EE XXX: Electromagnetic Interference and Compatibility- part-3

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   7.1 Ionizing and Non-ionizing Radiation
   7.2 Units of radiation measurement
   7.3 Safety standards for non-ionizing radiation
   7.4 Relating SAR to the exposure fields
   7.5 Numerical problems

References Material

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2. V Prasad Kodali, "Engineering Electromagnetic Compatibility", IEEE Press, Newyork, 2001.
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9. William G Duff, "Designing Electronics Systems for EMC", SciTech Publishing (15th May 2011) ISBN-10: 1891121421, ISBN-13: 978-1891121425
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Course Syllabus:

BASIC THEORY

Introduction to **Course** EMI and EMC, Intra and inter system EMI, Elements of Interference, Sources and Victims of EMI, Conducted and Radiated EMI emission and susceptibility, Case Histories, Radiation hazards to humans, Various issues of EMC, EMC Testing categories, EMC Engineering Application.

COUPLING MECHANISM

Electromagnetic field sources and Coupling paths, Coupling via the supply network, Common mode coupling, Differential mode coupling, Impedance coupling, Inductive and Capacitive coupling, Radiative coupling, Ground loop coupling, Cable related emissions and coupling, Transient sources, Automotive transients. Categorization of the electromagnetic interference: emission, susceptibility, transients, crosstalk, shielding and compatibility, signal integrity.

EMI MITIGATION TECHNIQUES

Working principle of Shielding and Murphy‟s Law, LF Magnetic shielding, Apertures and shielding effectiveness, Choice of Materials for H, E, and free space fields, Gasketting and sealing, PCB Level shielding, Principle of Grounding, Isolated grounds, Grounding strategies for Large systems, Grounding for mixed signal systems, Filter types and operation, Surge protection devices, Transient protection.

STANDARDS AND REGULATION

Need for Standards, Generic/General Standards for Residential and Industrial environment, Basic Standards, Product Standards, National and International EMI Standardizing Organizations; IEC, ANSI, FCC, AS/NZS, CISPR, BSI, CENELEC, ACEC. Electro Magnetic Emission and susceptibility standards and specifications, MIL461E Standards.

Test Set-ups, units (e.g. $dB\mu Vm^{-1}Hz^{-1}$), Antenna facture etc.

EMI TEST METHODS AND INSTRUMENTATION

Fundamental considerations, EMI Shielding effectiveness tests, Open field test, TEM cell for immunity test, Shielded chamber , Shielded anechoic chamber, EMI test receivers, Spectrum analyzer, EMI test wave simulators, EMI coupling networks, Line impedance stabilization networks, Feed through capacitors, Antennas, Current probes, MIL -STD test methods, Civilian STD test methods.

BASICS OF BIOLOGICAL EFFECTS OF EM WAVES

Mechanism of interaction of EM waves with live tissue, Ionizing and non-ionizing radiation And their effects, Measurement techniques of EM radiation.

List of Symbols and Abbreviations

Symbols

ε	**:** Permittivity
θ	**:** Angle of elevation, angle
λ	: Wavelength
μ	**:** Permeability
ν	: Frequency (especially in the context of photon energy)
ϕ	**:** Azimuth angle
σ	: Target Cross section
τ	**:** Pulse width
ω	**:** Angular frequency
c	: Velocity of electromagnetic waves

Abbreviations

AF	**:** Antenna Factor
DUT	: Device under Test (Some literature refers it as times called **EUT**: Equipment under test)
EM	**:** Electromagnetic (waves, energy, radiation)
EMI	: Electromagnetic interference
EMC	: Electromagnetic Compatibility
EMICP	**:** Electromagnetic Interference Control Procedure
EMITP	**:** Electromagnetic Interference Test Procedure
EMP	**:** Electromagnetic Pulse
ERP	**:** Effective Radiated Power
ESD	**:** Electrostatic Discharge
IF	: Intermediate Frequency
FFT	: Fast Fourier Transform
FM	: Frequency modulation
MoSFET	**:** Metal Oxide semiconductor Field Effect Transistor
IGBT	: Insulated gate bipolar transistor.
NF, F_n	**:** Noise Figure
PCB	: Printed Circuit board(s); they are also referred as ‘printed wiring boards’
RBW	: Resolution bandwidth
RF	: Radio Frequency
RMS	: Root Mean Squared
SNR	: Signal to Noise Ratio

Chapter-6

Intra System EMC compliance

In the foregone chapters we have seen the EMI mechanism, the EMC standards and some of the guidelines to minimize the EMI keeping the functionality the same. In this chapter we shall discuss the EMI inside the system. Modern systems are getting more and more complicated and there has been user demands to make the systems compact. A typical system consists of different types of signals as given below. A representative picture is shown in Fig.6.1

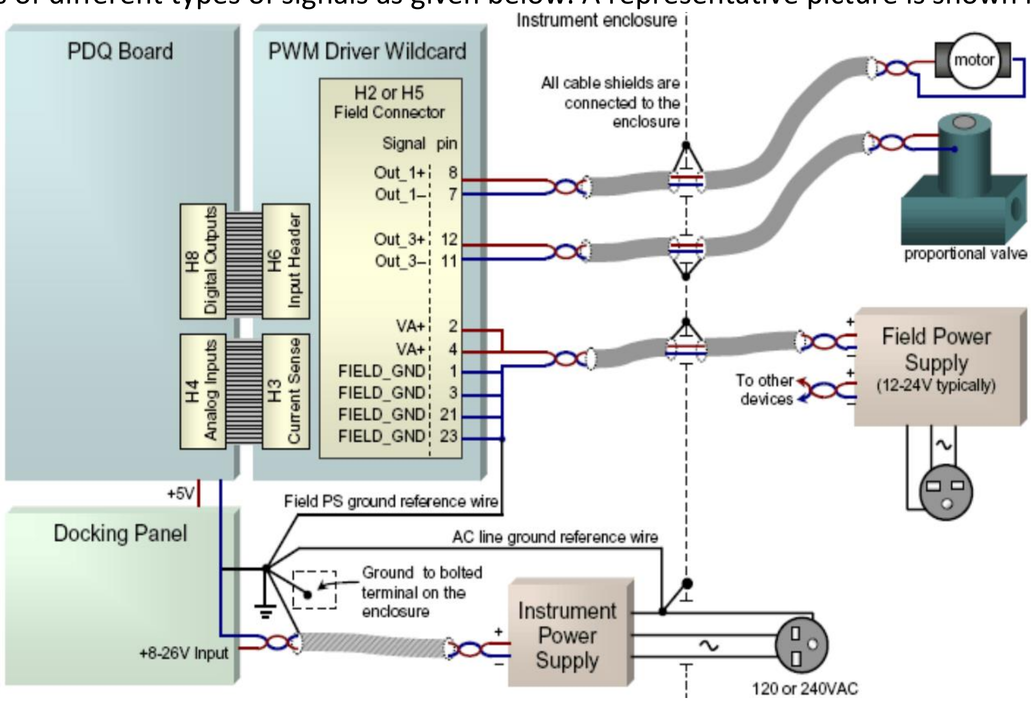


Fig 6.1 Panel of an electrical System

Fig. 6.1 1 shows that the circuitry components are segregated either in in separate 'sub-enclosures' or mounted in area demarcated for specific type of components. As an example, power switching components and subsystems are grouped together. Whereas, low current control and monitoring digital electronics components are located together. The components having higher EMI generating strength and good susceptibility are grouped together.

Similarly there are different conductors carrying various signals and lower supply currents. Following are the types of signal/ power carried by lines.

(a) Power supply lines
(b) Power drive and switching lines
(c) Control lines
(d) Digital processing signals
(e) Analog sensing lines.

