Module 14:
Cabling
4.0 Introduction

In previous sections, it was seen that the amount and type of interaction that occurs between an electrical component/circuit and an EM field depends greatly on the electrical length of the component/circuit. As a result, cables can play an important role in the behavior of electrical systems.

- Cables tend to be the longest components in an electrical system.

- Cables may act as antennas, and as such may receive unwanted signals from distant sources, or may transmit unwanted signals to distant receivers.

- Cables may conduct unwanted signals into shielded enclosures.

In this section, the mechanisms by which coupling occurs between EM fields and cables, and between pairs of cables, will be discussed. In this section several assumptions are made:

1. Shields are made of non-magnetic materials
2. Coupling between the source and receptor is such that the behavior of the source is not affected.
3. Fields excited by currents which are induced in the receptor circuit do not disturb the original source field.
4. Cables are short compared to a wavelength.
Throughout this section, it must be remembered that because the cables are assumed to be short compared to a wavelength, equivalent circuit representations containing lumped elements can be used. This method of analysis breaks down when the cables are a significant portion of a wavelength long, however.

Three coupling mechanisms are considered:

1. Capacitive (electric) coupling - results from interaction between circuits and electric fields.

2. Inductive (magnetic) coupling - results from interaction between circuits and magnetic fields.

3. Electromagnetic coupling (radiation)

The distinction between coupling mechanisms is necessary because in the near field, often either the electric or magnetic field is dominant. In this case, coupling due to electric or magnetic fields is considered separately. In the far field both magnetic and electric fields dominate, and electromagnetic coupling is considered.

14.1 Capacitive coupling

Consider two conductors, C1 and C2 that are capacitively coupled:
Figure 1: Capacitively coupled conductors

\[ C_{12} = \text{Stray capacitance between conductors 1 and 2} \]
\[ C_{10} = \text{Capacitance between conductor 1 and ground} \]
\[ C_{20} = \text{Capacitance between conductor 2 and ground} \]
\[ R = \text{Resistance between conductor 2 and ground} \]

\( R \) is the resistance of circuitry associated with conductor 2, and \( C_{20} \) is the stray capacitance between conductor 2 and ground, and the capacitance associated with circuitry connected to conductor 2.

An equivalent circuit may be drawn:

Figure 2. Equivalent circuit for capacitively coupled conductors.
For this equivalent circuit:

\[ V_i = \text{source of interference} \]

\[ V_N = \text{noise voltage which exists between conductor 2 and ground.} \]

Stray capacitance \( C_{1o} \) has no effect on noise coupling and is therefore neglected. The noise voltage \( V_N \) is found from

\[ V_N = \frac{Z_1}{1 + j\omega C_{12}} \cdot V_i \]

where

\[ Z_1 = \frac{R}{1 + j\omega C_{2o} R} \]

Then

\[ V_N = \frac{R}{1 + j\omega C_{2o} R} \cdot \frac{1 + j\omega C_{12} R}{1 + j\omega C_{12} R} \cdot V_i = \frac{R}{1 + j\omega C_{2o} R + j\omega C_{12} R} \cdot V_i = \frac{j\omega R C_{12}}{1 + j\omega C_{2o} R + j\omega C_{12} R} \cdot V_i \]

or

\[ V_N = \frac{j\omega \left[ C_{12} / (C_{12} + C_{2o}) \right]}{j\omega + 1/R (C_{12} + C_{2o})} \cdot V_i \]

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For most practical cases, the assumption

\[ R \ll \frac{1}{j\omega (C_{12} + C_{20})} \]

can be made. This is done because under most conditions the impedance of the circuitry described by \( R \) is smaller than the sum of the impedances associated with \( C_{12} \) and \( C_{20} \). As a result

\[ V_{IN} = j\omega RC_{12} V_1 \]

It is seen that, for this model, the capacitively coupled noise voltage is proportional to the frequency of the noise source, the resistance of the circuitry associated with conductor 2, the noise source magnitude \( V_1 \) and the capacitance between conductors 1 and 2.

