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DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

UNIT – II
EMI COUPLING PRINCIPLES

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SUBJECT CODE   : **EC8072**

SUBJECT NAME   : **ELECTROMAGNETIC INTERFERNCE & COMPATIBILITY**

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UNIT II
EMI COUPLING MECHANISM

2-1 ELECTROMAGNETIC FIELD SOURCES AND COUPLING PATHS

Coupling Path Classifications:

1) *Conductive coupling* - a conductive path exists between the emitter and the receptor (power cords, ground returns, interface cables, cases, etc.)

2) *Radiative coupling* - no conductive path exists between the emitter and the receptor (electromagnetic coupling), the receptor lies in the far-field of the emitter, the emitter "radiation field" decays as $1/R$ where R is the separation distance between the emitter and the receptor.

3) *Inductive (magnetic) coupling* - no conductive path exists between the emitter and the receptor (electromagnetic coupling), the receptor lies in the near-field of the emitter where the magnetic field is dominant, the proximity of the emitter and receptor leads to "mutual coupling" (the emitter radiation is affected by the presence of the receptor).

4) *Capacitive (electric) coupling* - no conductive path exists between the emitter and the receptor (electromagnetic coupling), the receptor lies in the near- field of the emitter where the electric field is dominant, the proximity of the emitter and receptor leads to "mutual coupling" (the emitter radiation is affected by the presence of the receptor).

2-1-1 Radiation Coupling

The Radiation coupling between an emitter and a receptor results from a transfer of electromagnetic energy through a radiation path. Various types of radiation coupling are,

- Coupling of natural and similar electromagnetic environment to the receptor, such as a power line. The power transmission line here acts as a receiving antenna. A receptor may also receive electromagnetic environmental noise or interference through exposed connectors (or connections) and from exposed signal or other lines in the equipment or circuit.

- Coupling of electromagnetic energy from nearby equipment via direct radiation.

Radiated coupling results when electromagnetic energy is emitted from a source, propagates to the far-field, and induces voltages and currents in another circuit. Unlike common impedance coupling, no conducted path is required. Unlike electric and magnetic field coupling, the victim circuit is not in the electromagnetic near field of the source. Radiated coupling is the only possible coupling mechanism when the source and victim circuits (including all connected conductors) are separated by many wavelengths.

2-1-2 Conduction Coupling

The conduction coupling between an emitter and a receptor occurs via a direct conduction path between the emitter and receptor. Examples of such coupling are:

- Interferences can be carried by power supply lines when emitter and receptor operate from the same power supply line. For example, common mains power supply is a frequent source of conducted interference.

- Interferences are also carried from emitter to receptor by signal or control lines, which are connected between the two.

2-1-3 Combination of Radiation & Conduction

A combined result of the above two basic interference coupling mechanisms, radiation and conduction, is a most common source of electromagnetic energy coupling. Examples for interference coupling are

- Coupling of electric and magnetic fields in cable harnesses and multi conductor transmission lines and so forth.

- Radiation from an emitter picked up by the power supply lines and/or signal lines connected to other equipment (this interference enters the receptor as a conducted interference on these power and signal lines).

- Radiation from power transmission lines (especially strong transients or surges) and from signal or control cables coupling into the power or signal cables connected to other equipment.

The interference coupling in cable harnesses, multi conductor transmission lines and c1osely spaced wires on printed circuit boards is a result of the inductive coupling or capacitive coupling of electromagnetic energy. The inductive

coupling between two loops (current carrying conductors) is predominant in low series impedance circuits and at lower frequencies.
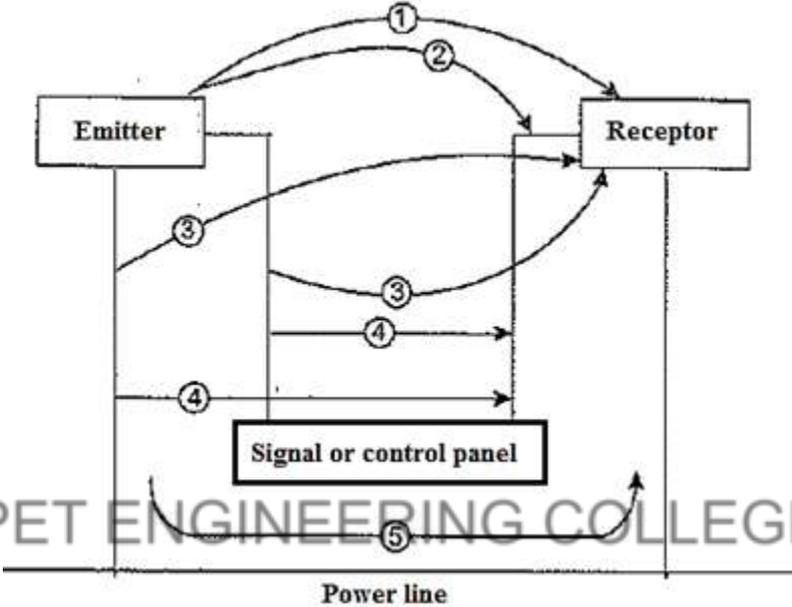

Figure: 2-1 Electromagnetic coupling between emitter and receptor

The capacitive transfer of interference occurs in the presence of high impedance to ground, and is more predominant at higher frequencies; Apart from a reactive transfer of interference, a resistive transfer may also take place through voltage drop in common ground path between two equipment. The voltage drops across common ground impedance caused by a current flow in one circuit acts as an interference signal source to the second circuit. The interference current so generated is conducted along the line and presents itself at the load terminals of the neighboring circuit.

EMI COUPLING MECHANISM

Radiation of electromagnetic energy can occur when cables or signal transmission lines are poorly shielded. Radiation may also occur from exposed wires carrying signals, especially in printed circuit boards, and at exposed solder joints. In a transmission line connected to a source at one end, and terminated in an arbitrary load at the other end, there are three main components of the electromagnetic energy. These are

1) Axial wave transferring signal power from its source to the load.

2) A radial component supplying line losses.

3) A radiated wave which represents losses into the surrounding space.

The first component also readily offers a path for conducted interferences. The last path, which facilitates radiation coupling, is more significant at high frequencies when the separation between transmission lines is comparable to the wavelength. Radiation coupling is also a significant factor in digital circuits where sub microsecond and sub-nanosecond pulses are involved. In case of steady state excitation with a waveform represented by a harmonic function, the strength of interfering signals received via radiation depends on the ratio of a distance between the conductors to the line length. In case of an excitation of a line by a pulse, the radiation coupling depends on the ratio of the distance between conductors to the pulse duration

2-2 COUPLING VIA THE SUPPLY NETWORK

Power-line coupling, in which either radiated EMI picked up by power lines or transients directly generated on the

power lines couple to the victim's power cable and from there to victim circuits.

Low voltage (up to 1000V) electric power supply lines in several countries are three-wire lines. The three wires are the line (or phase), neutral, and safety ground conductors. The distance between the equipment/apparatus connected to the power supply line, and the actual location of electrical earth is small. In this situation, common-mode surges, and interference, would be smaller than the differential-mode interferences.

In power distribution systems with two-wire lines, the bond between neutral and earth is located remotely, or far away, from the service entrance to the building. In this case, the common-mode interferences would predominate over the differential-mode interferences.

2-2-1 Transients on Power Supply Lines

Electrical transients and other disturbances are induced in the power supply lines as a result of natural electromagnetic phenomena, and from the operation of a variety of equipment. The most common natural phenomena of lightning can induce transients on overhead power supply lines either by a direct strike, or by way of induction from a strike on a nearby structure. Machine operations such as local load switching, switching-off or switching-on of heavy electrical equipment, motor control activation, arc welders, and industrial cranes can induce substantial electrical transients in the power supply lines.

Transients can appear on the AC power line as a transient voltage difference between the phase and neutral

conductors, between the line and ground conductors, or between the neutral and ground conductors. A digital oscilloscope with a pair of voltage probes can be used to measure the voltage V_{PG} between the phase and ground conductors, and the voltage V_{NG} between the neutral and ground conductors. When the probe detects a transient, the oscilloscope is triggered and the data are sent to a computer for storage and processing.