These lines are also segregates into three categories, with similar philosophy, as follows:

- Very dirty zone: High EMI lines (e.g. power switching), classically routed through black cable ducts often metallic to provide extra shielding..
- Dirty zone: Moderate EMI carrying lines (e.g. relay switching signals), classically routed through grey ducts.
- Clean zone: Noise sensitive/ low EMI lines (e.g. sensor signals) classically routed through white cable ducts.

Fig. 6.2 shows conventional panel wiring example. (It may also be noted that the sources with High EMI are placed on the right side when looking into the panel.

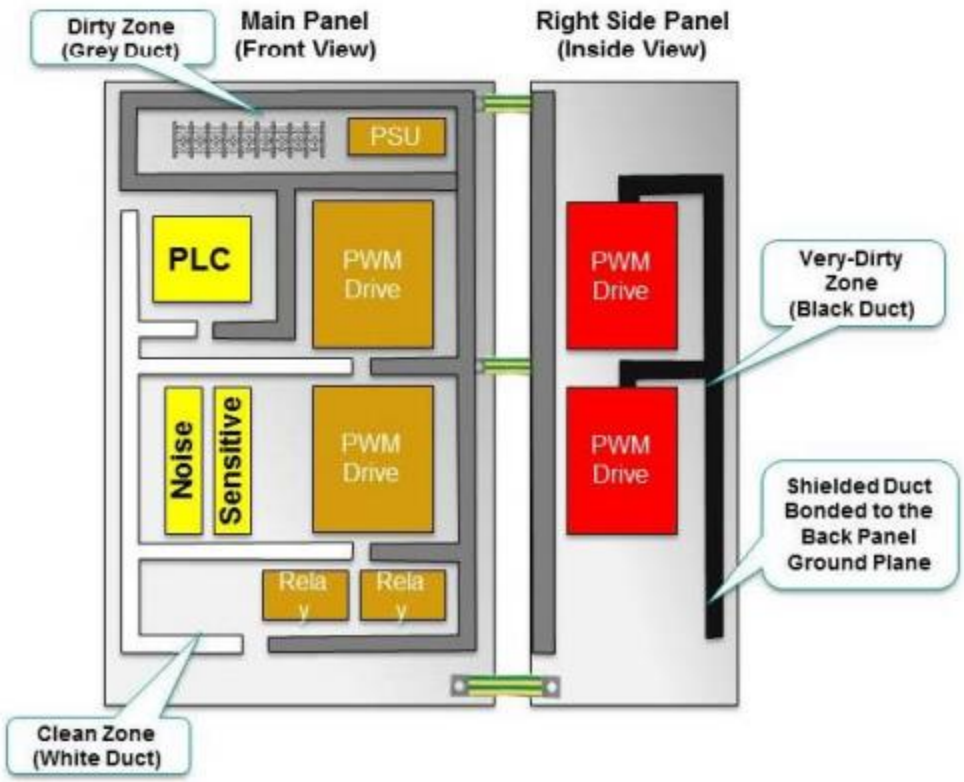


Fig 6.2 Component placement and wire routing in the panel

6.1 EMI between different subsystems

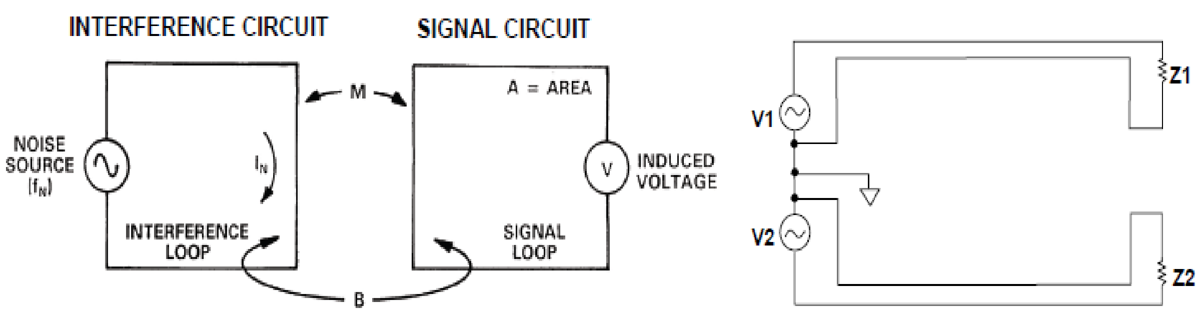
It is obvious that the spatial segregation described above is to avoid the EMI amongst each other. This EMI is possible by either by conducted or radiated coupling. We shall mathematically formalize these coupling mechanisms. The most of the cases individual subsystems are electromagnetically compliant. Section 6.2 presents some discussion on this subject. The EMI occur mainly ‘en-route’ of connection cables. If the cables carry frequencies higher than 50 kHz, the coupling is computed using detailed RF analysis. Generally, most of the intra-sub-system connections carry low frequency signals. The higher frequency signals are generally handled inside the sub-system or on the ‘Printed Circuit Board (PCB)’. Occasional connections of the higher frequencies are carefully done with shielded cables with high shield effectiveness. In this view we restrict this discussion to the EMI of lower (< 50 kHz) signals. The

simplest way of estimating the coupling amongst the interconnecting cables is by computing the inductances and the mutual inductances of the cables. Approximate expression for the inductance of a straight wire of length 'l' and radius 'r'is given in 6.1 (a) and the mutual inductance of parallel wires of length l, separated by a distance 'd' is given in 6.1(b).
(Source: [http://g3ynh.info/zdocs/refs/NBS/Rosa1908.pdf pp 305-309](http://g3ynh.info/zdocs/refs/NBS/Rosa1908.pdf))

$$\text{(a) } L \approx 2l\left[\log\frac{2l}{r}-1\right] \text{ and (b) } M \approx 2l\left[\log\frac{2l}{d}-1+\frac{d}{l}\right] \qquad \dots \quad (6.1)$$

We have seen similar expression with constant 0.75 (instead of 1) in (5.5). such differences are due to the different approximations for permeability and end-geometries of the conductors. Nevertheless, it serves practical purpose. The EM coupling depends on the ratio of self and mutual inductance. This approach does not assume any description of the signal or the return.

As the operating frequency of the signal increases, the radiation due to the circuit loop induces significant EMI. Fig. 6.3 shows a representative case of two independent circuits, where induced voltage is proportional to the area of the loop, given by (6.2). Fig 6.4 shows different types of loops.



(a) Voltage induced due to the adjacent loop (b) recommended routing for reduced EMI

Fig 6.3 EMI due to the mutual coupling between adjacent circuit loops

Source:(https://www.analog.com/media/en/training-seminars/design-handbooks/Basic-Linear-Design/Chapter12.pdf)

$$V_{induced} = \omega M I_{loop} = \omega AB \qquad \dots \quad (6.2)$$

Where, M- Mutual Inductance, B- magnetic flux density, A-area of signal loop, $\omega=2\pi f$- Angular frequency of the interference.

