with shield current flowing uniformally around the circumference of the shield.

Magnetic Coupling Between Shield and Inner Conductor

- This equation shows that the mutual inductance between the shield and the center conductor is equal to the shield inductance. $M = L_S$
- The voltage V_N induced into the center conductor due to a current I_S in the shield is: $V_N = j\omega M I_S$

The current I_S is equal to $$I_S = \frac{V_S}{L_S}\left(\frac{1}{j\omega + R_S/L_S}\right)$$

- Where L_S and R_S are the inductance and resistance of the shield.

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

Because $L_S = M$

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

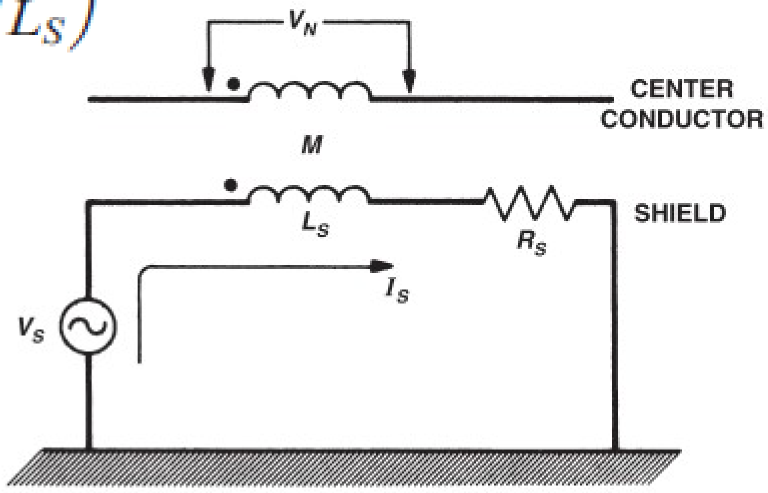


FIGURE 2-14. Equivalent circuis of shielded conductor.

Magnetic Coupling Between Shield and Inner Conductor

- A plot of this Eq. is shown in Fig. 2-15.
- The break frequency for this curve is defined as the shield cutoff frequency (ω_c) and occurs at:

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

- The noise voltage induced into the center conductor is zero at dc and increases to almost V_S at a frequency of $5R_S/L_S$ rad/s.
- Therefore, if shield current is allowed to flow, a voltage is induced into the center conductor that nearly equals the shield voltage at frequencies greater than five times the shield cutoff frequency.

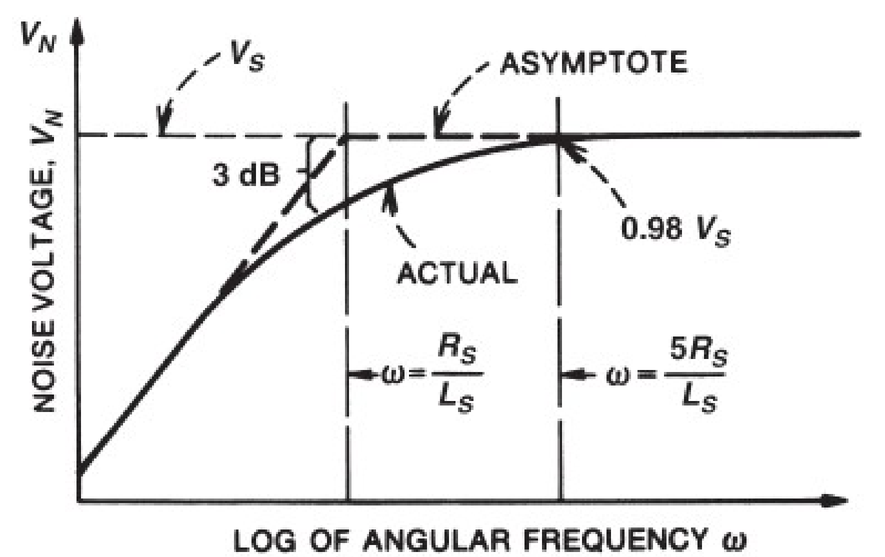


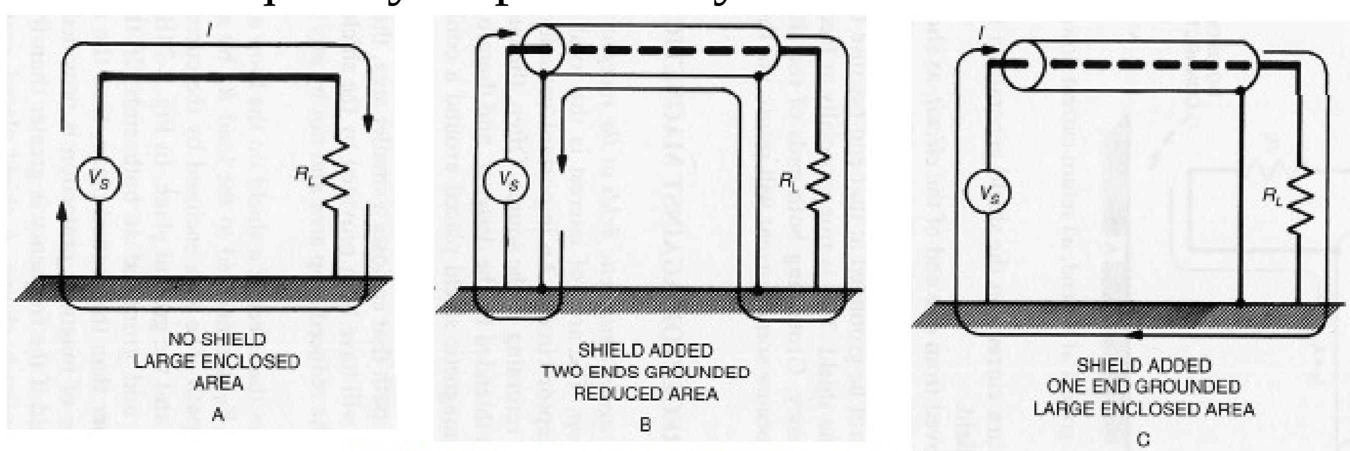
FIGURE 2-15. Noise voltage in center conductor of coaxial cable because of shield current.