2-2-2 Propagation of Surges in Low-Voltage AC Lines

In the transmission line behavior, a distinction has to be made between two concepts: surge impedance of the transmission line, and impedance of the line to the surge. The first is the classical transmission line parameter, also called "characteristic impedance" $Z_0 = \sqrt{L/C}$ and applies for long lines and short pulses. It is independent of the line length and frequency. The second, impedance to the surge, is indeed dependent on the line length, and is the impedance of the complex (real and imaginary) network of distributed parameters, R, L, and C, of the wiring configuration. This impedance is also dependent on the frequency, so that rigorous analysis would involve computation over the frequency spectrum of the impulse of interest. For practical applications, it would be more convenient, to define the impedance of a line to the surge as the ratio of voltage to current Consider the following points for evaluating surge protection schemes:

a) Surge propagation in wiring systems should be considered as a case of classical transmission lines only if the lines are long enough to contain the surge front.

b) For typical voltage or current surges produced by lightning or switching, the surge impedance (characteristic impedance $Z_0 = \sqrt{L/C}$) is not the significant parameter. Rigorous analysis requires considering the frequency spectrum of the impulse and the line impedance at the significant frequencies of that spectrum.

c) Isolating power transformers are intended to serve as ground isolators, or ground-loop breaks. They do not provide appreciable attenuation of line-to-line transients unless they are operating with their series reactance combined with a well-defined shunt load on the secondary

d) Ferro-resonant line conditioners can provide attenuation of fast line-to-line transients with ratios of 100:1 or higher. Adding a small fixed load on the output side can raise this attenuation to 150:1, or more.

e) The connection options for surge suppressors must be matched to the protection requirements for optimum protection at minimum cost. Universally applicable solutions always tend to be more expensive.

f) Careful design is required for impulse generators. Improvisation can lead to meaningless results and wasted time.

g) In testing for surge protection evaluation, the timing of the surge with respect to the power line frequency can be significant.

h) The pure and sanitary test waves specified by test standards are intended to obtain reproducible results

rather than to duplicate surges occurring in reality. Complex wiring system (within a building or within equipment) will promptly transform the pure wave form into a distorted form, but that does not prevent consistent results, since an agreement exists on the initial test wave.

2-3 INDUCTIVE AND CAPACITIVE COUPLING

2-3-1 Inductive Coupling

Inductive (magnetic) coupling - no conductive path exists between the emitter and the receptor (electromagnetic coupling), the receptor lies in the near-field of the emitter where the magnetic field is dominant, the proximity of the emitter and receptor leads to "mutual coupling" (the emitter radiation is affected by the presence of the receptor).

When current flows in a circuit terminated with a load, it produces a magnetic flux proportional to the current. This magnetic flux may induce noise voltage (VN) into an adjacent channel, generating a loop current in the disturbed circuit. This type of coupling is one of the most common. The geometry of the conductors, as well as the geometric range between two lines in space, determines the value of L_{mutual} and, consequently, the intensity of the inductive coupling. Another important factor is the environment that contains the lines. For example, metallic raceway or cable tray can help attenuate or propagate unwanted signals beyond the initial source of interference.

In order to reduce the effect of inductive coupling between circuits, it is important to maintain cable geometry along the entire channel length and to keep adequate separation

between circuits. The intensity of the magnetic field is directly proportionate to the current present in the disturbing channel (i.e., power line) and inversely proportionate to the distance between the lines (i.e., power lines and telecommunications lines).
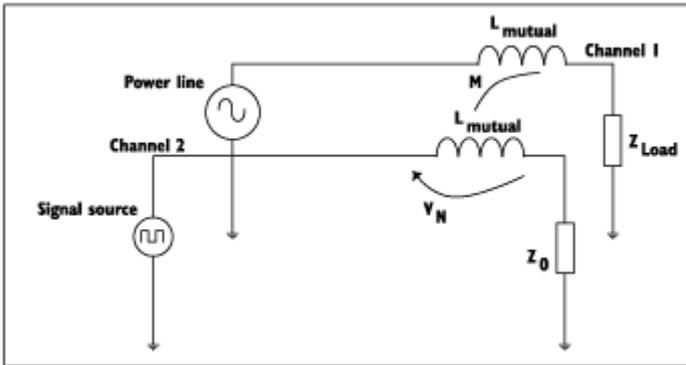

Figure 2-2 Inductive coupling between a power line and a telecommunications channel

A time varying external current $i_1(t)$ generates a magnetic field B(t), which induces a disturbing voltage $u_{dist}(t)$ in a neighboring circuit. In an equivalent circuit model this may be described by a coupling of both circuits via a coupling inductance M. The voltage $u_{dist}(t)$ generates a common mode current $i_2(t)$, which itself generates a magnetic field to weaken the external field. The current $i_2(t)$ is superimposed on the currents of the disturbed system and may lead to malfunctions of the system. The coupling of magnetic fields of the different systems can be modeled by an equivalent circuit model by mutual inductances of the coupled circuits.
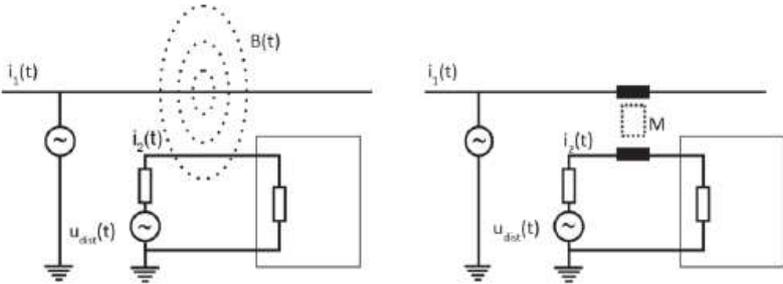
Figure 2-3 Inductive coupling, Field model (left) and Equivalent circuit (right).

The strength of the coupling depends mainly on three parameters:

- The magnitude of the disturbing current

- The distance between source and drain

- The frequency of the disturbing field

The disturbing signal becomes large and significant if:

- The currents of the external circuits are large

- The currents of a go-and-return line are unbalance.

- The circuits are close together and cover a large area.

- The signals of the external circuit vary rapidly in time and therefore have large high-frequency content.

Inductive coupling, however, may also be useful in controlling disturbance. If the installation of cable trays and coaxial cables is done properly, (i.e. they are reliably connected with short connections with low impedance, also at high frequencies) they provide shielding of the cables (via inductive coupling) against external magnetic fields, especially at higher frequencies.

2-3-2 Capacitive Coupling

Capacitive (electric) coupling - no conductive path exists between the emitter and the receptor (electromagnetic coupling), the receptor lies in the near- field of the emitter where the electric field is dominant, the proximity of the emitter and receptor leads to "mutual coupling" (the emitter radiation is affected by the presence of the receptor).

Capacitive coupling is represented in Figure 2-4 as a simplified, discrete model of distributed coupling. Capacitive coupling occurs between power and tele-communications cables carried in parallel for some extent in a given installation.
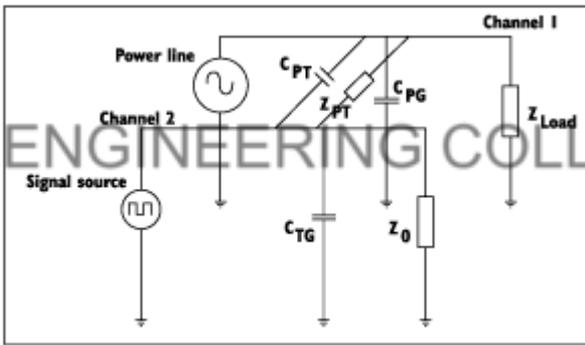
Figure 2-4 Capacitive coupling between a power line and a telecommunications channel

The capacitance between the two lines, referred to in Figure 2-4 as C_{PT}(Power line to Telecommunications line capacitance), is caused by coupling between these two circuits. The value of this capacitance will vary with the distance between circuits - higher for short distances and lower for large distances. To reduce the voltage noise level due to the

capacitive coupling between channels, either the capacitance C_{PT} can be decreased (decreasing the capacitive coupling) or the impedances Z_{PT} and Z_0 can be increased. In instances where it is not possible to change these parameters, screened cabling can be employed to shield the channel from the disturbing circuit, thereby reducing the value of C_{PT}.

The time varying electrical field of an external system produces time varying charges in the disturbed system. The flow of the displacement currents can be modeled in an equivalent circuit by stray capacitances, which connect the two systems and cause the disturbing voltages.
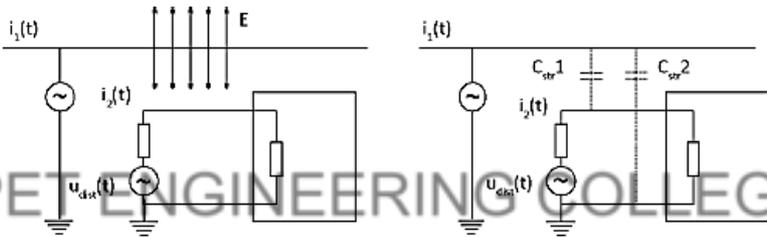
Figure 2-5 Capacitive coupling a) field model, b) equivalent circuit.

Similar to the case of the inductive coupling, the capacitive coupling becomes large if:

- The two circuits are close together

- The voltage difference of the two circuits is large

- The signals in the external circuit vary rapidly in time and therefore possess large high frequency content

2-4 COMMON-MODE AND DIFFERENTIAL MODE COUPLING

Noise is classified into two types according to the conduction mode.