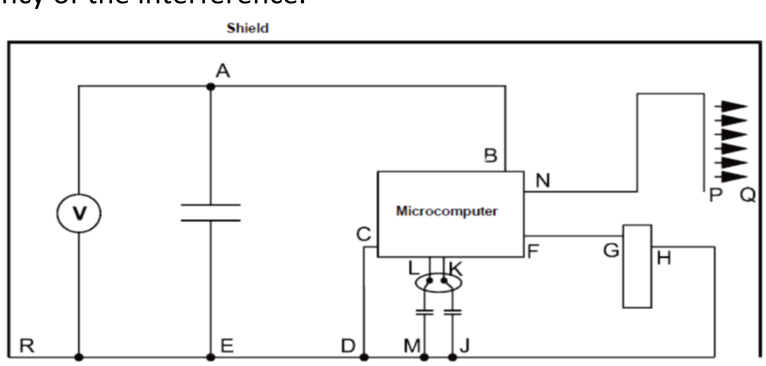


Fig 6.4 Loop formation in typical circuit and their coupling

Signal Loop: F-G-H-D-C Bypass Loop: A-B-C-D-E Crystal Loop K-J-M-S

Open loop causing internal radiation: NP radiates to Q and Hence to loop→ Q-R-D-C

Source: http://www.ti.com/lit/an/szza009/szza009.pdf: PCB Guidelines for Reduced EMI Ti

Often in electronics systems multiple signal-wires are need to be routed. Considering the EMI due to loop coupling, we have guidelines for routing long lines (carrying signals, power or data) on panel in the panel as well as for PCBs. Fig 6.4 shows comparison between the mutual inductance offered by different routing technique. It is straightforward to appreciate that routing signal return lines together will reduce the 'loop area (as shown in 6.3)' thereby reducing mutual inductance. Going further the twisted pair line routing reduces this area further having lowest possible value of mutual inductance. The twisted pair also reduces the 'common-mode noise'.

The twisted pair of signal and return cabling gives lesser coupling compared to the second option of running corresponding signal and return lines together. This is due to the fact that loop area is further reduced. This is often associated with lesser mutual coupling. The twisted pair offers additional advantage in terms of reduced common mode noise.

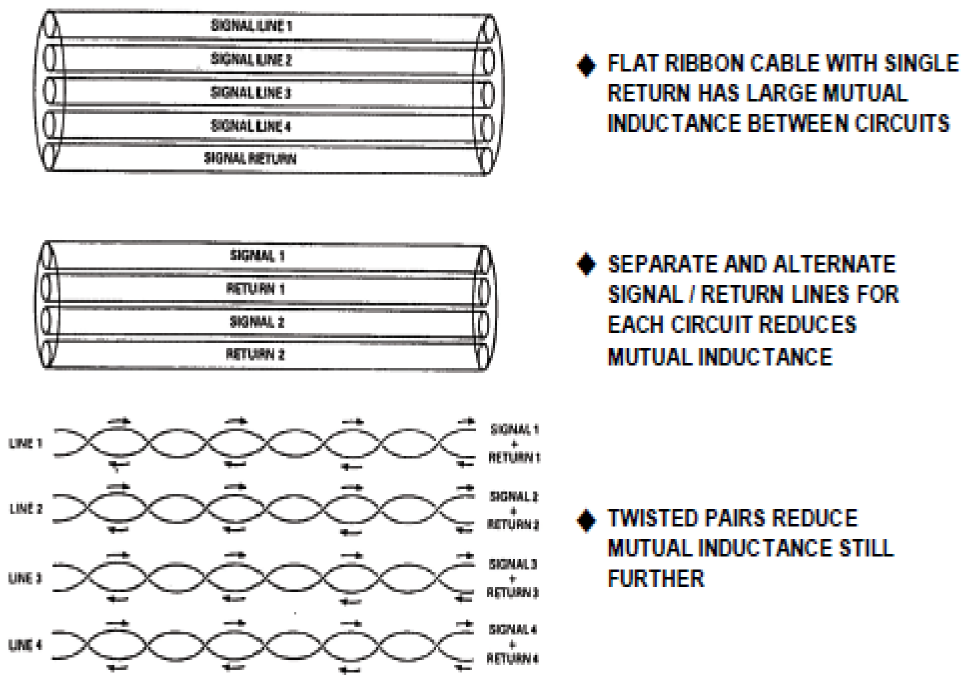


Fig 6.4 Guidelines for reducing the coupling in multi-signal cable

https://www.analog.com/media/en/training-seminars/design-handbooks/Basic-Linear-Design/Chapter12.pdf

6.2 EMI on the printed circuit board (PCB)

In modern electronic systems, the circuitry has become compact and the PCBs have reduced in size. As a result of this the Emi issues are more pronounced and careful design need to be done. In this section, we shall discuss some of the design aspects that require attention.

6.2.1 Component Selection

Component selection also has a bearing on the EMI compliance. Basic information and guidelines for the selection of the components are as follows:
(Sounce: https://www.nxp.com/docs/en/application-note/AN2321.pdf)

Resistors: Surface mount resistors are always preferred over leaded types because of their low parasitic elements. For the leaded type, the carbon film type is the preferred choice, followed by the metal film (they are mechanically rugged, i.e for temperature and vibration), then the wire wound. The metal film resistor, with its dominant parasitic elements at relatively low frequencies (in the MHz), is therefore suitable for high power density or high accuracy circuits. The wire wound resistor is highly inductive; therefore it should be avoided in frequency sensitive and high frequency applications. They are the best choice for high power handling circuits. In pull-up/pull-down resistor circuits, the fast switching from the transistors or IC circuits create ringing. In order to minimize this effect, all biasing resistors must be placed as close as possible to the active device and its local power and ground.

Capacitors: Aluminium electrolytic capacitors are usually constructed by winding metal foils spirally between thin layers of dielectric, which gives high capacitance per unit volume but increases internal inductance of the part. Tantalum capacitors are made from a block of the dielectric with direct plate and pin connections. This construction gives a lower internal inductance than aluminium electrolytic capacitors. Ceramic capacitors are constructed of multiple parallel metal plates within a ceramic dielectric. The dominant parasitic is the inductance of the plate structure and this usually dominates the impedance for most types in the lower MHz region.

The difference in frequency response of different dielectric materials mean a type of capacitor is more suited to one application than another. Aluminium and tantalum electrolytic types dominate at the low frequency end, mainly in reservoir and low frequency filtering applications. In the mid-frequency range (from kHz to MHz) the ceramic capacitor dominates, for decoupling and higher frequency filters. Special low-loss (usually higher cost) ceramic and mica capacitors are available for very high frequency applications and microwave circuits. The capacitors have 'self-resonant' frequencies. These frequencies are likely to appear as EMI. Table 6.1 gives approximate values of self-resonant frequencies of the capacitors.

Table 6.1: Self resonent frequencies of Capacitors

Capacitor Value	Through Hole (0.25 lead)	Surface Mount (0805)
1.0 µF	2.5MHz	5 MHz
0.1 µF	8 MHz	16 MHz
0.01 µF	25 MHz	50 MHz
1000pF	80 MHz	160 MHz
100 pF	250 MHz	500 MHz
10 pF	800 MHz	1.6 GHz

6.2.2 Transient suppression

The circuit schematic must take care of the DC-transients generated during the circuit operations. Relays, switches and transformers are common sources of the DC transient. These transients are supressed by the diode arrangement shown in Fig. 6.5.

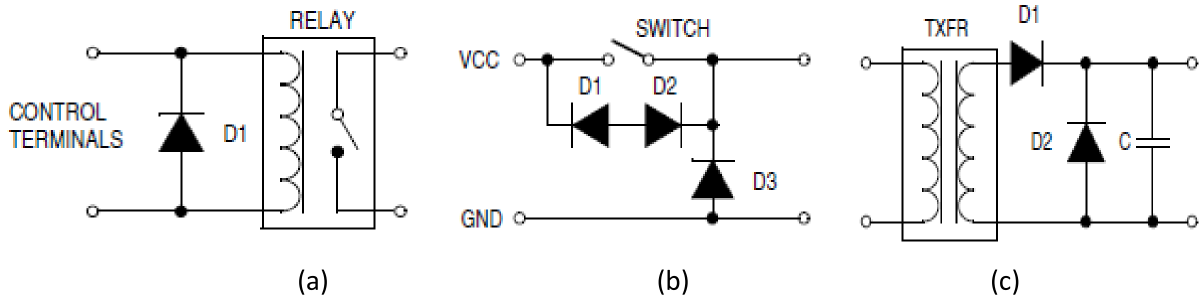


Fig 6.5 DC transient suppression using diodes for (a) relays (b) switches (c) transformers

In these sections we have learned that in order to reduce the EMI the signal return or the ground must be laid along the corresponding signals to reduce the loop area. Also avoid the internal radiation from dipoles formed by signal which are open or with bad impedance matching.