SHIELDING A RECEPTOR AGAINST MAGNETIC FIELDS

- The best way to protect against magnetic fields at the receptor is to decrease the area of the receptor loop.
- The area of interest is the total area enclosed by current flow in the receptor circuit.
- An important consideration is the path taken by the current in returning to the source. Often, the current returns by a path other than the one intended by the designer, and therefore, the area of the loop changes.
- If a nonmagnetic shield placed around a conductor causes the current to return over a path that encloses a smaller area, then some protection against magnetic fields will have been provided by the shield.
- This protection, however, is caused by the reduced loop area and not by any magnetic shielding properties of the shield.

SHIELDING A RECEPTOR AGAINST MAGNETIC FIELDS

- Figure illustrates the effect of a shield on the loop area of a circuit.
- The source V_S is connected to the load R_L by a single conductor, using a ground return path.
- The area enclosed by the current is the rectangle between the conductor and the ground plane.
- In Fig.B, a shield is placed around the conductor and grounded at both ends. If the current returns through the shield rather than the ground plane, then the area of the loop is decreased, and a degree of magnetic protection is provided.
- The current will return through the shield if the frequency is greater than five times the shield cutoff frequency as previously shown.



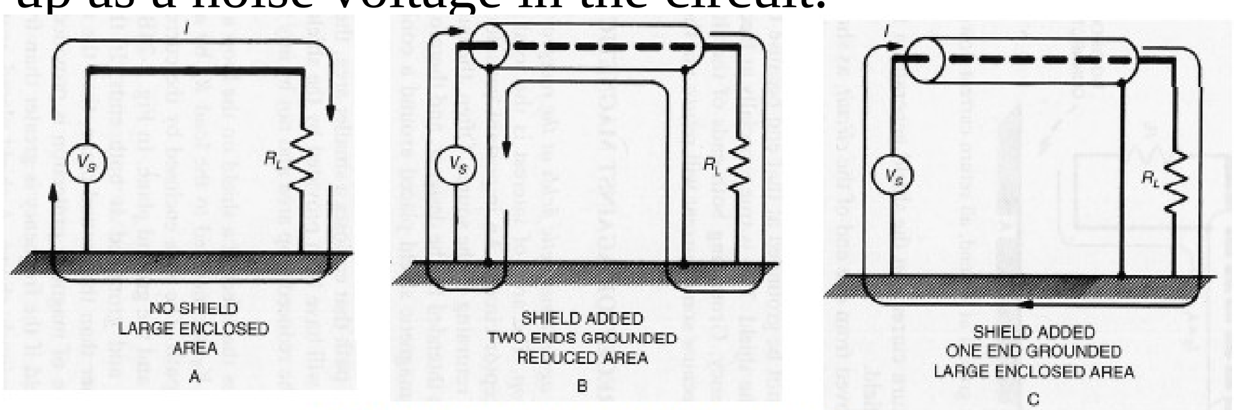
Effect of shield on receptor loop area.

SHIELDING A RECEPTOR AGAINST MAGNETIC FIELDS

- A shield placed around the conductor and grounded at one end only, as shown in Fig.C, does not change the loop area and therefore provides no magnetic protection.
- The arrangement of Fig.B does not protect against magnetic fields at frequencies below the shield cutoff frequency because then most of the current returns through the ground plane and not through the shield.
- At low frequencies, this circuit also has two other problems, as follows:

(1) Because the shield is one of the circuit conductors, any noise current in it will produce an IR drop in the shield and appear to the circuit as a noise voltage, and

(2) If there is a difference in ground potential between the two ends of the shield then it will show up as a noise voltage in the circuit.



Effect of shield on receptor loop area.

COAXIAL CABLE VERSUS TWISTED PAIR

- **Twisted pair cables** were used for frequencies from 100 kHz to 10MHz.
- Twisted pair cables do not have as uniform characteristic impedance as coaxial cables, as the two conductors do not maintain a constant position with respect to each other when the cable is flexed or bent.
- Today's cable designers have been able to extend the normal useful frequency of twisted pairs up to 10 MHz with some applications [e.g., Ethernet and high-definition multimedia interface (**HDMI**)] extending up to hundreds of megahertz.
- These high-performance cables have less capacitance and are more tightly and uniformly twisted.
- In addition, in some cases, they have the two wires of the pair bonded together so they remain in the exact same relationship to each other over the length of the cable.
- **Bonded twisted pair** cables provide a more uniform characteristic impedance and are more immune to noise and produce much less radiation.
- A twisted pair cable is inherently a balanced structure and effectively rejects noise

COAXIAL CABLE VERSUS TWISTED PAIR

- A **coaxial cable** grounded at one end provides a <u>good degree of protection from capacitive (electric field) pickup</u>.
- But if a noise current flows in the shield, then a noise voltage is produced because in a coax the shield is also part of the signal path, this voltage appears as noise in series with the input signal.
- A **double-shielded**, or triaxial, cable with insulation between the two shields can eliminate the noise voltage produced by the shield resistance. Unfortunately, triaxial cables are <u>expensiv</u>e and awkward to use.
- <u>A coaxial cable at high frequencies, however, acts as a triaxial cable because of skin effect.</u>
- For a typical coaxial cable, the skin effect becomes important at about 1 MHz. The noise current flows on the outside surface of the shield, whereas the signal current flows on the inside surface. For this reason, a coaxial cable behaves better at high frequency.
- A triaxial cable has characteristics similar to a shielded twisted pair and is effective in cancelling noise voltage.

COAXIAL CABLE VERSUS TWISTED PAIR

- An unshielded twisted pair, unless its terminations are balanced, provides very little protection against capacitive (electric field) pickup, but it is very good for protection against magnetic field pickup.
- The effectiveness of twisting increases as the number of twists per unit length increases.
- When terminating a twisted pair, the more the two wires are separated, the less the noise suppression.
- Therefore, when terminating a twisted pair, shielded or unshielded, do not untwist the conductors any more than necessary to make the termination.
- **Twisted pair cables, even when unshielded, are very effective in reducing magnetic field coupling.**
- Only two conditions are necessary for this to be true.
- First, the signal must flow equally and in opposite directions on the two conductors.
- Second, the pitch of the twist must be less than one twentieth of a wavelength at the frequencies of concern. (One twist per inch will be effective up to about 500 MHz.)