Common-mode and ground-loop coupling, in which radiated fields couple into ground loops that convert interference to undesired common- mode currents, and to differential- mode currents (the failure mechanism.) common mode noise which is conducted on all lines in the same direction.

Differential-mode coupling, in which radiated fields penetrate signal and control cables to develop interfering voltages at the victim. Differential mode noise which is conducted on the signal (VCC) line and GND line in the opposite direction to each other. This type of noise is suppressed by installing a filter on the hot (VCC) side on the signal line or power supply line.

The electromagnetic disturbances carried by electrical power supply lines are classified into two categories, common-mode currents/voltages and differential-mode (or normal mode) currents/voltages. The common-mode (CM) interferences are defined as the unwanted electrical potential differences between any (or all) current-carrying conductor(s) and the reference ground. The differential-mode (DM) interferences are defined as the unwanted potential differences between any two current-carrying conductors. Thus with reference to the three conductor lines shown in Figure 2-6(a),
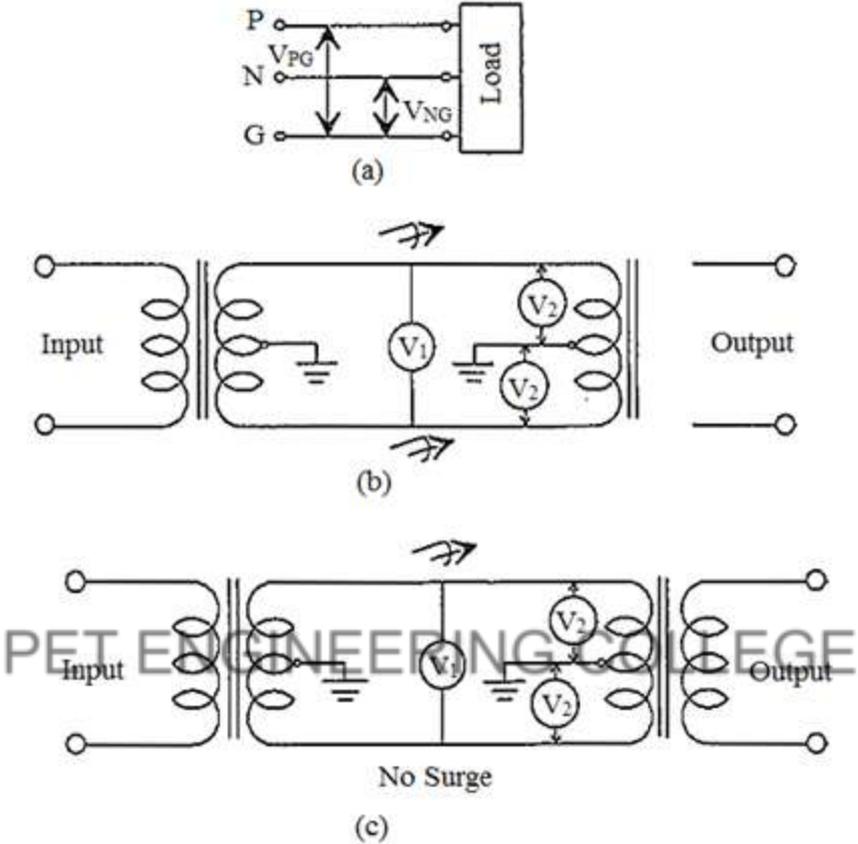
Figure 2-6 Common and differential mode interferences

The common-mode voltage V_c and the differential-mode voltage V_d are given by

$$V_c = (V_{PG} + V_{NG})/2 \qquad (2.11a)$$

$$V_d = (V_{PG} - V_{NG})/2 \qquad (2.11b)$$

Where V_{PG} and V_{NG} are the voltages between phase and ground wires, and neutral and ground wires, respectively. In terms of

currents, the CM interference current exits from the source via the phase and neutral conductors, and returns from the load via the ground conductor. The DM interference current exits from the source via the phase conductor and returns from the load via the neutral conductor, or vice-versa.

Figure 2-6(b) shows a balanced circuit. The sender and the receiver transformer windings have a grounded center tap. No metallic conductor is used to connect the two grounded terminals. If an interference voltage is simultaneously coupled to the two conductors, the voltmeter V_1 will not read a voltage difference, whereas the voltmeter V_2 will. This is common-mode interference.
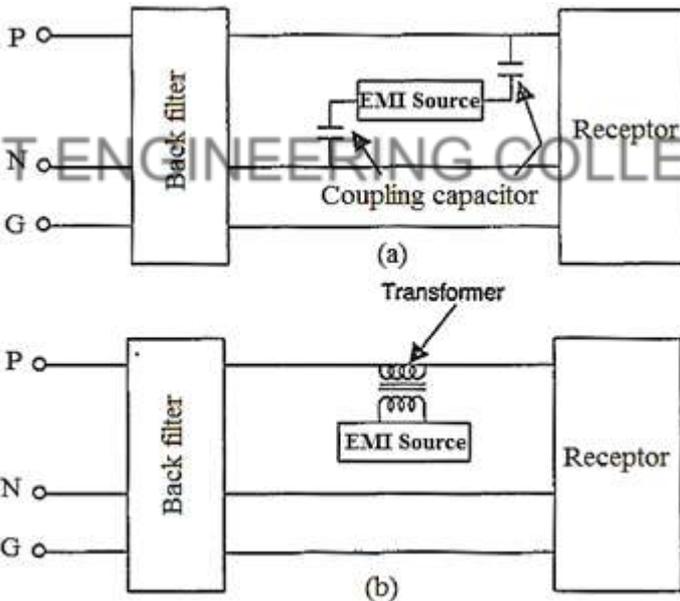
Figure 2-7 Examples of coupling conducted EMI (a) Common mode (b) Differential mode

On the other hand, if the interference voltage is coupled to only one of the lines as shown in Figure 2-6(c), then both voltmeters V_1 and V_2 will read a voltage difference. This is the differential-mode interference.

The conducted EMI can be injected into the lines to simulate either common-mode disturbances or differential-mode disturbances. Some example circuits that enable the injection of conducted EMI into the circuit are shown in Figure 2-7. A back filter prevents the injected EMI from reaching the mains supply, or any apparatus other than the receptor.
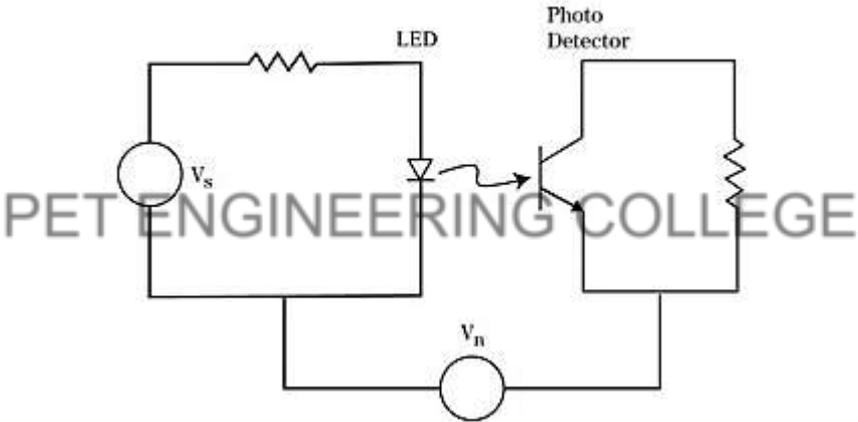
Figure:2-8 Use of optical isolation to combat common-mode impedance.

Common-mode radiated EMI effects resulting from emissions that are radiated or picked up by a ground loop may be reduced by the application of one or more of the following techniques:

- Minimize the common-mode ground loop area by routing interconnecting wires or cable close to the ground.

- Reduce the common-mode ground loop currents by floating circuits or equipments; using optical isolators; or inserting common-mode filters, chokes, or isolation transformers.

- Use balanced circuits or balanced drivers and receivers.