6.2.3 PCB layout considerations

Modern circuits are miniature and have closely spaced components, either discrete or fabricated on single chip. Providing ground plane on the PCBs is the easiest ways of providing signal return in proximity to the signal line. Some of the common techniques are as follows:

6.2.3.1 Signal return/ ground area: Multi-layered PCBs are fabricated in order to have very close signal return, thus minimizing EMI amongst the loops. Fig. 6.6 shows a representative picture of the layout for microcomputer ground.

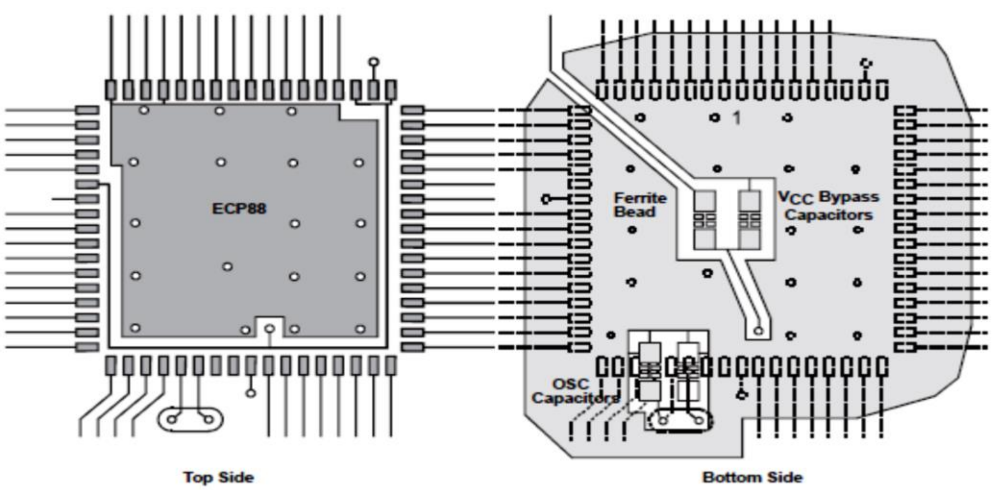


Fig 6.6 Layout of Microcomputer ground

Source: http://www.ti.com/lit/an/szza009/szza009.pdf: PCB Guidelines for Reduced EMI Ti

In practical situations, this ground plane must be maintained keeping the component-footprints, their mounting pods and connections. Fig 6.7 shows some preferred methods making layout of components, tracks and the ground planes.

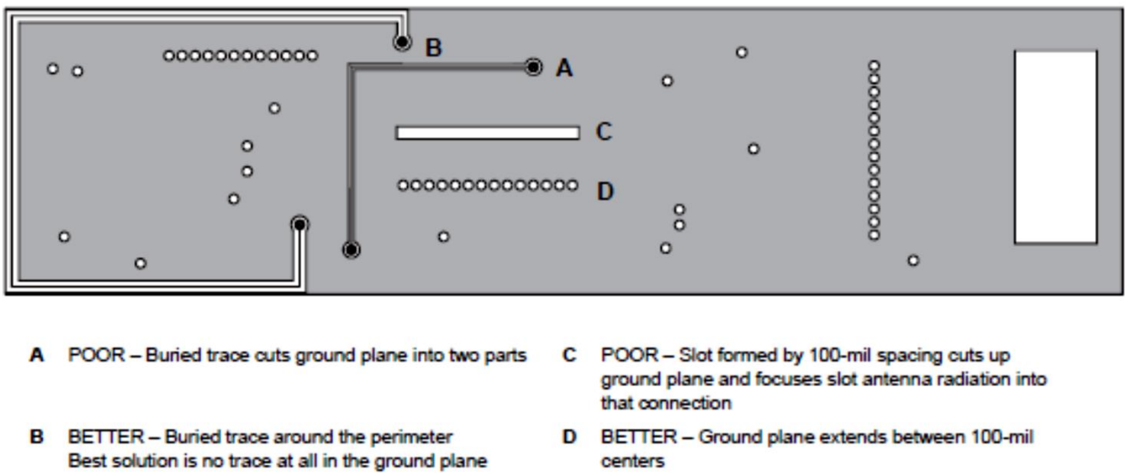


Fig 6.7 Preferred way of track routing and providing for the through hole pins.
Source: [http://www.ti.com/lit/an/szza009/szza009.pdf:](http://www.ti.com/lit/an/szza009/szza009.pdf) PCB Guidelines for Reduced EMI Ti

In multi-layer boards, there is often a space constraint. The effect of ground plane is achieved by gridding the ground (and supply) lines; see. Fig 6.8.

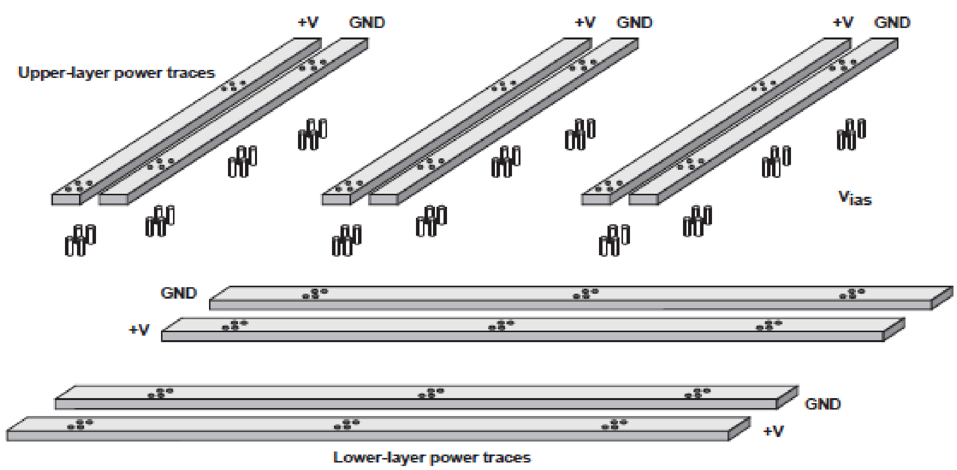


Fig 6.8 Gridding ground technique
Source: [http://www.ti.com/lit/an/szza009/szza009.pdf:](http://www.ti.com/lit/an/szza009/szza009.pdf) PCB Guidelines for Reduced EMI Ti

While planning PCBs, it is advisable to put different zones for different types of signals and connectors. Fig. 6.9 shows a representative example.

6.2.3.2 Connections of signals to the PCB: The PBC is connected to multiple signal lines receiving as well as transmitting to other parts of the systems. Planning different regions for analog and digital/ controller circuits and finalizing the connector locations must done before detailing the component layout. Fig. 6.9 shows a representative example.

In literature, there are many sources which offer guidelines for the PCB design. These are advices generally for specific context. Therefore, at times, they appear conflicting to each other. Design based on fundamental electromagnetic laws gives reliable EMC performance.