BRAIDED SHIELDS (Read)

- Most cables are actually shielded with braid rather than with a solid conductor.
- The advantage of braid is flexibility, durability, strength, and long flex life.
- Premium cables with double and even triple shields, as well as silver-plated copper braid wires, are used in some critical military, aerospace, and instrumentation applications.

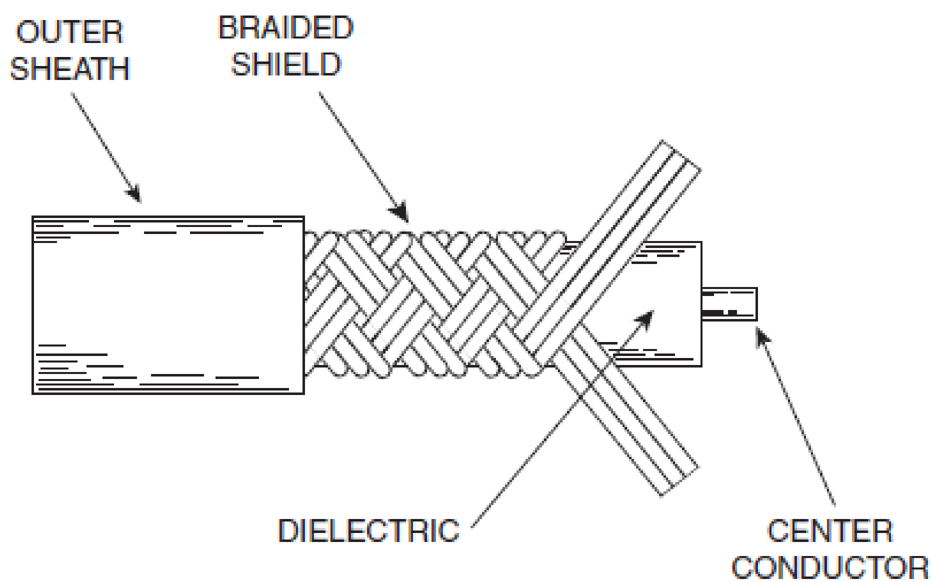


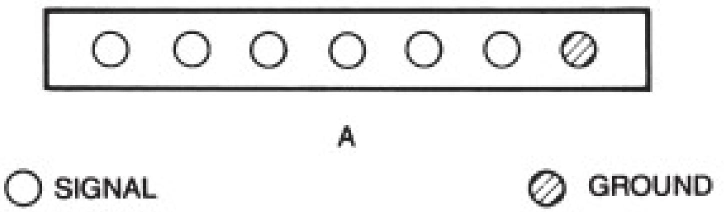
FIGURE 2-33. Cable with a braid shield.

RIBBON CABLES

- A major cost associated with the use of cables is the expense related to the termination of the cable.
- The advantage of ribbon cables is that they allow low cost multiple terminations, which is the primary reason for using them.
- Ribbon cables have a second advantage. They are **"controlled cables"** because the position and orientation of the wires within the cable is fixed, like the conductors on a printed wiring board
- The **major problem** associated with the use of ribbon cables relates to the way the individual conductors are assigned with respect to signal leads and grounds.

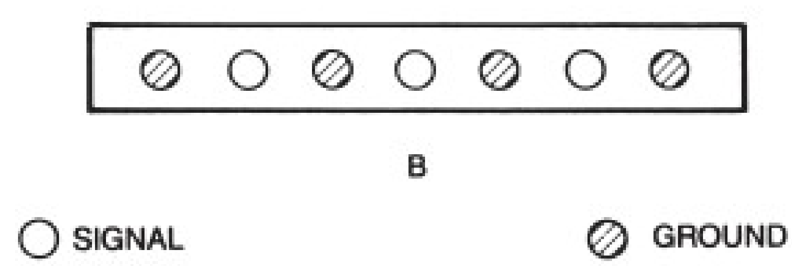
RIBBON CABLES

- **Figure A** shows a ribbon cable where **one conductor is a ground and all the remaining conductors are signal leads**.
- This configuration is used because it minimizes the number of conductors required; however, it has three problems.
- First, it produces large loop areas between the signal conductors and their ground return, which results in radiation and susceptibility.
- The second problem is the common impedance coupling produced when all the signal conductors use the same ground return.
- The third problem is crosstalk between the individual conductors—both capacitive and inductive; therefore, this configuration should seldom be used.
- If it is used, the single ground should be assigned to one of the center conductors to minimize the loop areas.



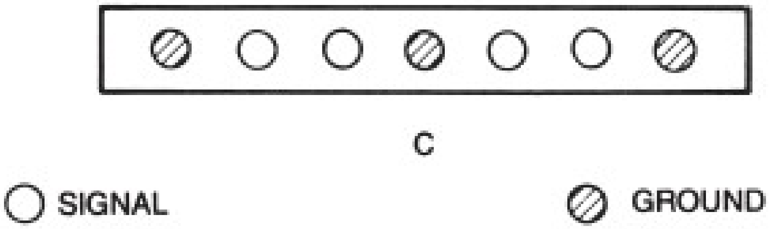
RIBBON CABLES

- **Figure B** shows a better configuration. In this arrangement, the loop areas are small because **each conductor has a separate ground return next to it.**
- Because each conductor has a separate ground return, common impedance coupling is eliminated, and the crosstalk between leads is minimized.
- This is the preferred configuration for a ribbon cable, even though it does require twice as many conductors as Fig A.
- In applications where crosstalk between cables is a problem, two grounds may be required between signal conductors.