2-5 IMPEDANCE COUPLING

Galvanic coupling or Impedance coupling occurs when different circuits use common lines and/or coupling impedances. This may happen, for example, when different circuits use the same voltage source in their circuit. The underlying principle of the impedance coupling can be readily seen in Figure 2-9.
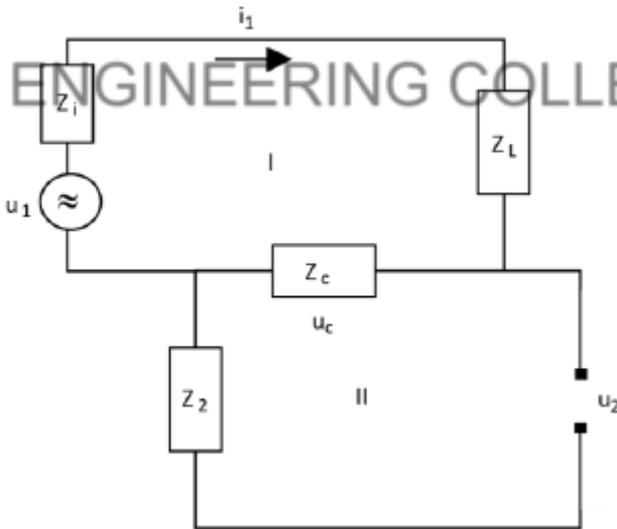

Figure 2-9 Impedance coupling

Circuit I may be part of a power supply network and circuit II part of a data transfer network. The voltage which is superimposed on the signal, u_2, due to the common coupling impedance, $Z_c = R_c + jwL_c$, is given by:

$$u_c = Z_c i_1 \approx (u/(Z_i + Z_L)) * Z_c$$

where $Z_c \ll Z_i + Z_L$

If the current i_1 and/or the coupling impedance Z_c are large enough, the superimposed voltage u_k may be large enough compared to the signal u_2 to disturb the data circuit.

The impedance of the shared line consists of resistive and inductive components, $Z_c(w) = R_c + jwL_c$. While the resistive part of the coupling remains of the same importance for all frequencies (neglecting skin effect), the inductive part becomes of increasing importance at high frequencies.

For the purposes of illustration, let us assume that the ground or return of subsystem 2 is attached to the ground of subsystem 1 as shown in figure 2-10 , and both subsystems subsequently share the same return thereafter. The return current I_2 for subsystem 2 combines with that of subsystem 1, and both pass through the common ground impedance Z_{G1}, developing a voltage drop across that part of the return of $Z_{G1}(I_1 + I_2)$. Observe that the signal fluctuations that are unique to subsystem 2 are contained in I_2, and are therefore included in the voltage drop $Z_{G1}I_2$. Thus the ground point of subsystem 1 is varying at a rate that is proportional to the signals in subsystem 2. Therefore, the signals in subsystem 2 will couple to subsystem 1 by virtue of this nonzero impedance of the ground and the sharing of the ground return by both signals. Similarly, the voltage of the ground point for subsystem 2 is $Z_{G1}I_1 + (Z_{G1} + Z_{G2})I_2$. Thus the ground point for subsystem 2

has the signals of subsystem 1 imposed on it through Z_{G1}. This is often referred to as common-impedance coupling.
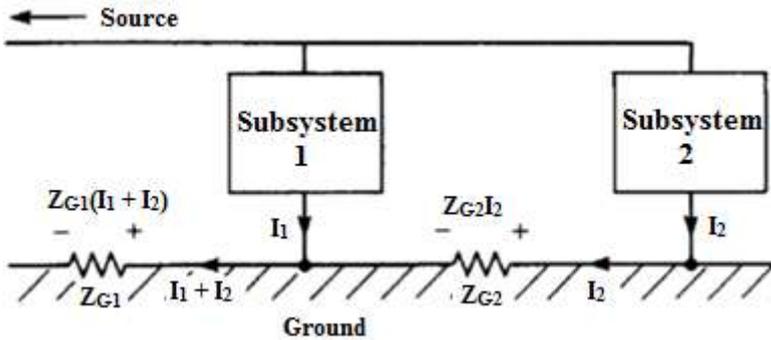

FIGURE 2-10 Illustration of common-impedance coupling

In order to minimize this common-impedance coupling, the ground system in digital subsystems tends to be multipoint, using a large ground plane such as in inner plane board or placing numerous alternate ground paths in parallel such as with a ground grid, thus reducing the impedance of the return path. It is also important to route the signal conductors in close proximity to the ground returns, since this will also reduce the impedance of the return.

2-6 GROUND LOOP COUPLING

2-6-1 Common Ground-impedance

Common-impedance coupling, in which two or more units or systems are connected to the same safety wire, ground grid or plane at more than one place (multipoint grounding.)

Common impedance coupling (also called conducted coupling) may occur anytime a source circuit and a victim circuit share part of their respective current paths.
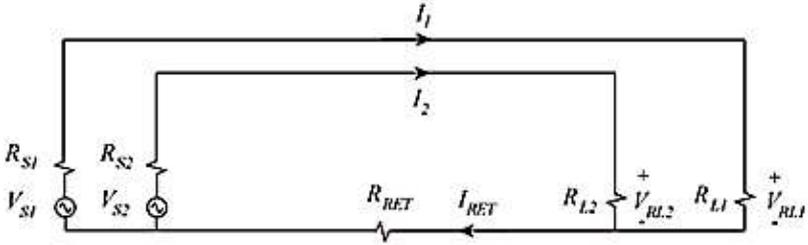
Figure: 2-11 Two circuits sharing a common signal return

Consider the two simple circuits shown in Figure 2-11. Each circuit has its own source, signal wire and load, but they both share a wire for the signal return current. If the shared wire had zero impedance, the voltage across each circuit's load resistor would depend only on that circuit's source voltage. However, a small amount of impedance in the shared wire causes a voltage to appear across R_{L2} when there is a signal in Circuit 1 and vice versa.

This phenomenon is called *crosstalk* and is generally defined as,

Crosstalk in dB

$$= 20 \log \left| \frac{coupled\ voltage\ appearing\ at\ receiver\ in\ Circuit\ 2}{signal\ voltage\ in\ Circuit\ 1} \right| (2.1)$$

or in this case,

$$X_{talk_{21}} = 20 \log \left| \frac{V_{RL2}}{V_{RL1}} \right|_{when\ V_{S1}=0} \qquad (2.2)$$

To calculate the crosstalk in Circuit 2 due to the signals in Circuit 1, we set $V_{S2} = 0$ and determine the ratio V_{RL2}/V_{RL1}. Applying Kirchhoff's voltage law (KVL) to the Circuit 2 current loop, we have,

$$V_{S2} + I_2 R_{S2} + I_2 R_{L2} + (I_1 + I_2) R_{RET} = 0 \qquad (2.3)$$

Setting $V_{S2} = 0$, we can express I_2 in terms of I_1,

Setting $V_{S2} = 0$, we can express I_2 in terms of I_1,

$$I_2 = \frac{-R_{RET}}{R_{S2} + R_{L2} + R_{RET}} I_1 \qquad (2.4)$$

Noting that $I_1 = V_{RL1}/R_{L1}$ and $I_2 = V_{RL2}/R_{L2}$, we can express the voltages across the load resistances as,

$$\frac{V_{RL2}}{R_{L2}} = \frac{-R_{RET}}{R_{S2} + R_{L2} + R_{RET}} \frac{V_{RL1}}{R_{L1}} \qquad (2.5)$$

The crosstalk can now be expressed as,

$$20 \log \left| \frac{V_{RL2}}{R_{L2}} \right| = 20 \log \left| \frac{-R_{RET}}{R_{S2} + R_{L2} + R_{RET}} \frac{V_{RL1}}{R_{L1}} \right| \qquad (2.6)$$

Generally, for practical common impedance coupling situations, the impedance of the common return path will be much less than the load impedances of either circuit. Otherwise, the return path would severely attenuate the signals. In most cases, it is much quicker to estimate the voltage dropped across the signal return path as,

$$V_{RET} = I_{signal} R_{RET} \qquad (2.7)$$

In the case above, I_{signal} was I_1, the intentional current. Once we have estimated V_{RET}, we can use KVL to determine what fraction of this voltage appears across the victim circuit's load resistance. In this case,

$$V_{RL2} \approx \frac{R_{L2}}{R_{L2} + R_{S2}} V_{RET}$$

$$\approx \frac{R_{L2}}{R_{L2} + R_{S2}} R_{RET} I_1$$

$$\approx \frac{R_{L2}}{R_{L2} + R_{S2}} R_{RET} \frac{V_{RL1}}{R_{L1}} \qquad (2.8) \text{ and}$$

the crosstalk is,

$$X_{talk_{21}} \approx 20 \log \left[\frac{R_{RET}}{R_{L2} + R_{S2}} \left(\frac{R_{L2}}{R_{L1}} \right) \right] \quad (2.9)$$

This approach generally yields very good estimates of the crosstalk and is much simpler to apply to complex configurations with many possible signal return paths.