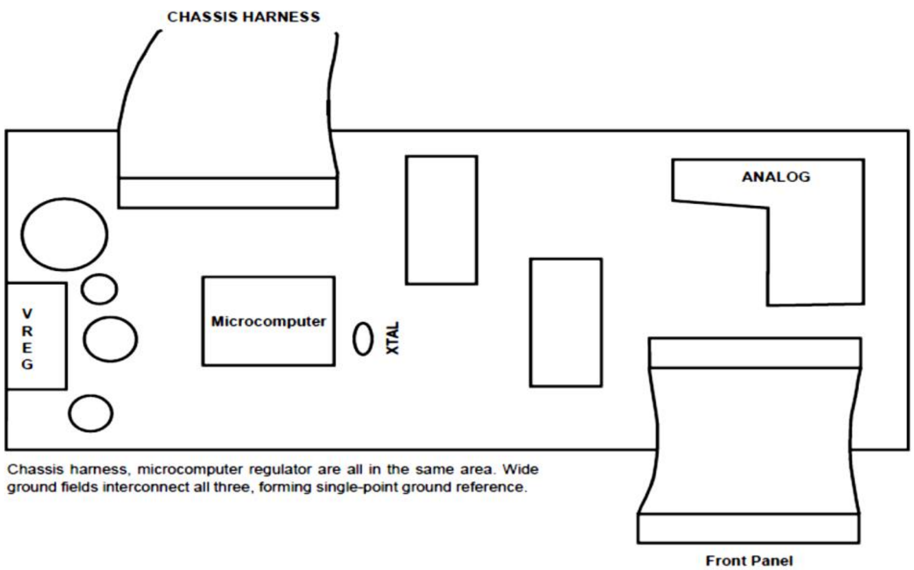


Fig 6.9 Example of demarcating zones for different circuit-types and connectors on PCB
Source: http://www.ti.com/lit/an/szza009/szza009.pdf: PCB Guidelines for Reduced EMI Ti

Modern circuits are getting miniaturized. As a result, the 'intra-component' distance is shrinking and leading to higher probabilities of EMI. On the other hand, the signal frequencies are also increasing making the compact circuitry more susceptible to EMI.

Careful analysis of the EMI and EMC aspects is required while designing the electronic systems. The best strategy is to consider the signal lines as 'microwave transmission lines' or 'transmission lines' with distributed parameters. This is mainly because modern PCBs are multilayered and the layers are often of different material!

6.2.3.3 Layout of signal tracks on the PCBs

The PCB can be made EMI-EMC compliant by modelling the signal tracks as transmission lines and addressing 'impedance matching' and 'signal coupling to the adjacent lines'.

(i) **Impedance matching**: It is well known that the impedance matching ensures complete transfer of signal power. Improper impedance matching leads to part of the signal power travelling in opposite direction (reflected wave). This signal leads to higher transients/ ringing on the signal lines.

This can be illustrated by an experiment. A 10 pF capacitor was introduced at the put pins, on the evaluation board of AD 8001, high speed current amplifier. The increase in the ringing on the signal lines is shown in Fig. 6.10. Fig 6.11 shows modelling of a signal line on a PCB in the context of Impedance matching.

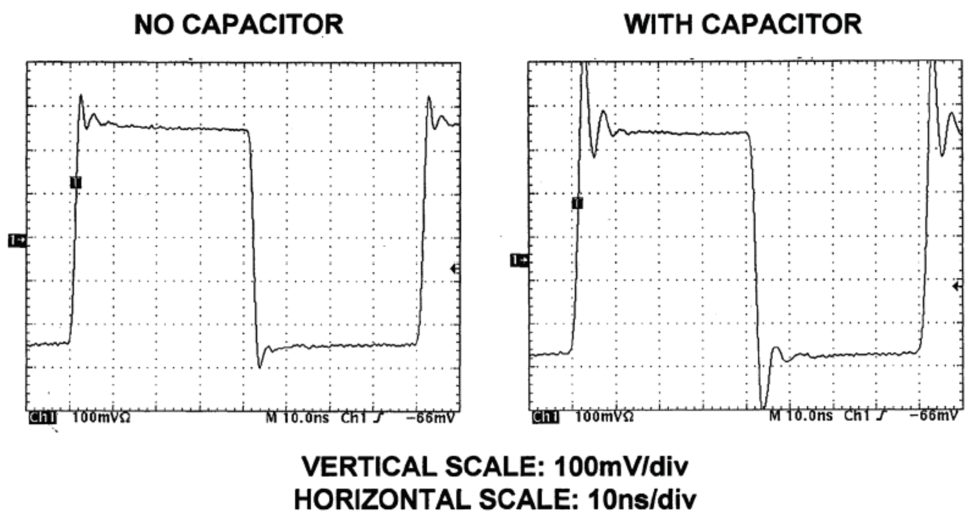


Fig 6.10 Increase in signal ringing due to 10pF capacitor at the input of AD 8001.
Source:https://www.analog.com/media/en/training-seminars/design-handbooks/Basic-Linear-Design/Chapter12.pdf

The impedance offered by various components and the PCB trace to an input of MoS device is shown in Fig. 6.12 It is seen that it offers very high impedance. This mismatch is expected to give rise to ringing on signal lines. An appropriate matching impedances need to be added outside the device.