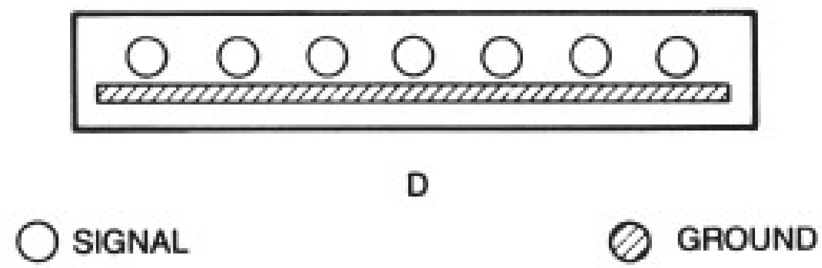
RIBBON CABLES

- A configuration that is only slightly inferior to Fig. B, and one that used 25% fewer conductors is shown in Fig. C.
- This configuration also has a ground conductor next to every signal conductor and therefore has small loop areas.
- Two signal conductors share one ground, so some common impedance coupling occurs, and the crosstalk is higher than in Fig. B because there is no ground between some of the adjacent signal conductors.
- This configuration may provide adequate performance in many applications and has the lowest cost-to-performance ratio.



RIBBON CABLES

- Ribbon cables are also available with a **ground plane across the full width** of the cable as shown in **Fig.D**.
- Here the loop areas are determined by the spacing between the signal conductor and the ground plane under it and since it is usually less than the lead-to-lead spacing in the cable, the loop areas are smaller than that of Fig. B.
- The ground current will flow under the signal conductor if the cable is terminated with a full-width electrical contact to the ground plane, which is difficult to do and so terminating this kind of cable properly is not easy often not used.
- Shielded ribbon cables are also available; however, unless the shield is properly terminated with a 360^0 connection (a difficult thing to do), their effectiveness is considerably reduced.
- Outside conductors in a shielded ribbon cable are not as well shielded as the conductors located closer to the center of the cable Therefore, critical signals should not be placed on the outside conductors of shielded ribbon cables.



SIGNAL GROUNDS

- A ground is often defined as an equipotential point or plane that serves as a **reference potential** for a circuit or system voltage definition of ground.
- Low-impedance path for current to return to the source current definition of a ground.
- Voltage is always **relative**, or with respect to something and Current, on the other hand, is **definitive**—the current always wants to return to the source.

Three basic objectives of signal grounding are as follows:

1. Not to interrupt the ground return path
2. Return the current through the smallest loop possible
3. Be aware of possible common impedance coupling in the ground

The impedance of any conductor can be written as

$$Z_g = R_g + j\omega L_g \qquad (3\text{-}1)$$

- Equation 3-1 clearly shows the effect that frequency has on ground impedance.
- At low frequency, the resistance Rg will be dominant.
- At high frequency, the inductance Lg will be the dominant impedance.

SIGNAL GROUNDS

- In designing a ground, it is important to know **the path taken by ground current.**
- Ground voltage, just like all other voltage, obeys Ohms law; therefore,

$$V_g = I_g Z_g \tag{3-2}$$

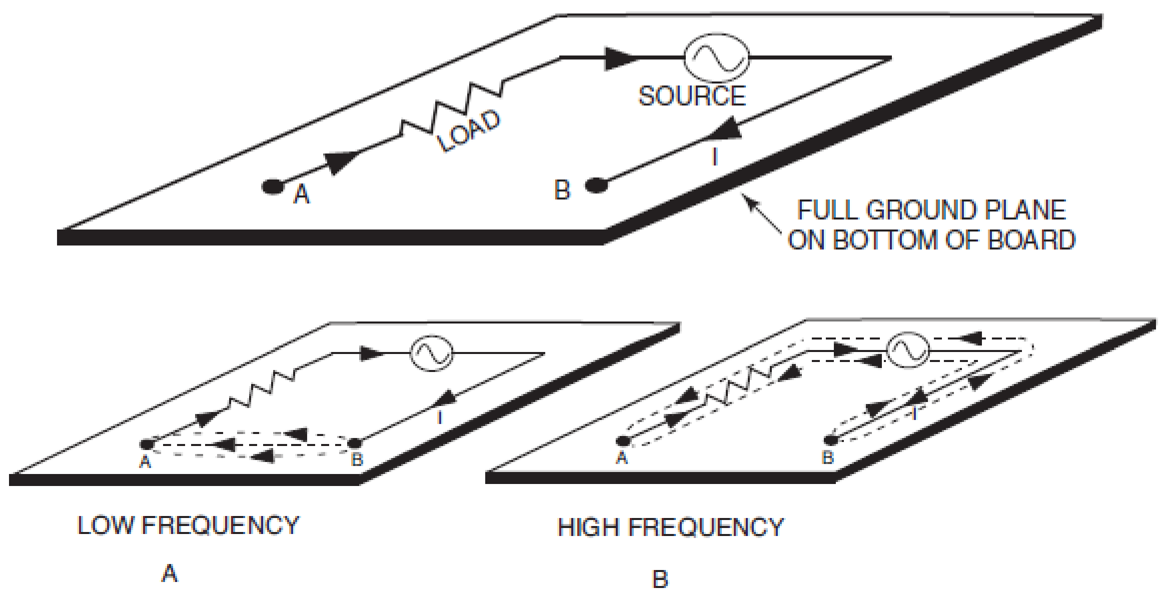
Equation 3-2 points out two ways to minimize the ground noise voltage Vg.

1. Minimize the ground impedance Zg
2. Decrease Ig by forcing the ground current to flow through a different path

- The **first approach** is commonly used at high frequency and with digital circuits, by using a ground plane or grid.
- The **latter approach** is commonly used with low-frequency analog circuits by using single-point grounding.
- With single-point grounding, we can direct the ground current to flow where we want it to flow.

SIGNAL GROUNDS

- Consider the case of the double-sided PCB as shown, which consists of a trace routed on the topside of the board and a solid ground plane on the bottom of the board.
- At points A and B, vias pass through the board connecting the topside trace to the ground plane to complete the current loop.
- The question is, exactly how does the current flow in the ground plane between points A and B?
- At low frequencies, the ground current will take the path of least resistance, which is directly between points A and B as shown in Fig. 3-12A.
- However, at high frequencies, the ground current takes the path of least inductance, which is directly under the trace as shown in Fig B, because this represents the smallest loop area. Therefore, the current return paths are different at low frequency and at high frequency.