Ground-related interference often involves one of two basic coupling mechanisms. The first mechanism results from the fact that the signal circuits of electronic equipment share the ground with other circuits or equipment. This mechanism is called common-ground impedance coupling. Any shared impedance can provide a mechanism for interference coupling. Figure 2-12 illustrates the mechanism by which interference is coupled between culprit and victim circuits via the common-ground impedance. In this case, the interference current, I, flowing through the common-ground impedance, Z, will produce an interfering signal voltage, V_c, in the victim circuit. It should be emphasized that the interference current flowing in the common impedance may be either a current that is related to the normal operation of the culprit circuit or an intermittent current that occurs due to abnormal events (lightning, power faults, load changes, power line transients, etc.).
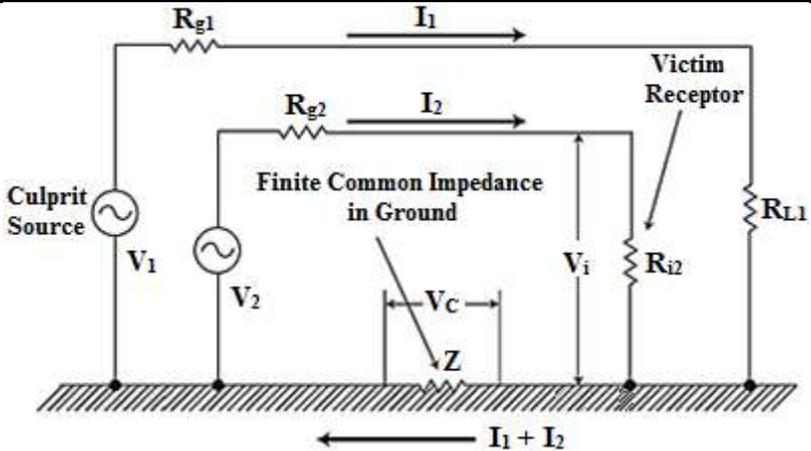
Figure 2-12 Common-mode impedance coupling between circuits

Common-impedance coupling becomes a problem when two or more circuits share a common ground and one or more of the following conditions exist.

- A high-impedance ground (at high frequency: too much inductance; at low frequency: too much resistance)

- A large ground current

- A very sensitive, low-noise margin circuit, connected to ground.

Two or more devices are interconnected by the power supply and communication cables. When external currents (lightning, fault currents, disturbances) flow via these common-mode impedances, an undesirable voltage appears. This stray voltage can disturb low-level or fast electronic circuits. All cables, including the protective conductors, have impedance, particularly at high frequencies.
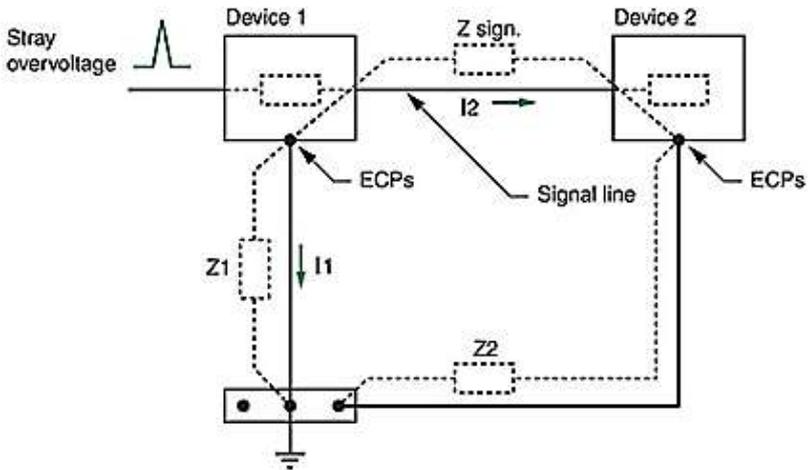
Figure 2-13 common-mode impedance coupling

The exposed conductive parts (ECP) of devices 1 and 2 are connected to a common earthing terminal via connections with impedances Z_1 and Z_2.

The stray overvoltage flows to the earth via Z_1. The potential of device 1 increases to Z_1I_1. The difference in potential with device 2 (initial potential $= 0$) results in the appearance of current I_2.

$$Z_1 * I_1 = (Z_{sign} + Z_2)I_2 \quad \rightarrow \quad \frac{I_2}{I_1} = \frac{Z_1}{(Z_{sign}+Z_2)}(2.10)$$

Current I_2, present on the signal line, disturbs device 2.

At high frequency, the impedance of the stray capacitance between the circuits and ground is low. The ground current flows through the capacitance. The result is a multipoint ground at high frequency.
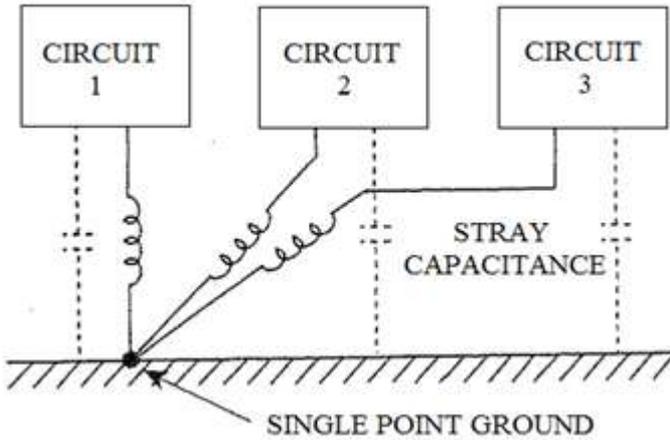
Figure 2-14 single point grounding

To reduce the effects of common-ground impedances, it is necessary to:

- Reduce impedance

- Mesh the common references

- Use short cables or flat braids which, for equal sizes, have a lower impedance than round cables

- Install functional equi-potential bonding between devices.

- Reduce the level of the disturbing currents by adding common-mode filtering and differential-mode inductors
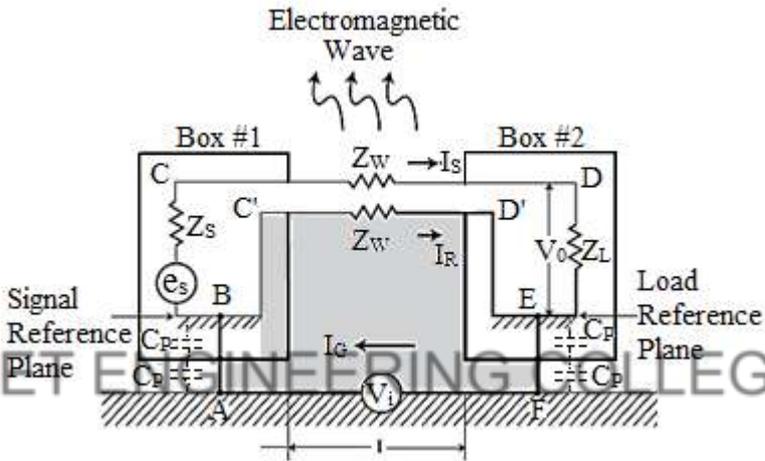
2-6-2 Ground Loops
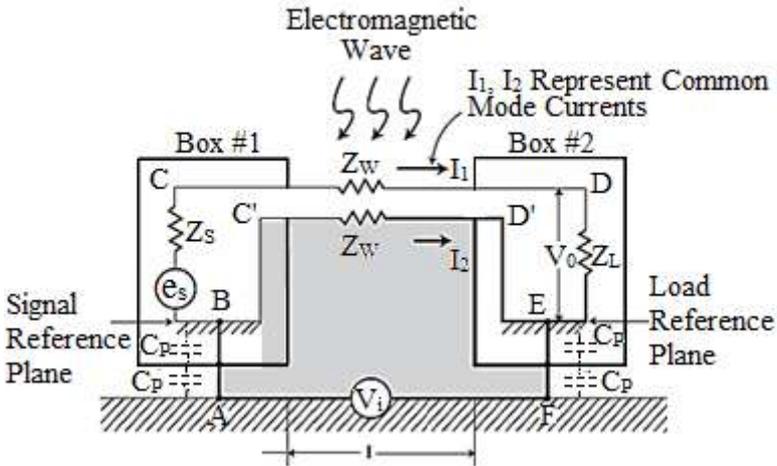
(a)Susceptibility Case

The EMI coupling mechanism via ground is a radiation mechanism as shown in Figure 2-15(a) whereby the ground loop, acts as a receiving or transmitting antenna. For this EMI coupling mechanism, the characteristics of the ground (resistance or impedance) do not play an important role, because the induced EMI voltage (for the susceptibility case) or the emitted EMI field (for the emission case) is mainly a function of the EMI driving function (field strength, voltage, or current), the geometry and dimensions of the ground loop, and the frequency of the EMI signal.

It should be noted that both the conducted and radiated EMI coupling mechanisms identified involve a "ground loop." However, it should be recognized that ground loop EMI problems can exist without a physical connection to ground. In particular, at RF frequencies, distributed capacitance to ground

can create a ground loop condition even though circuits or equipment's are floated with respect to ground. Also, it should be noted that, for both of the EMI coupling mechanisms involving the ground loop, the EMI currents in the signal lead and the return are flowing in the same direction. This EMI condition (where the currents in the signal lead and the return are in phase) is referred to as common-mode EMI.