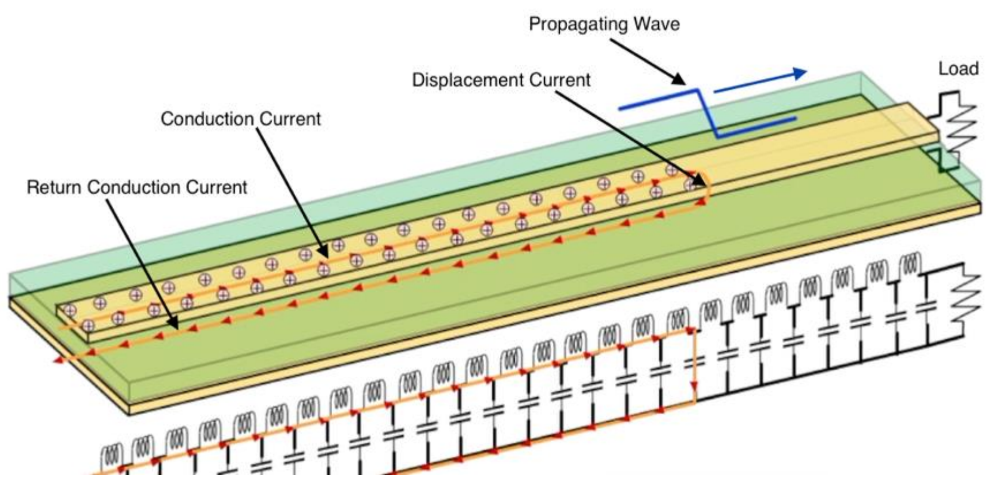


Fig 6.11 Modeling PCB signal trace as a transmission line

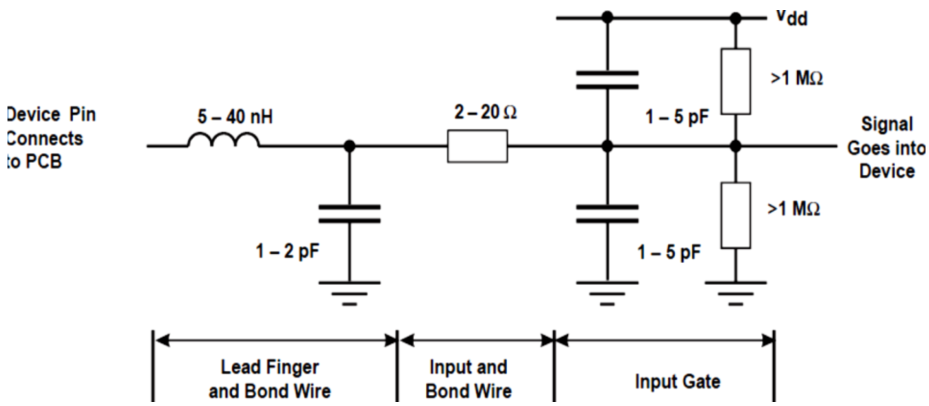
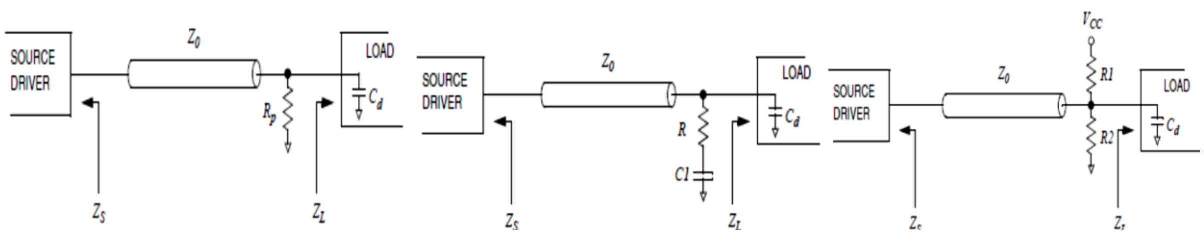


Fig 6.12 Impedance Increase in the ringing on signal line due to the introduction of 10pF capacitor at the input of AD 8001. Source: https://www.analog.com/media/en/training-seminars/design-handbooks/Basic-Linear-Design/Chapter12.pdf

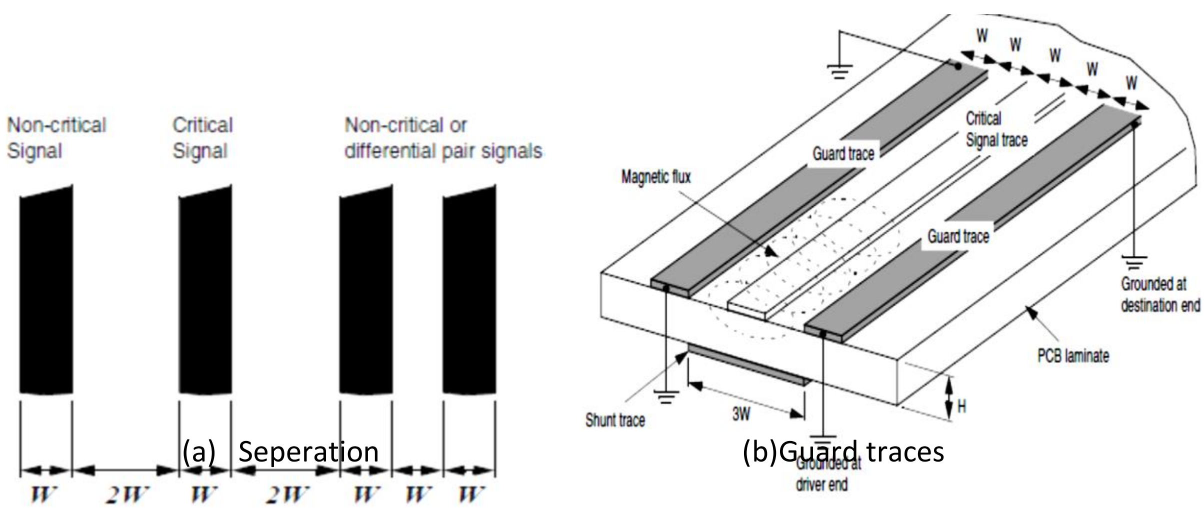
Different types of impedance matching techniques are used. Fig. 6.13 shows the schematic diagrams of these techniques. The component values are chosen to match the impedance. In some cases, the resisters of the Thevenin termination are replaced by Diodes. This configuration performs the function of limiting the signal overshoots.



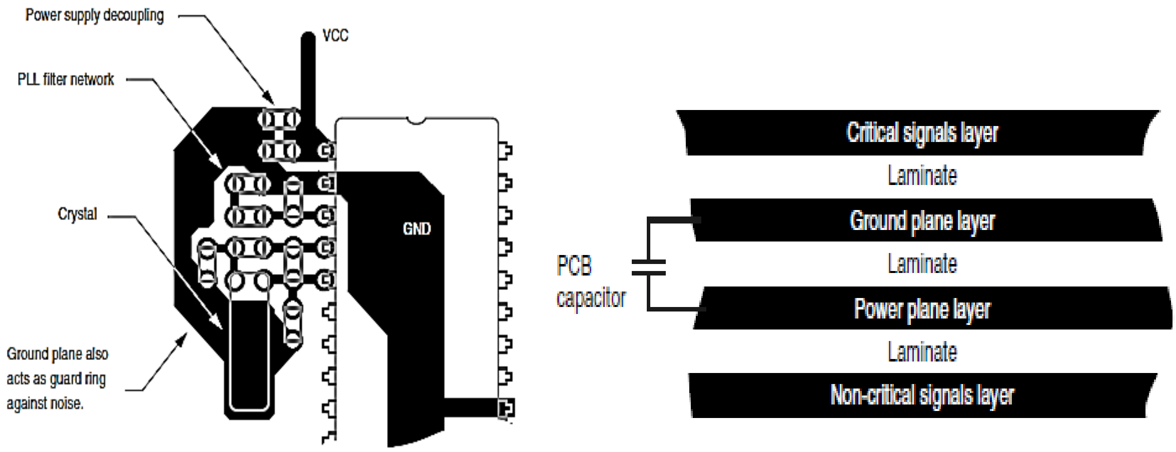
(a) Parallel Termination (b)R-C Termination (c) Thevenin Termination

Fig 6.13 Different technique to match the track impedance to that of the device

Source: https://www.nxp.com/docs/en/application-note/AN2321.pdf



(a) Seperation (b)Guard traces



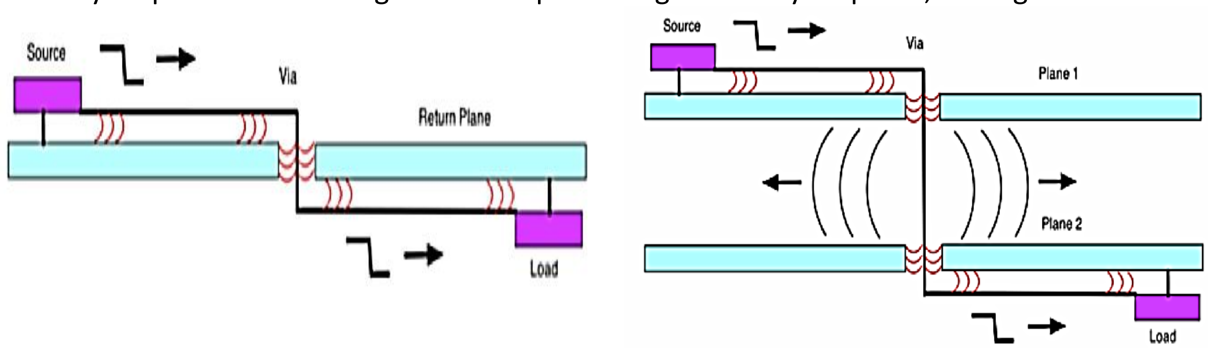
(c) Ground ring (b) Alternate layers in Multi-layered PCBs

Fig 6.14 Techniques of reduction in signal coupling

Source: https://www.nxp.com/docs/en/application-note/AN2321.pdf

(ii) Limiting the coupling to adjacent lines. Signal coupling to neighbouring tracks is another aspect that needs attention. Fig 6.11 shows the visualization indicating that the PCB trace can be modelled as a 'microstrip line'. The EM wave travelling through such lines have electric as well as magnetic field lines around the lines and beyond the physical dimensions of the trace. Limiting signal coupling is achieved by restricting the field lines in smaller space, not interfering with the field lines of the neighbouring traces. For that purpose, the tracks are separated by around the track-width for non-critical signals and twice the track width for critical signals. Often, critical signal tracks are protected by guard traces and extending the ground areas near the tracks. The illustrations for the same are shown in Fig 6.14 (a) thro (d).