- In most instances, \( \omega, R, \) and \( V_1 \) cannot be changed. Thus in order to reduce \( V_{IN} \), \( C_{12} \) must be reduced.

- \( C_{12} \) may be changed by changing the orientation of conductor 2 with respect to conductor 1, by employing some type of shield, or by increasing the separation between conductor 1 and conductor 2.

If \( R \) is such that

\[ R \gg \frac{1}{j\omega (C_{12} + C_{20})} \]

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then
\[ U_N = \left( \frac{C_{12}}{C_{12} + C_{20}} \right) U_i \]

It is seen that in this case \( U_N \) is independent of frequency.

\[ v_N = j\omega R C_{12} U_i \]

\[ v_N = \frac{C_{12} U_i}{C_{12} + C_{20}} \]

\[ \omega = \frac{1}{R \left( C_{12} + C_{20} \right)} \]

![Graph showing the relationship between voltage and frequency with annotations](image)

Figure 3. Response of simplified equivalent circuit for capacitively coupled conductors.

- **Shielding to reduce capacitive coupling**

Consider the case where conductor 2 has an infinite resistance to ground, and a coaxial cylindrical shield is placed around the conductor:

![Diagram showing a coaxial shielded system with voltage sources](image)

Figure 4. Conductor 2 shielded

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The equivalent circuit for this is

![Circuit Diagram](image)

Figure 5. Equivalent circuit for shielded conductor.

Now let \( z_1 = \frac{1}{j \omega C_{10}} \) and let \( z_2 = \frac{1}{j \omega C_{50}} \). Using this it can be seen that the noise voltage induced on the shield is

\[
U_s = \frac{Z_2}{Z_1 + Z_2} U_i = \frac{1}{j \omega C_{50}} \cdot \frac{1}{j \omega C_{10}} U_i = \left( \frac{C_{10}}{C_{10} + C_{50}} \right) U_i
\]

and thus the voltage induced on conductor 2 is

\[
U_{N2} = U_s = \left( \frac{C_{10}}{C_{10} + C_{50}} \right) U_i
\]

If the shield is grounded, then \( U_s = 0 \) and the noise voltage induced on conductor 2 is likewise \( U_{N2} = 0 \).

The expressions above represent the case where the conductor 2 does not extend beyond the edges of the shield. If conductor 2 does extend beyond the edges of the shield, the equivalent circuit must be modified.

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Figure 6. Conductor 2 extends beyond shield.

\[ C_{12} = \text{capacitance between conductor 1 and conductor 2} \]
\[ C_{20} = \text{capacitance between conductor 2 and ground} \]

Here the value of \( C_{12} \) depends on the length of conductor 2 that extends beyond the shield. An equivalent circuit may be constructed.

Figure 7. Equivalent circuit for conductor 2 extending beyond shield.
In this case, even if the shield is grounded, a noise voltage is induced between conductor 2 and ground. With the shield grounded, $V_N$ is more easily determined from a simplified equivalent circuit shown below.

![Circuit Diagram]

Figure 8. Simplified equivalent circuit.

Let $\mathcal{E}_1 = \frac{1}{J\omega C_{12}}$ and $\mathcal{E}_2 = \frac{1}{J\omega(C_{25}+C_{26})}$ then

$$V_N = \frac{1}{J\omega(C_{25}+C_{26})} \frac{1}{\frac{1}{J\omega C_{12}} + \frac{1}{J\omega(C_{25}+C_{26})}} \mathcal{E}_1 = \frac{1}{\frac{1}{C_{12}} + \frac{1}{C_{25}+C_{26}}} \mathcal{E}_1$$

$$= \frac{1}{\frac{C_{25}+C_{26}}{C_{12}} + 1} \mathcal{E}_1$$

Therefore

$$V_N = \frac{C_{12}}{C_{25}+C_{26}+C_{12}} \mathcal{E}_1.$$
Therefore, for good electric field shielding:

1. The length that the center conductor extends beyond the shield must be minimized.
2. The shield must be well grounded.