(b)Emission Case

Figure 2-15 Common-mode radiation into and from ground loops

Ground loops exist in a system when there is multiple current return paths or multiple connections to earth ground. Current flowing in a ground loop generates a noise voltage in the circuit. The most obvious way to eliminate the loop is to break the connection between the transducer and ground or between the receiver and ground. When this is not possible, isolation of the two circuits is a universal way to break the loop. Isolation prevents ground loop currents from flowing and rejects ground voltage differences.

EMI COUPLING MECHANISM

The EMI control techniques that will be effective for ground loop problems are

i. Reduce the coupling of EMI into the ground loop or provide suppression of the common- mode EMI that is coupled into the ground loop.

ii. Use filters or ferrites in ground loops to limit common-mode currents or provide a common-mode voltage drop.

iii. Use a common-mode choke or a common mode isolation transformer to suppress ground-loop EMI. These devices may provide on the order of 60dB

iv. Use optical isolators and/or fiber optics to block common-mode EMI effects Optical isolators provide a high degree of common-mode rejection at frequencies up to and including the HF band (i.e., 3 to 30MHz).

v. Use balanced circuits to minimize effects of common-mode EMI in the ground loop. With a perfectly balanced circuit, the currents flowing in the two parts of the circuit will produce equal and opposite voltages across the load, so the resulting voltage across the load is zero. Balanced circuits can provide significant (greater than 20dB) common-mode reduction for low-frequency conditions. However, at higher frequencies (above 30MHz), other effects start to predominate, and the effectiveness of balanced circuits diminishes.

2-7 CABLE RELATED EMISSION AND COUPLING

Cable-to-cable coupling occurs when two wires or cables are run close to each other. The below figure shows how cable-to cable coupling works. Figure 2-16 shows two lengths of cable (or other conductors) that are running side-by-side.
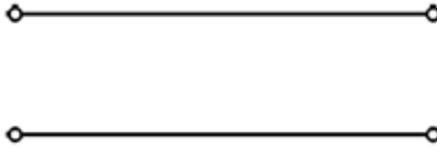
Figure 2-16 Parallel Conductors

Because any two conducting bodies have capacitance between them, called stray capacitance, a time-varying signal in one wire can couple via that capacitance into the other wire. That is referred to as capacitive coupling. This stray capacitance, as shown in Figure 2-17 makes the two cables behave as if there were a coupling capacitor between them.
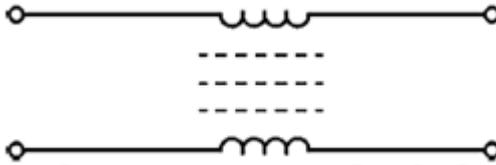

Figure 2-17 Capacitive Coupling

Another mechanism of cable-to-cable coupling is mutual inductance. Any wire carrying a time-varying current will develop a magnetic field around it. If a second conductor is placed near enough to that wire, that magnetic field will induce a similar current in the second conductor. That type of coupling is called inductive coupling. Mutual inductance, as shown in Figure 2-18, makes the cables behave as if a poorly wound transformer were connected between them.

In cable-to-cable coupling, either or both of those mechanisms may be responsible for the existence of an

interference condition. Though there is no physical connection between the two cables, the properties we have just described make it possible for the signal on one cable to be coupled to the other. These effects, when combined are known as the make it possible for the signal on one cable to be coupled to the other. These effects, when combined are known as the transmission line the basic transmission line equations are derived for distributed parameters R (series resistance), G (shunt conductance), L (series inductance), and C (shunt capacitance), all defined per unit length of line.

Figure 2-18 Inductive Coupling

Either or both of the above-mentioned properties cause the cables to be electromagnetically coupled such that a time varying signal present on one will cause a portion of that signal to appear on the other. The "efficiency" of the coupling increases with frequency and inversely with the distance between the two cables. One example of cable-to-cable coupling is telephone "crosstalk", in which several phone conversations can be overheard at once. The term crosstalk is now commonly used to describe all types of cable-to-cable coupling.

2-7-1 Cross-Talk in Transmission Lines

Coupling of electromagnetic energy from one cable to another in multi conductor transmission lines results from magnetic field coupling when the two cables are located close to each other. Magnetic field coupling results from the flux linkage caused by the current flow in one wire and an equivalent loop area formed by another wire and its return path. Both the above linkages account for inductive coupling.

Coupling of electromagnetic energy between wires may also occur through an electric field coupling between wires within a cable harness. This coupling is a result of a capacitive reactance between the wires. Electromagnetic energy transfer or coupling from one transmission line to another due to the above phenomenon is called cross-talk. This is a most common source of electromagnetic interference generation in electrical and electronics circuit.

For an (n+1) conductor line, the zero-th conductor is treated as the reference ground conductor with zero potential and the n conductors have voltages $V_i(Z)$ an ground conductor with zero potential and currents $I_i(Z)$ for values of i= 1,2, ... n.

Under steady state conditions (after transients have subsided), the transmission line equations may be written as follows

$$\begin{bmatrix} V1(Z) \\ V2(Z) \\ \cdot \\ \cdot \\ \cdot \\ Vn(Z) \end{bmatrix} = -j\omega[L] \begin{bmatrix} I1(Z) \\ I2(Z) \\ \cdot \\ \cdot \\ \cdot \\ In(Z) \end{bmatrix} \& \begin{bmatrix} I1(Z) \\ I2(Z) \\ \cdot \\ \cdot \\ \cdot \\ In(Z) \end{bmatrix} = -j\omega[C] \begin{bmatrix} V1(Z) \\ V2(Z) \\ \cdot \\ \cdot \\ \cdot \\ Vn(Z) \end{bmatrix} \quad (2.12)$$

EMI COUPLING MECHANISM

where [L] and [C] are the inductance and capacitance matrices of the multi conductor line. These matrices are symmetric because of reciprocity. They satisfy the condition:

$$[L][C] = \mu \in [U] \tag{2.13}$$

where [U] is the unit matrix, and μ and $\in$ are the permeability and permittivity of the medium.

For electrically short lines (length << wavelength)) the expression for the currents at the o/p terminals are obtained as

$$I_i(l) = Aj\omega L_{ij}\hat{I}_1 + Bj\omega C_{ij}V_1 \tag{2.14}$$

The first term in is the inductive coupling contribution to $I_i(l)$ caused by mutual inductance $L_{ij} = L_{ji}$ between the two circuits. The second term represents the capacitive coupling contribution to $V_i(l)$ resulting from mutual capacitance $C_{ij} = C_{ji}$ between the two circuits.
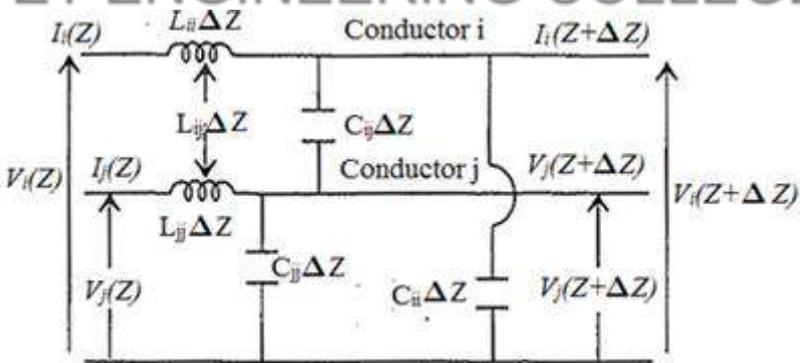

Figure 2-19 Equivalent circuit representation of coupled lines

The above expression can be utilized for estimating the cross-talk between any pair of lines *i* and *j*, and also the total

signal coupled to a particular line as a result of the excitation in all other terminals.

2-7-2 Analysis of Cable to Cable Coupling

Electric field coupling occurs when energy is coupled from one cable to another through an electric field. This is most likely to happen when the impedance of the source circuit is high.