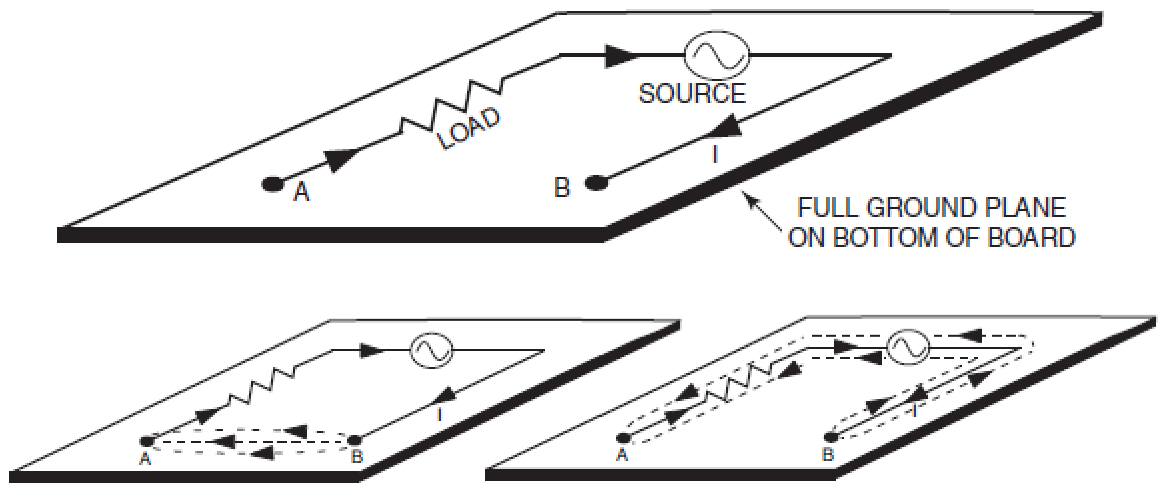


(A) at low frequency the return current takes the path of least resistance

(B), at high frequency the return current takes the path of least inductance.

SIGNAL GROUNDS

- Notice that for the low-frequency case (Fig. A), the current flows around a very large loop, which is undesirable.
- However in the high-frequency case (Fig.B), the current flows around a small loop.
- One can therefore conclude that **high frequency ground currents** do what we want them to (i.e., flow through a small loop), and as designers all we have to do is not to interrupt them or prevent them from flowing as they desire.
- **Low-frequency ground currents**, however, may or may not flow as we want them to (i.e., flow through a small loop), so we often must direct the current (or force the current) to flow where we want.
- It is important to therefore understand that no single ground system is proper for all applications.



LOW FREQUENCY

A

(A) at low frequency the return current takes the path of least resistance

HIGH FREQUENCY

B

(B), at high frequency the return current takes the path of least inductance.

SIGNAL GROUNDS

Signal grounds can be divided into the following three categories:

1. Single-point grounds
2. Multipoint grounds
3. Hybrid grounds

1. Single-Point Ground Systems

- Two subclasses of single-point grounds are as follows: those with series connections and those with parallel connections.
- The series connection is also called a common or daisy chain,
- The parallel connection is often called a separate or star ground system.

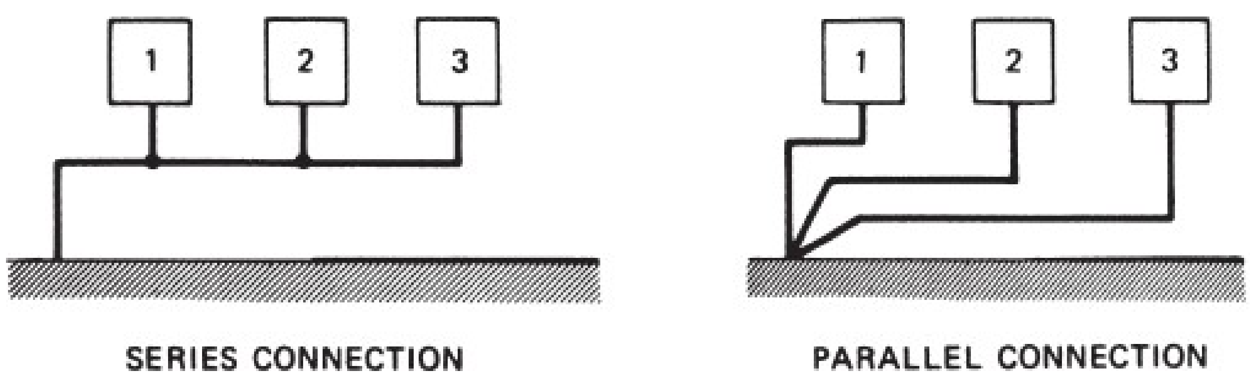


FIGURE 3-13. Two types of single-point grounding connections.

SIGNAL GROUNDS

1. Single-Point Ground Systems

- Single-point grounds are most effectively used at low frequency, from dc up to about 20 kHz.
- They should usually not be used above 100 kHz, although sometimes this limit can be pushed as high as 1 MHz.
- With single-point grounding, we control the ground topology to direct the ground current to flow where we want it to flow, which decreases Ig in the sensitive portions of the ground.
- From Eq. 3-2, we observe that decreasing Ig, decreases the voltage drop in that portion of the ground.
- The most undesirable single-point ground system is the common or daisy chain ground system.

$$V_g = I_g Z_g \qquad (3\text{-}2)$$

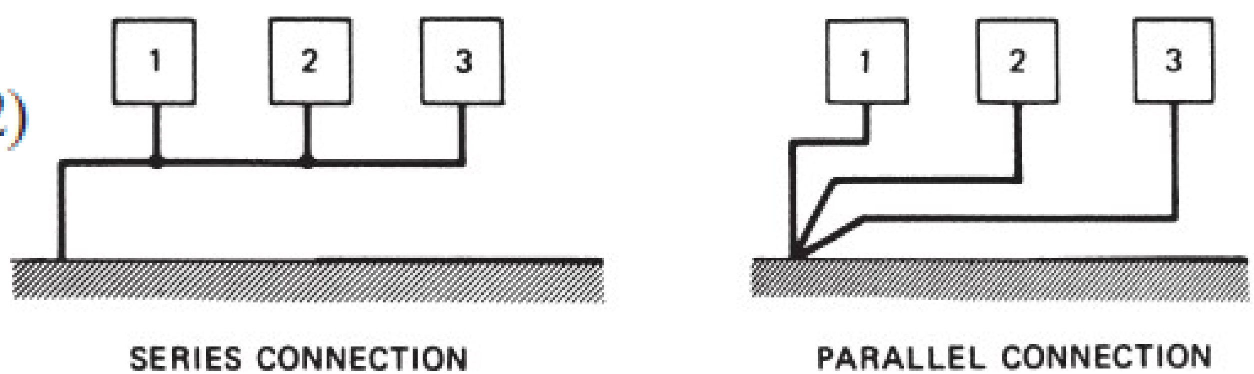


FIGURE 3-13. Two types of single-point grounding connections.