A single ground connection is usually sufficient if the cable is less than \( \frac{\lambda}{20} \) long. Cables longer than this may require multiple grounds.

If the resistance \( R \) from conductor 2 to ground is finite, the equivalent circuit in Figure 7 becomes

![Equivalence circuit](image1)

Figure 9. Equivalent circuit for finite resistance for conductor 2 to ground.

Again, the behavior of the circuit is more easily determined from a simplified equivalent circuit.

![Simplified equivalent circuit](image2)

Figure 10. Simplified equivalent circuit.
The simplified equivalent circuit of Figure 10 is the as that of Figure 2 with \( C_{20} \) replaced by \( C_{20} + C_{28} \). As a result, if

\[
R \ll \frac{1}{j\omega (C_{12} + C_{20} + C_{28})}
\]

Then

\[
V_N = j\omega RC_{12} V_1
\]

This expression for the noise voltage is the same as for the unshielded conductor. In this case however, \( C_{12} \) is much smaller due to the presence of the shield. (because \( C_{12} \) is the capacitance that exists between the unshielded portion of conductor 2 and conductor 1).

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If a braided shield is used in place of a solid shield, capacitance existing from conductor 1 to conductor 2 through the holes in the shield must be modeled.

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14.2 Inductive coupling

As discussed in chapter 2, a current flowing in a conductor gives rise to a magnetic field. The magnetic flux \( \Phi \) associated with this magnetic field is related to the current by

\[
\Phi = LI
\]

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where the constant of proportionality $L$ is inductance. It was seen in chapter 2 and following chapters that inductance depends on the geometry of the circuit in which it flows, as well as the permeability of the medium in which the circuit is immersed.

It was also seen that a current flowing in one closed conducting circuit can induce a current in a second closed circuit. A mutual inductance exists between these circuits.

$$L_{12} = \frac{\Phi_{12}}{I_1}$$

where $\Phi_{12}$ is the magnetic flux supported by current $I_1$ in circuit 1, which penetrates the area enclosed by circuit 2.

Faraday's law states

$$\oint \mathbf{E} \cdot d\mathbf{l} = -\frac{d}{dt} \int \mathbf{n} \cdot \mathbf{B} d\mathbf{s}.$$  

For sinusoidal sources, this becomes

$$\oint \mathbf{E} \cdot d\mathbf{l} = -j\omega \int \mathbf{n} \cdot \mathbf{B} d\mathbf{s}.$$  

In a closed conducting loop $C$, Faraday's law indicates that a magnetic flux penetrating the area $A$ bounded by the contour $C$ gives rise to an electromotive force given by

$$\text{emf} = -\oint_c \mathbf{E} \cdot d\mathbf{l}.$$  

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This emf may manifest itself as a noise voltage

\[ v_n = -j \omega \int_{A}^{B} \hat{n} \cdot \hat{B} \, ds. \]

The noise voltage \( v_n \) may be expressed in terms of mutual inductance as

\[ v_{n1} = j\omega L_{12} i_1. \]

Consider the two magnetically coupled circuits shown below.

![Circuit Diagram](image)

Figure 11. magnetically coupled circuits

\[ i_1 \text{ = current in the interfering circuit} \]

\[ L_{12} \text{ = mutual inductance between circuits 1 and 2} \]

It is seen that the induced noise voltage \( v_n \) in circuit 2 may be reduced by reducing the frequency of operation \( \omega \), minimizing the area 'A' of circuit 2, or reducing the magnitude of the...
magnetic field $|\vec{B}|$. The magnetic field present near circuit 2 may be reduced by physically separating circuits 1 and 2, or by replacing the single-conductor/ground-plane configuration of circuit 1 with a pair of twisted wires (twisting causes the $\vec{B}$-fields of the wires to cancel).