Consider the two circuits sharing a common return plane shown in Figure 2-20. If the return plane had zero resistance, the common impedance coupling would be zero. However, it is also possible for coupling to occur between the two circuits due to the electric field lines that start on one signal wire and terminate on the other. For example, if one of the signal voltages is +1volt and the other is zero volts, then the potential difference between the two signal wires results in electric field lines that start on the +1volt wire and terminate on the zero-volt wire. Schematically, this can be represented by a capacitor between the two signal wires.
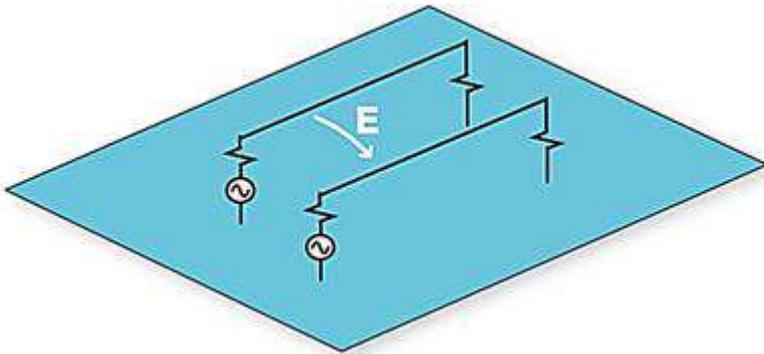

Figure 2-20 Two circuits above a signal return plane

Of course, there are other electric field lines that start on the +1volt wire and terminate on the zero-volt plane. This can be represented by a capacitance between the wire and the plane. A schematic representation of the two circuits in Figure 2-120 that includes the electric field coupling capacitances is shown Figure 2-21.
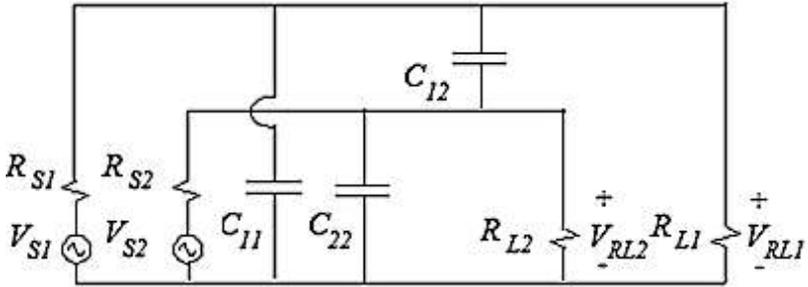

Figure 2-21 Schematic representation of the circuits in Figure2-13 including capacitive coupling paths.

In this case, the capacitance between the wires, C_{12}, is readily calculated using the formula for the capacitance between two wires and the capacitances C_{11} and C_{22} can be calculated using the formula for the capacitance of a wire above a ground plane. Once the capacitances have been determined, and values have been assigned to all the elements in Figure 2-14, the crosstalk due to electric field coupling can be calculated using the same basic formula used for common impedance coupling,

$$X_{talk_{21}} = 20 \log \left| \frac{V_{RL2}}{V_{RL1}} \right|_{when\ V_{s2}=0} \qquad (2.15)$$

If we try to find the exact solution, the procedure for analyzing this circuit with 9 elements can be time consuming.

However, if we redraw the circuit and take advantage of the relative size of some of the impedances, we can greatly simplify the analysis.
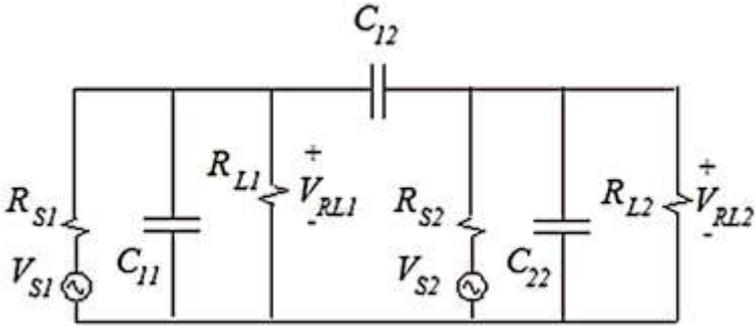

Figure 2-22 More intuitive schematic representation of the circuits in Figure 2-21

First, let's redraw the circuit in Figure2-21 as shown in figure 2-22. By putting Circuit 1 on the left side of the schematic and Circuit 2 on the right side, the important coupling, C_{12}, is clearer. Also, it is helpful to recognize that the impedances of the self-capacitances C_{11} and C_{22} are almost always much higher than the load impedances that they are in parallel with. If this were not true, the signal reaching the load would be significantly attenuated. Therefore, we can usually neglect C_{11} andC_{22} when solving the circuit in Figure 2-22.

To calculate the crosstalk in Circuit 2 due to the signals in Circuit 1, we set $V_{S2} = 0$ and determine the ratioV_{RL2} / V_{RL1}. If the coupling is relatively weak (i.e. if the coupling is not loading down the source circuit), then the impedance of C_{12} is large relative to the impedances in Circuit 1. This means the value of V_{RL1} is independent of the Circuit 2 parameters and

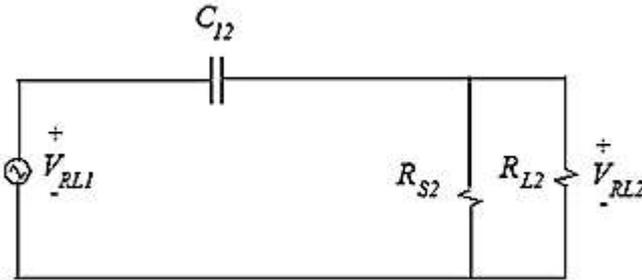the circuit can be represented in the simple form shown in Figure 2-23.

Figure 2-23 An even simpler representation of the circuits in Figure 2-22

Now the circuit is relatively easy to solve. The crosstalk can be expressed as,

$$20 \log \left| \frac{V_{RL2}}{V_{RL1}} \right| = 20 \log \left| \frac{R_{S2} \| R_{L2}}{R_{S2} \| R_{L2} + \left(\frac{1}{j\omega C_{12}} \right)} \right| \quad (2.16)$$

2-8 FIELD-TO-CABLE COUPLING AND FIELD-TO-LOOP COUPLING (RADIATED COUPLING)
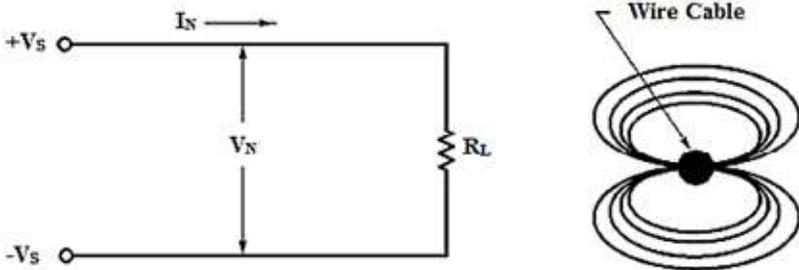

Figure 2-24 Field-to-cable coupling

EMI COUPLING MECHANISM

       The principle behind field-to-cable coupling is the same as that behind the receiving antenna. That is, when a conductor is placed in a time-varying electromagnetic field, a current is induced in that conductor as shown below. In this figure 2-24, we see a signal source V_S, driving a load, R_L. Nearby there is a current carrying wire (or other conductor). Surrounding the wire is an electromagnetic field induced by the current flowing in the wire. The circuit acts like a loop antenna in the presence of this field. As such, an interference current, I_N, and an interference voltage, V_N, are induced in the circuit. The magnitude of the induced interference signal is roughly proportional to the magnitude of the incoming field, the frequency of the incoming field, the size of the loop, and the impedance of the loop.
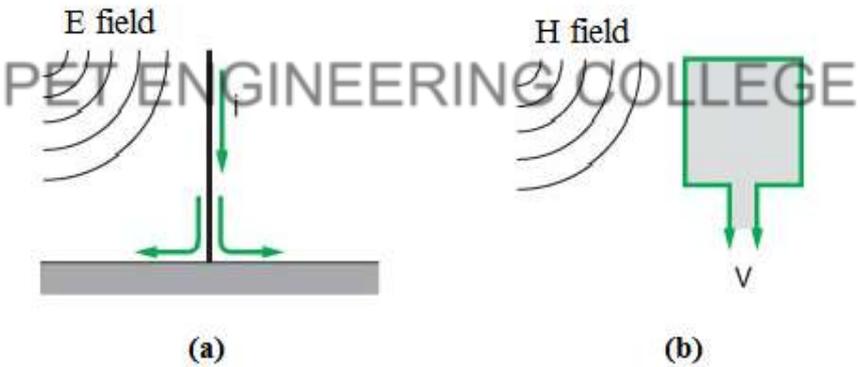

Figure2-25 (a) Field-to-cable coupling (b) Field-to-loop coupling

       In radiated interference, the disturber and the victim are coupled by a medium (e.g. air). The level of disturbance depends on the power of the radiating source and the effectiveness of the emitting and receiving antenna. An electromagnetic field comprises both an electrical field and a

magnetic field. The two fields are correlated. It is possible to analyze separately the electrical and magnetic components.

When a cable is subjected to a variable electrical field, a current is generated in the cable. This phenomenon is called field-to-cable coupling. Similarly, when a variable magnetic field flows through a loop, it creates a counter electromotive force that produces a voltage between the two ends of the loop. This phenomenon is called field-to-loop coupling. Example: Radio-transmission equipment (walkie-talkies, radio and TV transmitters, mobile services), Radar.

2-8-1 Counter-measures

To minimize the effects of radiated coupling, the measures below are required.