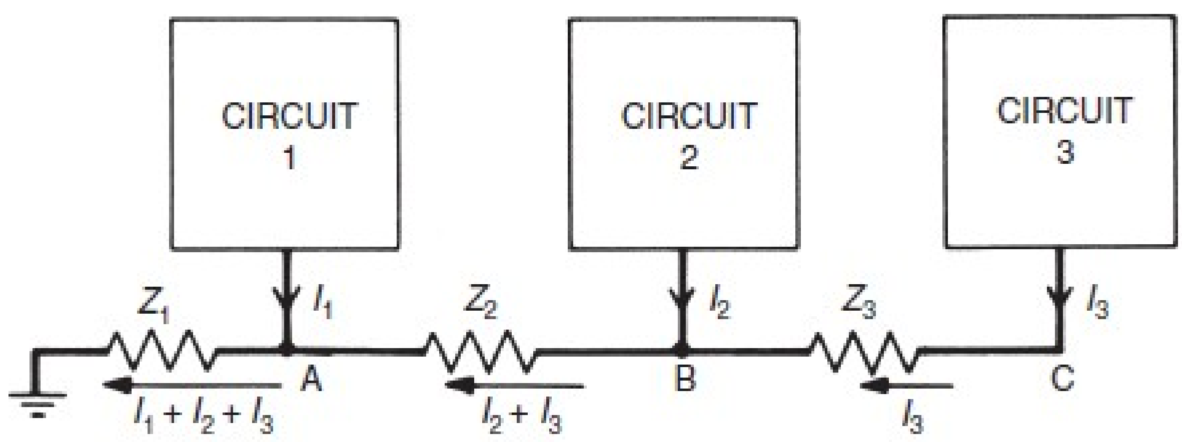
SIGNAL GROUNDS

1. Single-Point Ground Systems

- The system shown below is a series connection of all the individual circuit grounds.
- The impedances Z shown represent those of the ground conductors, and I1, I2, and I3 are the ground currents of circuits 1, 2, and 3, respectively.
- Point A is not a zero potential but is at a potential of $V_A = (I_1 + I_2 + I_3)Z_1$

and point C is at a potential of $V_C = (I_1 + I_2 + I_3)Z_1 + (I_2 + I_3)Z_2 + I_3Z_3$

- Although this circuit is the least desirable single-point grounding system, it is commonly used because of its simplicity.
- Note that point A is at a lower potential than points B or C.



SIGNAL GROUNDS

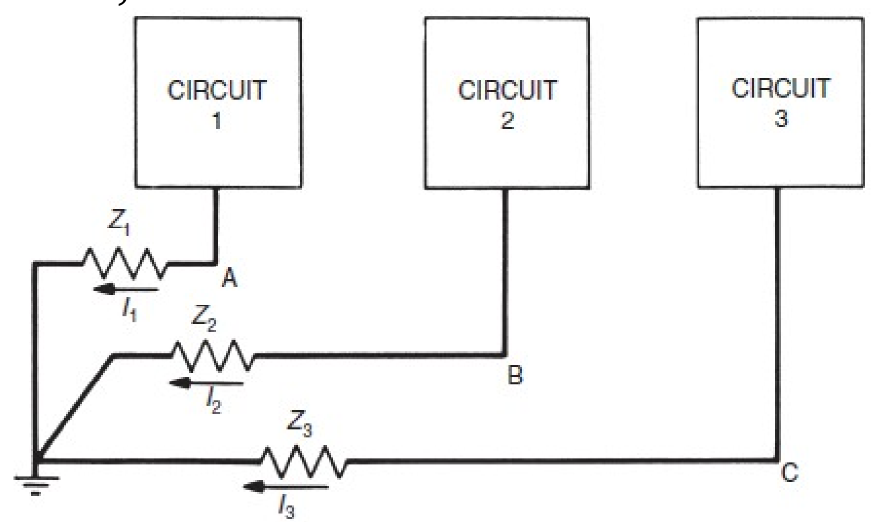
1. Single-Point Ground Systems

- The separate or parallel ground system shown in Fig. below is a more desirable single-point ground system.
- That is because no cross coupling occurs between ground currents from different circuits. The potentials at points A and C, for example, are as follows:

$$V_A = I_1 Z_1,$$

$$V_C = I_3 Z_3.$$

- The ground potential of a circuit is now a function of the ground current and impedance of that circuit only.
- This system can be mechanically cumbersome, however, because in a large system an unreasonable number of ground conductors may be necessary.
- Most practical single-point ground Systems are actually a combination of the series and parallel connection.



SIGNAL GROUNDS

1. Single-Point Ground Systems

- At high frequency, there is no such thing as a single-point ground.
- Figure 3-18 shows what happens when a single-point ground configuration is attempted at high frequencies.
- Because of their inductance, the ground conductors represent high impedances.
- However at high frequency, the impedance of the stray capacitance between the circuits and ground is low.
- The ground current therefore flows through the low impedance of the stray capacitance and not the high impedance that results from the inductance of the long ground conductors.
- The result is a multipoint ground at high frequency.