In case of the plated through holes (PTH) on 2 sided boards, the EM field remains confined. On the other hand, the PTH on multi-layered boards shows EM field propagation in intra-layer spaces. On t the signal can couple through intra-layer spaces, see Fig. 6.15.



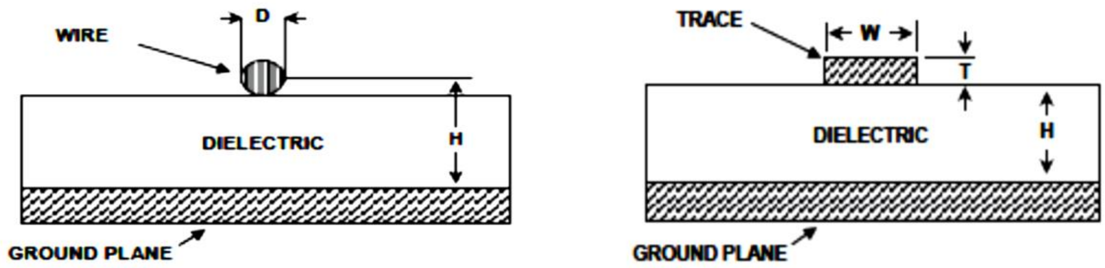
(a) (b)

Fig 6.15 E-field lines for plated through holes (a) two sided PCB (b) multi-layered PCB

6.3 Mathematical modelling of EMI on PCBs

This section associates established transmission line models with the signal line geometries. The mathematical expressions are sourced from the following link. https://www.analog.com/media/en/training-seminars/design-handbooks/Basic-Linear-Design/Chapter12.pdf.

Most of these expressions are empirical. Therefore, it is possible that other sources may present different expressions for the same entities. However, all such different expressions are generally within reasonable engineering approximations. Fig. 6.16 shows two common ways of signal connections from one module/ component to other.



(a)Wire along the metallic enclosures (b) Signal trace on PCB

Fig 6.16 Geometries for the intra-system signal lines

Source: https://www.analog.com/media/en/training-seminars/design-handbooks/Basic-Linear-Design/Chapter12.pdf

The expressions for the characteristics impedance (Z_0) with the relative dielectric constant ε_r for the dielectric material of the signal wire is given by (6.3). This value of Z_0 is considered while planning the terminations for the impedance matching as discussed in section 6.2.3.3.

$$Z_0(\Omega) = \frac{60}{\sqrt{\varepsilon_r}} \ln\left(\frac{4H}{D}\right) \qquad \text{... (6.3)}$$

Open traces are present on two-sided PCBs and on the outer surfaced on multi-layered PCBs. They are modelled as micro-strip lines with the geometries as shown in Fig. 6.16 (b). The expressions for the characteristic impedance, capacitance per unit length and the propagation delay are given in (6.4), (6.5) and (6.6).

$$Z_0(\Omega) = \frac{87}{\sqrt{\varepsilon_r + 1.41}} \ln\left(\frac{5.98H}{0.8W + T}\right) \qquad \text{... (6.4)}$$

$$C_0(pF/in) = \frac{0.67(\varepsilon_r + 1.41)}{\ln\left(5.9H/(0.8W+T)\right)} \approx C_0(pF/\mathrm{cm}) = \frac{0.264(\varepsilon_r + 1.41)}{\ln\left(5.9H/(0.8W+T)\right)} \qquad \text{... (6.5)}$$

The propagation delay corresponding to 50Ω line is

$$t_{pd}(ps/in) = 85\sqrt{0.45\varepsilon_r + 0.67} \approx t_{pd}(ps/\mathrm{cm}) = 33.465\sqrt{0.45\varepsilon_r + 0.67} \qquad \text{... (6.6)}$$

The value of the inductance can be computed from (5.5) for the wires and (5.5) for the PCB traces. The Impedance matching and the delay compensation between two different lines can be done using these expressions.

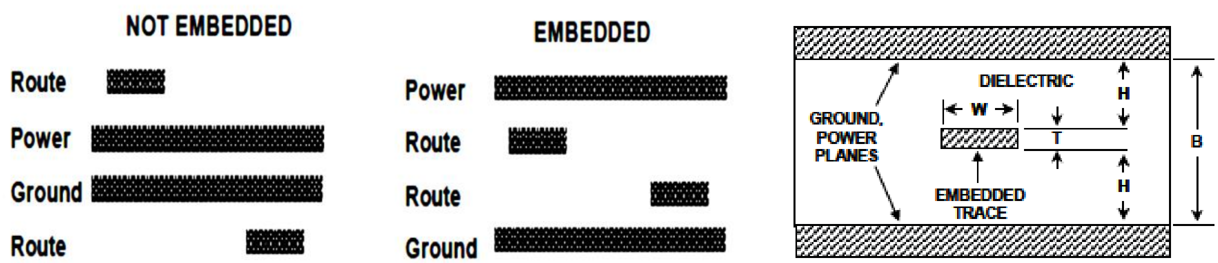
In multi-layered PCBs, the tracks are often embedded between the layers. Fig 6.17 shows the cross sections of such boards and (6.7), (6.8) and 6.9) are the relevant mathematical expressions. It can be seen that the embedded tracks have following advantages

(a) The tracks are shielded (the EM field is confined)
(b) It have lower impedance

Due to these factors, the embedded tracks show much better performance for frequencies greater than 100 MHz.

However, such arrangement has following disadvantages

(a) Prototyping and troubleshooting is very difficult.
(b) Decoupling such lines is also difficult.
(c) Sometimes the impedance becomes too low for impedance matching



(a)Open traces (b) Embedded traces (c) Stripline model for embedded traces

Fig 6.17 Geometries for the intra-system signal lines

Source: https://www.analog.com/media/en/training-seminars/design-handbooks/Basic-Linear-Design/Chapter12.pdf

$$Z_0(\Omega) = \frac{60}{\sqrt{\varepsilon_r}} \ln\left(\frac{1.9B}{(0.8W+T)}\right) \quad \dots (6.7)$$

$$C_0(pF/in) = \frac{1.41(\varepsilon_r)}{\ln\left[3.81H/(0.8W+T)\right]} \approx C_0(pF/\mathrm{cm}) = \frac{0.555(\varepsilon_r)}{\ln\left[3.81H/(0.8W+T)\right]} \quad \dots (6.8)$$

$$t_{pd}(ps/in) = 85\sqrt{0.45\varepsilon_r + 0.67} \approx t_{pd}(ps/\mathrm{cm}) = 33.465\sqrt{0.45\varepsilon_r + 0.67} \quad \dots (6.9)$$

The calculations of the capacitance and delays become significant while dealing with the layout for high speed logic circuitry. For impedance termination, general guideline recommends matching termination when the one-way propagation delay of the PCB track is equal to or greater than one-half (more conservatively, 'one-fourth') the applied signal rise/fall time (maximum of the two). For example, 5 cm micro-strip line over a substrate of ε_r= 4.0 introduces propagation delay of ≈ 270ps. This track needs to be terminated when the signal rise/ fall time is smaller than 500ps (conservatively, 1ns). The maximum allowable rise time for a given frequency is given by (6.10). The maximum frequency supported by the Therefore, maximum frequency for which the rise/ fall time of 500ps is tolerated is 700 MHz. For digital communications another factor of 1.75 is considered. In this view, the allowable bit rate becomes 400 Mbit s^{-1}.

$$t_r = \frac{0.35}{f_{\max}} \quad \dots \quad (6.10)$$

It may also be noted that the capacitive terminations increase the rise and fall time Fig. 6.18 shows the relation between the rise/ fall time with capacitive terminations for ADSP-210601 (SHARC-DSP processor from Analog Devices) operating with supply voltage of 3.3Vdc.