2-8-1-1 For field-to-cable coupling

- Reduce the antenna effect of the victim by reducing the height (h) of the cable with respect to the ground referencing plane

- Place the cable in an uninterrupted, bonded metal cableway (tube, trunking, cable tray)

- Use shielded cables that are correctly installed and bonded

- Add PECs

- Place filters or ferrite rings on the victim cable

2-8-1-2 for field-to-loop coupling

- Reduce the surface of the victim loop by reducing the height (h) and the length of the cable.

- Use the solutions for field-to-cable coupling.

- Use the Faraday cage principle.

Radiated coupling can be eliminated using the Faraday cage principle. A possible solution is a shielded cable with both ends of the shielding connected to the metal case of the device. The exposed conductive parts must be bonded to enhance effectiveness at high frequencies. Radiated coupling decreases with the distance and when symmetrical transmission links are used.

2-9 TRANSIENT SOURCES

Sources of transient EMI are Lightning, Nuclear EMP, Power line Faults, Noises and Relays, Electrostatic Discharge

2-9-1 Nuclear electromagnetic pulse (NEMP)

Nuclear electromagnetic pulse (NEMP) leads to the generation of electromagnetic interference (EMI) in its most severe form. Two broad phenomena of EMI generation are associated with nuclear explosions. When equipment or a system is located in the close proximity of a nuclear burst, the weapon's X-rays or γ-rays (the incident photons) interact with different materials of the system and lead to uncontrolled emission of electrons. Motion of these electrons creates electromagnetic fields, which may cause upset or burnout of system electronics. This is the system generated electromagnetic pulse (SGEMP).

2-9-1-1 EMP from Surface Burst

Consider the case of a nuclear explosion close to the ground or ocean surface, the density of air molecules in this region is higher and there are more frequent collisions between the generated electrons and air molecules. As a result, the lifetime of the electrons is less.

The electrons come to rest within a distance of a few meters at sea level. The effective lifetime of these electrons is of the order of a few nanoseconds because of their quick capture by the ground, and more frequent collisions with air molecules associated duration of the current pulse (called Compton current) is also of the same order.

The ground will short-circuit the radial electric field lines near it. Current loops are formed on the ground surface. These in turn produce a magnetic field in a direction perpendicular to the current lines and, therefore, transverse electric field nears the ground surface. Because of the presence of both electric and magnetic fields which are transverse to each other, the electromagnetic field is radiated

2-9-1-2 High Altitude Burst

In the case of an explosion at altitudes of 100km or more, γ-rays are more intense. The γ-rays at these altitudes have a spherical distribution, and the radius of the sphere increases with the speed of light. The downward moving γ-rays interact with atmosphere at altitudes of 40-50km. The density of air is less for altitudes higher than about 30km; and the γ-rays are absorbed at altitudes lower than about 30km. The current is therefore maximum at altitudes of about 30km.

Since only a part of the γ-rays (downward moving γ-rays only) intersect the atmosphere, the spherical symmetry is upset. This asymmetry, as well as the geo-magnetic field (earth's magnetic field), generate a transverse component of the electromagnetic field. The presence of orthogonal field components results in the propagation of electromagnetic waves. The radial component of the current can be regarded as a superposition of the Hertzian dipoles along the radial direction. The transverse component of current forms closed loops, and is therefore equivalent to a magnetic dipole.

The intensity of the electromagnetic field generated by nuclear explosion depends on the intensity of the nuclear detonation. The strong electromagnetic field produces a hazardous effect on electronic equipment. This field induces high voltage transients on power transmission lines. These fields can also couple into a cable with improper shielding.

2-9-2 ELECTRO STATIC DISCHARGE (ESD)

Electrostatic discharge (ESD) is a natural phenomenon in which accumulated static electric charges are discharged. This discharge produces electromagnetic interference. Static electricity is generated when two materials of different dielectric constants, for example wool and glass, rub against each other. Charging of a material body may also result from heating (loss of electrons), or through contact with a charged body. This static charge is discharged to another object which has a lower resistance to the ground. The effects of such a discharge, which results in electromagnetic interference, could vary from noise and disturbances in audio or measuring instruments to unpleasant electrical shocks to the equipment or person involved.

2-9-2-1 Charge Accumulation and Discharge

A common example involving accumulation of electrostatic charge occurs when a person wearing shoes with soles made of an insulating material such as polyurethane foam walks over a carpet made of wool or any synthetic material. Here the carpet is a good insulator and the shoe sole is also a non-conducting dielectric. As a person walks across the carpet, and as the carpet and the shoe sale rub against each other, the surface of the sole becomes charged. This charge is gradually transferred to the human body. In this manner, a charge of up to 10^{-6} coulombs or more can be accumulated depending upon the nature of the carpet, shoe sole and the distance the person has walked on the carpet. This could easily result in a voltage of up to 15mV. A sudden discharge of the accumulated static charge takes place when the person in this charged state touches a metallic item. The voltage a person can safely attain is about 35mV.
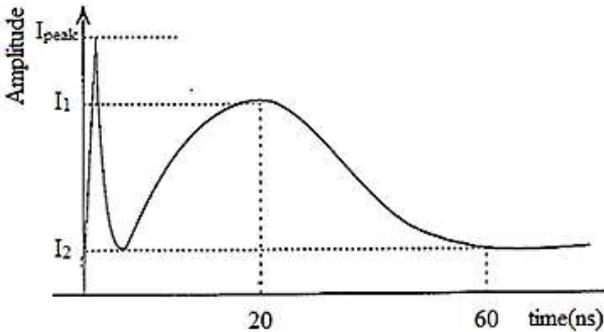

Figure 2-26 Waveform of electric discharge

An object with accumulated charges will seek the first available opportunity to discharge the unbalanced charges. This may occur smoothly by a progressive bleed of the charge through a moderately conducting path. On the other hand, an

electric arc, in which an intensive discharge takes place over a short period, is generated when a release of the charge occurs abruptly. When a discharge of micro coulombs takes place within tens of microseconds, the resulting average currents amount to several amperes, with peak values that can reach up to 100A.
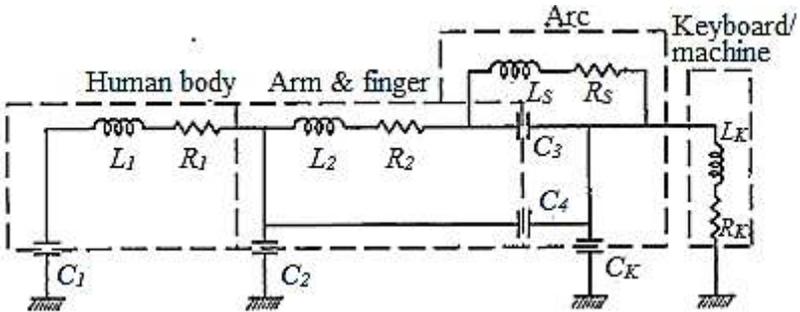

Figure 2-27 Equivalent circuit model for electro static discharge

The path of an ESD involving a human body (its forearm and finger) and an object through which discharge takes place may be represented as an equivalent electrical circuit. When the finger approaches very close to an object the large electrostatic field intensity may cause dielectric breakdown and result in an arc formation. Here, L_1 and R_1 are the inductance and resistance of the human body and C_1 is its capacitance to ground. L_2 and R_2 represent the inductance and resistance of the arm and finger, and they appear in series with L_1 and R_1. C_2 is the capacitance of the arm and finger to the ground. L_k and R_k represent the inductance and resistance of the object being approached. C_k represents the capacitance of object to the ground. The presence of C_3 and C_4 in the circuit indicates that the object does not-have a direct DC electrical connection with the forearm and the finger. While the charged

body/finger is approaching an object, a strong electric field is created in the gap between the finger and the object. This strong field gives rise to an electric arc. When arcing is taking place, C_3 is shunted by the arc and the resistance and inductance appearing in discharge is represented by L_S and R_S. The rise time of the pulse is given by the ratio $(L_1 + L_2) / (R_1 + R_2)$ and the pulse width depends upon the time constant, $(R_1 + R_2) \times (C_1 + C_2)$.

Transients can appear on the AC power line as a transient voltage difference between the phase and neutral conductors, between the line and ground conductors, or between the neutral and ground conductors.

Some basic techniques for quantitatively measuring the conducted electrical transients on power supply lines are:

In a simple setup, a digital oscilloscope with a pair of voltage probes can be used to measure the voltage V_{PO} between the phase and ground conductors, and the voltage V_{NO} between the neutral and ground conductors. It is necessary to carefully select the probes so that the time response function of each probe is able to respond accurately to the anticipated rise-time of the transient voltage or disturbance. When the probe detects a transient, the oscilloscope is triggered and the data are sent to a computer for storage and processing. For reliable data, the oscilloscope as a whole, and the probes, should have sufficient operating bandwidth, and the ability to detect transient voltages at the expected sample rates.