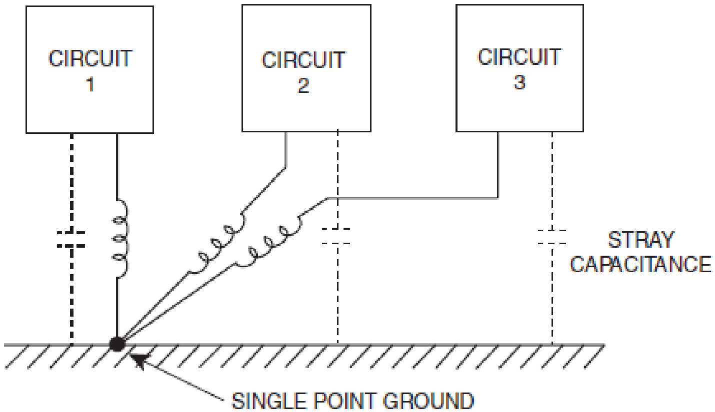
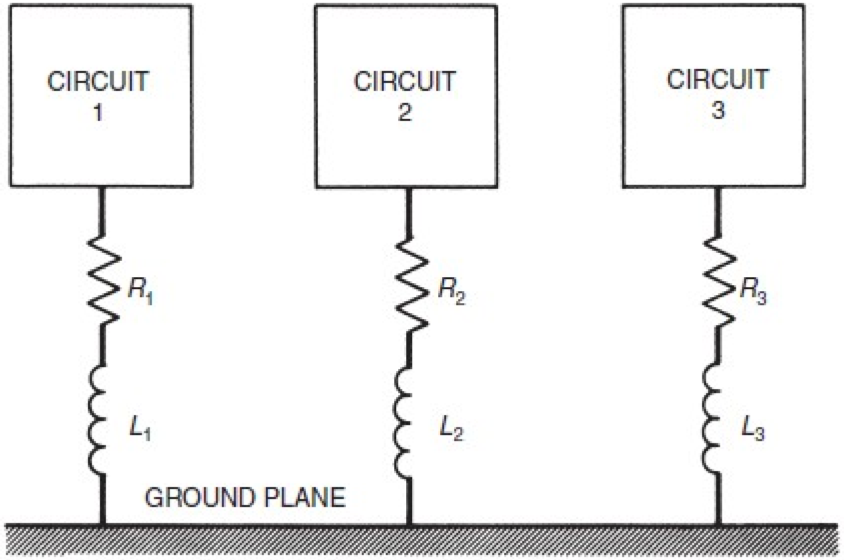


FIGURE 3-18. At high frequency, single-point grounds become multipoint grounds because of stray capacitance.

SIGNAL GROUNDS

2. Multipoint Ground Systems

- Multipoint grounds are used at high frequency (above 100 kHz) and in digital circuitry.
- Eq. 3-2 by minimizing the ground impedance Zg.
- From Eq. 3-1, we observe that at high frequency, this means minimizing the ground inductance, which can be done by the use of ground planes or grids.
- Where possible, use multiple connections between the circuits and the plane to reduce the inductance.
- In the multipoint system shown circuits are connected to the nearest available low-impedance ground plane.
- The connections between each circuit and the ground plane should be kept as short as possible to minimize their impedance.



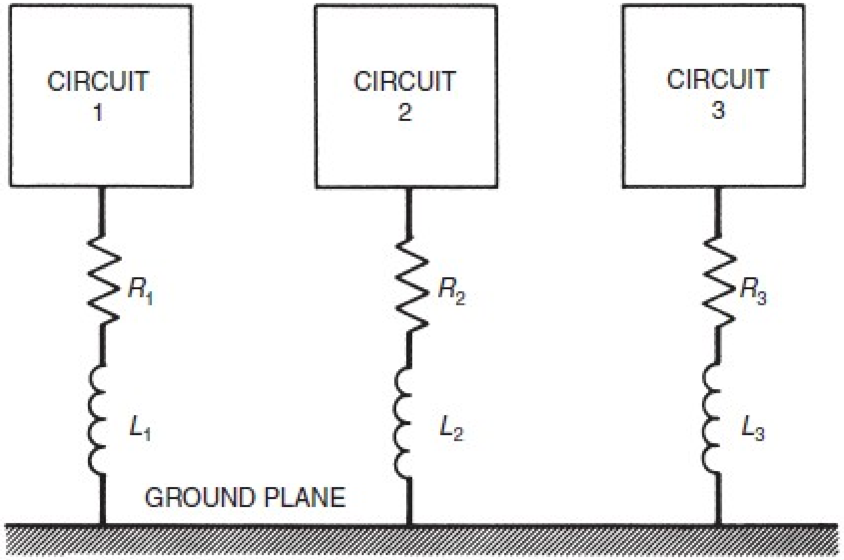
SIGNAL GROUNDS

2. Multipoint Ground Systems

- Increasing the thickness of the ground plane has no effect on its high frequency impedance because

1. It is the inductance not the resistance of the ground that determines its impedance and
2. High-frequency currents only flow on the surface of the plane because of the skin effect.

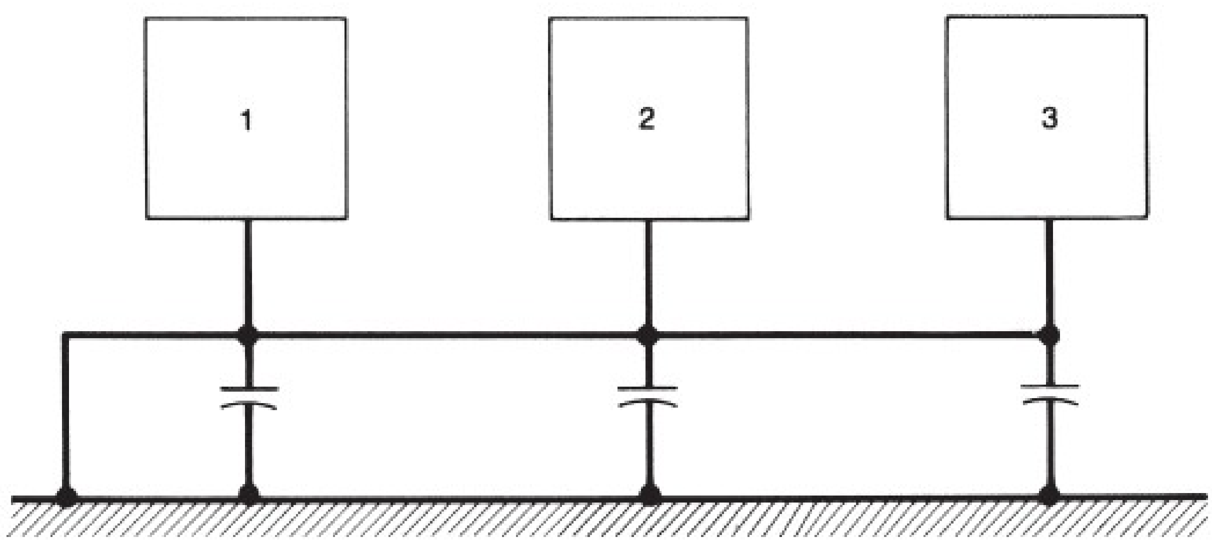
- A good low-inductance ground is necessary on any PCB that contains high frequency or digital logic circuits.
- The ground can be either a ground plane; or on a double-sided board, a ground grid.