As before, an equivalent circuit for the configuration shown in Figure 11 can be created.

![Figure 12. Equivalent circuit for magnetically coupled circuits.](image)

- **Shielding to reduce magnetic coupling**
  
  Consider the case where an ungrounded, non-magnetic shield is placed around conductor 2.

![Figure 13. Shielded conductor](image)
The equivalent circuit for this configuration is

![Circuit Diagram]

\[ U_1 = jωL_{12}i_1 \]

\[ U_2 = jωL_{15}i_1 \]

Figure 14. Equivalent circuit for magnetic shield.

If the shield is not grounded, it has no effect on the coupling that exists between circuit 1 and circuit 2. An open circuit voltage is induced across the shield however, given by

\[ U_3 = jωL_{15}i_1 \]

Grounding the shield at one end also does not affect the coupling between circuit 1 and circuit 2.

If the shield is grounded at both ends, a closed loop is formed. The magnetic flux due to the current \( i_1 \) in circuit 1 can couple to this closed loop, causing a current to flow. If the shield is properly oriented, the induced current flowing on the shield will give rise to a magnetic flux \( \Phi_S \) that is directed opposite to the flux \( \Phi_{12} \) over the area 'A' enclosed by circuit 2. This will have the effect of reducing the
induced noise voltage $V_n$. In order to determine the amount of this reduction, the interaction between the shield and conductor 2 must be determined.

- **magnetic coupling between shield and inner conductor**

  Consider a very long cylindrical conductor carrying an axially directed, uniformly distributed, time changing current.

  ![Diagram of a coaxial conductor with magnetic flux lines](image)

  **Figure 15.** Uniform current flowing on conducting cylinder.

  If the inner and outer surfaces of the conductor are concentric, then no magnetic field will exist in the region $0 < r < r_i$ (not easy to show this, but true).

  Now let a long, thin cylindrical conductor exist, coaxial with the cylindrical shield conductor.

  ![Diagram of a coaxial conductor/shield configuration](image)

  **Figure 16.** Coaxial conductor/shield configuration.
All of the magnetic flux supported by the current is flowing on the shield encircles the center conductor. The self-inductance of the shield is

\[ L_S = \frac{\Phi}{I_S} \]

The mutual inductance which exists between the shield and the center conductor is

\[ L_{sc} = \frac{\Phi}{I_S} \]

Thus the inductance \( L_{sc} \) between the shield and the center conductor is the same as \( L_S \), the self-inductance of the shield.

\[ L_{sc} = L_S \]

A noise voltage \( V_{nsc} \) induced on the center conductor can be determined. Consider the circuit depicted below.

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**Figure 17.** Equivalent circuit for coupling between shield and center conductor.
The noise voltage induced in the center conductor is given by

\[ V_{NSC} = j \omega L \xi_s. \]

The current flowing on the shield is

\[ I_s = \frac{V_s}{j \omega L_s + R_s} = \frac{V_s}{L_s} \left( \frac{1}{j \omega + R_s/L_s} \right) \]

therefore

\[ V_{NSC} = \left( \frac{j \omega L_s V_s}{L_s} \right) \left( \frac{1}{j \omega + R_s/L_s} \right). \]

Because \( L_s = L_{SC} \)

\[ V_{NSC} = \left( \frac{j \omega}{j \omega + R_s/L_s} \right) V_s. \]

A plot of this is shown below.

![Plot showing noise voltage induced on center conductor by shield current](image)

Figure 18. Noise voltage induced on center conductor by shield current.
The break frequency associated with this plot is known as the shield cut-off frequency

$$\omega_c = \frac{R_s}{L_s}.$$ 

The voltage induced on the center conductor $U_{sc}$ is zero when $\omega=0$ (dc) and increases to nearly $U_3$ at

$$\omega \approx \frac{5R_s}{L_s}.$$ 

**Magnetic coupling from open wire to shielded conductor**

Consider again the case of a non-magnetic shield placed around conductor 2. If the shield is grounded at both ends, the following magnetically coupled circuits result.