SIGNAL GROUNDS

3. Hybrid Grounds

- When the signal frequency covers a wide range both above and below 100 kHz, a hybrid ground may be a solution.
- A video signal is a good example of this; the signal frequencies can range from 30 Hz to tens of megahertz.
- A hybrid ground is one in which the system-grounding configuration behaves differently at different frequencies.
- Figure shows a common type of hybrid ground system that acts as a single-point ground at low frequency and as a multipoint ground at high frequency.



SIGNAL GROUNDS

3. Hybrid Grounds

- A practical application of this principle is the cable-shielding configuration shown in Fig. 3-22.
- At low frequency, the capacitor C is a high impedance and the cable shield is single-point grounded at the load end only.
- At high frequency, the capacitor C is a low impedance and the cable shield is effectively grounded at both ends.

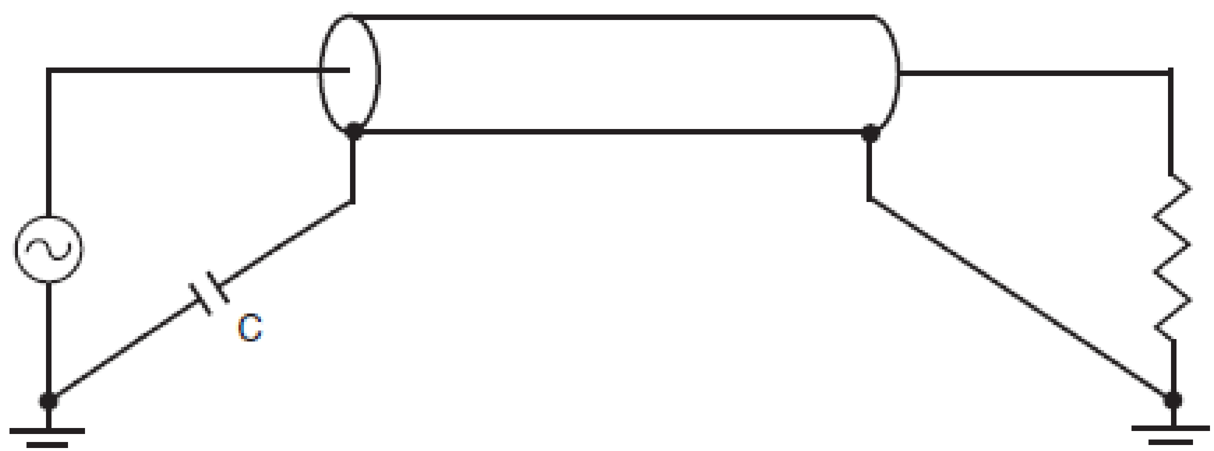


FIGURE 3-22. Example of a hybrid grounded cable shield.

SIGNAL GROUNDS

3. Hybrid Grounds

- This hybrid ground, although not very common, can be used when many equipment enclosures must be grounded to the power system ground, but it is desirable to have a single-point signal ground for the circuitry.
- The ground inductors provide a low-impedance safety ground at 50/60 Hz, and ground isolation at higher frequencies.
- Another application might be if the equipment is conducting a noise current out on the ground conductor, which causes the power cable to radiate, thereby failing regulatory electromagnetic compatibility (EMC) requirements.
- If the ground conductor is removed, the product passes EMC, but that is a safety violation.
- An inductor or choke (e.g., 10 to 25 mH) added in series with the ground wire will provide a low impedance at 50/60 Hz, while providing a high impedance at the much higher noise frequencies.

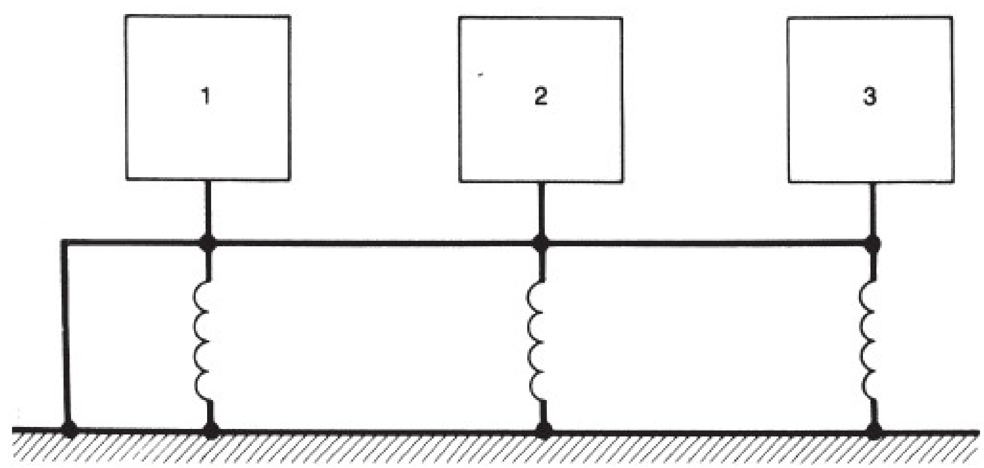


FIGURE 3-23. A hybrid ground connection that acts as a multipoint ground at low frequencies and a single-point ground at high frequencies.