Figure 19. Coupling between source, shield and receptor circuits.
The current $i_1$ flowing in the source circuit gives rise to a magnetic flux which penetrates the areas bounded by the receptor circuit, and the closed shield circuit (because the shield is grounded at both ends). This induces noise voltages $U_2$ in the receptor circuit, and $U_S$ in the shield circuit. The induced voltage $U_S$ causes a current $i_S$ to flow in the shield circuit. This current $i_S$ gives rise to a magnetic flux which induces a second voltage $U_C$ in the receptor circuit. Careful application of Faraday’s law (not done here) reveals that the polarity of $U_C$ is opposite that of $U_2$, therefore the total noise voltage induced in circuit 2 is

$$U_N = U_2 - U_C$$

Because $L_{1S}$ (the mutual inductance between the source circuit and the shield) is equal to $L_{12}$ (the mutual inductance between the source and receptor circuits), the induced...
noise voltage in the receptor circuit is found to be

\[ U_N = jwL_{12}i_2 \left[ \frac{R_s/L_s}{jw + R_s/L_s} \right] \]

- If \( w \) is small, then \( \frac{R_s/L_s}{jw + R_s/L_s} \approx 1 \) and

\[ U_N \approx jwL_{12}i_2 \]

which is the same as for an unshielded receptor circuit.

- If \( w \) is large, then

\[ U_N \approx L_{12}i_2 \left( \frac{R_s}{L_s} \right) \]

Figure 20. Induced noise voltage for shielded and unshielded conductor.
It is seen that at low frequency, the noise voltage induced in the shielded receptor circuit is the same as that which would be induced in an unshielded circuit. At frequencies above the shield cutoff frequency the induced noise voltage in the receptor circuit stops increasing and remains constant. The shielding effectiveness is the difference between the curves for shielded and unshielded conductors.

The equivalent circuit for the source/shield/receptor system is shown below.

![Equivalent circuit](image)

Figure 21. Equivalent circuit for source/shield/receptor system.

14.3 **Shielding to prevent magnetic radiation**

Electric and magnetic fields surround a current-carrying conductor.

![Fields surrounding a conductor](image)

Figure 22. Fields surrounding a conductor.
One method of preventing interference is to shield the source of interference.

- A shield placed around the conductor and grounded at one point will cause electric field lines to terminate on the shield, providing good electric field shielding. Such a shield will have little effect on magnetic fields.

![Diagram](image1)

Figure 23. Effect of shield grounded at one point.

- If a current flows on the shield which is equal in magnitude to the conductor, but oppositely directed, it gives rise to a magnetic field which cancels the magnetic field supported by the current on the center conductor in the region outside the shield.

![Diagram](image2)

Figure 24. Current-carrying shield.
Consider a circuit grounded at both ends, carrying a current $i_1$, with a coaxial shield.

![Coaxial shield diagram]

Figure 25. Shielded circuit

To prevent magnetic field radiation, the shield must be grounded at both ends, and the return current must flow from A to B in the shield, instead of on the ground plane.

The equivalent circuit for the configuration of Figure 25 is shown below.

![Equivalent circuit diagram]

Figure 26. Equivalent circuit
The mesh equation around the loop \( A-R_s-L_s-B-A \) gives

\[ 0 = i_s(j\omega L_s+R_s) - i_1(j\omega L_1) \]

but \( L_s = L_1 \), then

\[ L_s = i_1 \left( \frac{j\omega}{j\omega+R_s/L_s} \right) = i_1 \left( \frac{j\omega}{j\omega+\omega_c} \right) . \]

From this it is seen that if \( \omega \gg \omega_c \), then \( i_s \approx i_1 \).

- Thus the shield provides a low inductance return path (and thus good magnetic shielding) when the frequency of operation is high.

- At low frequency (below the shield cut-off frequency \( \omega_c \)) the cable provides less magnetic shielding and more current returns via the ground plane.

Thus magnetic radiation from the conductor in Figure 25 can be reduced if the coaxial shield is grounded at both ends. The reduction occurs because the return current on the shield supports a field that cancels the field of the center conductor.

14.4 Shielding a receptor against magnetic fields

Magnetic coupling at a receptor circuit can be
reduced by decreasing the area enclosed by the receptor circuit. The area enclosed by the circuit depends greatly on the return path taken by the current in the circuit. Often the current returns via an unintended path. A non magnetic shield placed around a conductor provides magnetic shielding if it cuts to reduce circuit loop area.

Figure 27. Effect of shield on loop area.

- A shield grounded at both ends loses effectiveness at low frequency.

- At high frequency, a coaxial cable actually consists of three isolated conductors; the center conductor, the inner surface of the shield cut, the outer surface of the shield. The inner and outer surfaces of the shield are isolated because of skin effect.
14.5 Braided shields and twisted pairs

- Twisted pairs used below 100kHz (although in some applications frequency may reach 10MHz). Above 1MHz losses in twisted pairs increase considerably.

- Coaxial cable has a more uniform characteristic impedance than twisted pairs, and lower loss. Coaxial cable is useful from DC to VHF frequencies, with some applications extending to UHF. Above a few hundred megahertz losses in coaxial cable become large.

- Unshielded twisted pairs provide little protection against capacitive coupling, but are good against magnetic coupling. Shielded twisted pairs provide protection from low frequency magnetic coupling.

- Most cables are actually shielded with braid rather than a solid outer conductor.

- Advantages of braid are flexibility, durability, strength and long flex life.

- Braided shields typically provide only 60-98% coverage of the inner conductor, and are thus less effective than solid shields.
- Braided shields provide slightly reduced electric field shielding, but greatly reduced magnetic field shielding. (typically 5-30dB less effective than a solid shield for magnetic field protection).

- Braided shield begins to lose effectiveness when holes become large compared to a wavelength.

14.6 Shield Terminations

The shielding techniques discussed in this section require that a uniformly distributed current exists on the shield. Magnetic shielding effectiveness depends greatly on how the shield is terminated.

- A pigtail connection causes shield current to be concentrated on one side of the shield.

Figure 28. Pigtail termination of braided shield.
For maximum effectiveness, shields should be terminated uniformly across the conductor cross section.

- For maximum effectiveness, shields should be terminated uniformly across the conductor cross section.

![Diagram of a termination](image)

Figure 29. Improved termination for banded shield.

- A pigtail termination that is only a small fraction of the total shield length can significantly degrade shielding effectiveness.

- Maximum shield effectiveness is achieved only if the shield is properly terminated. This requires:
  1. Low impedance ground connection
  2. 360° (or nearly that) contact between shield and ground.

14.6 Ribbon cables

A major expense of cables is the cost of fabricating the cable termination.

- Ribbon cables allow low-cost multiple terminations.
- The positions of wires within a ribbon cable are fixed, thus noise characteristics are relatively uniform from cable to cable.

- A ribbon cable with one ground wire and many signal wires has large loop areas between signal and ground paths, which may result in radiation and susceptibility. Also, crosstalk may occur between signal wires.

Figure 30. Ribbon cable with one ground wire

- Loop areas can be reduced by providing a separate ground return for each signal wire. This also minimizes crosstalk.

Figure 31. Ribbon cable with multiple ground wires.
- Ribbon cables may also provide a ground plane across the width of the ribbon.

![Diagram of ribbon cable with ground plane and signal wires]

Figure 32. Ribbon cable with ground plane

This is only effective if a proper termination is provided for the ground plane.

References