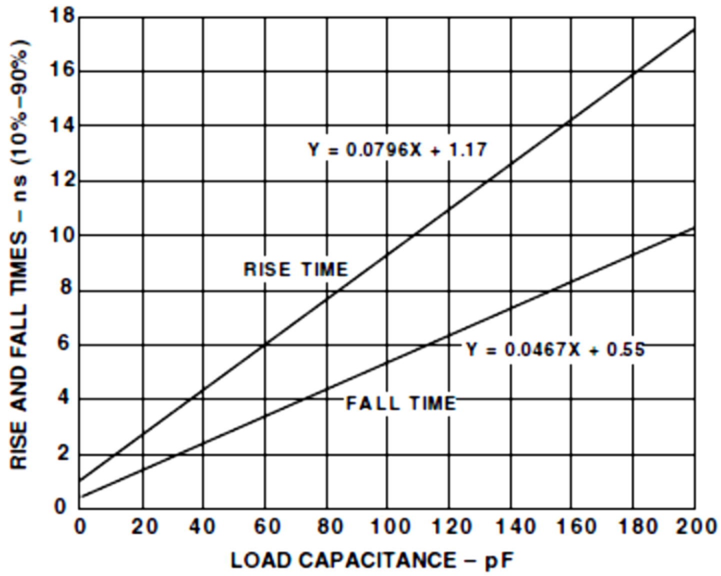


Fig 6.18 Rise and fall time for DSP processor ASDP-210601 with respect to capacitive loads

Source: https://www.analog.com/media/en/training-seminars/design-handbooks/Basic-Linear-Design/Chapter12.pdf

Most of the layouts are done with minimal distance signal lines. However, the inter-module data connections are often longer and the use of termination may be required. Nevertheless efforts are made to avoid terminations; as they require power dissipation. This is explained by following example.

Fig. 6.19 A shows a cable terminated in a 'Thevenin impedance' of 50Ω. This is done using two resistors of 91 Ω and 120 Ω making it to +1.4 V (midpoint of logic threshold of 0.8 V and 2.0 V). This arrangement adds power consumption of about 50 mW. Figure also shows the resistor values for the supply voltage of +5V.

Alternatively, source termination method, shown in Fig 6.19 B can be used. In this method, a series resistor of 39 Ω is used in series of source impedance, which is generally 10 Ω. This arrangement absorbs the reflected waveform. However, this method requires that the end of the transmission line be terminated in an open. Due to this additional 'Fan-out is not possible.

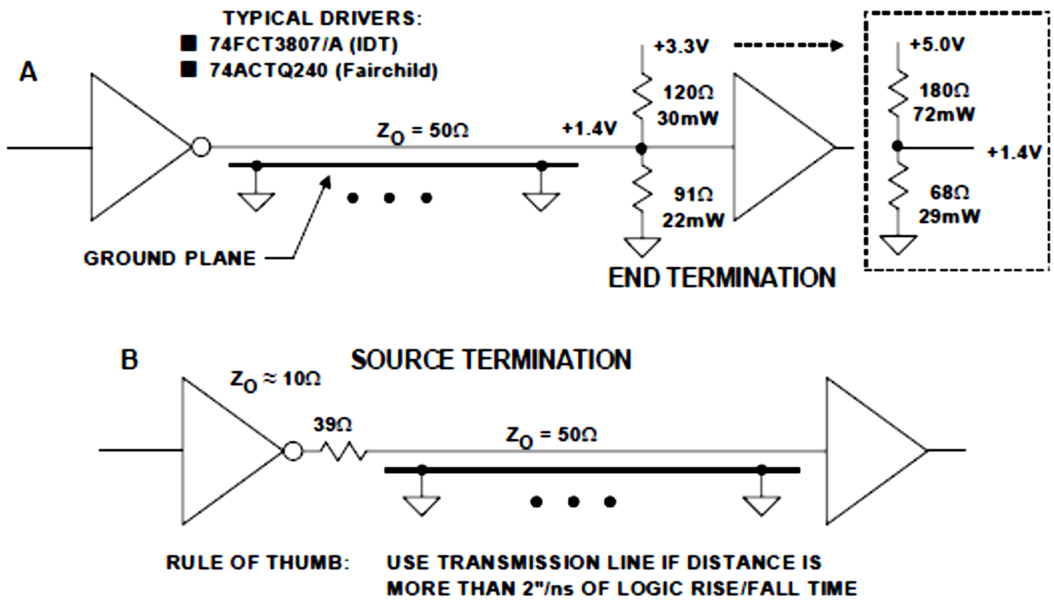


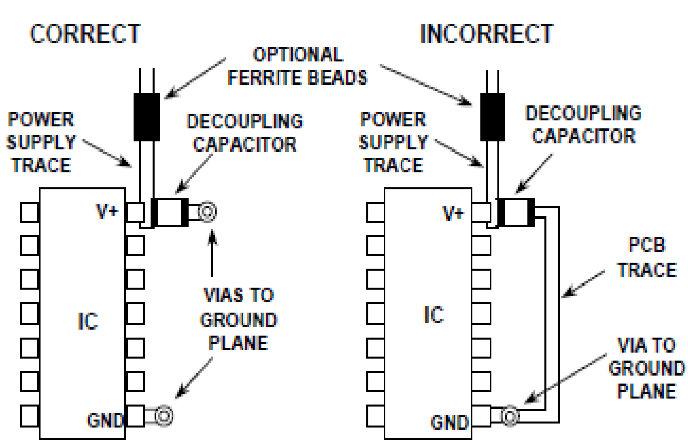
Fig 6.19 Termination option to the digital line drivers

Source: https://www.analog.com/media/en/training-seminars/design-handbooks/Basic-Linear-Design/Chapter12.pdf

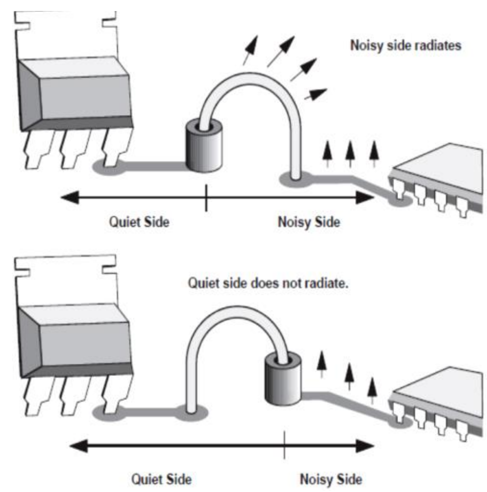
6.4 Miscellaneous EMI mitigating techniques on

Some of the techniques used in the PCB layout to minimize the intra-track radiations are as follows.

(a) Using Decoupling capacitors and ferrite beads: The power supply line needs to cater for the current requirement of the device. In high speed devices, the current demand on the supply connections. Fig 6.20 shows the correct ways using the ferrite beads and the de-coupling capacitors.



(a)



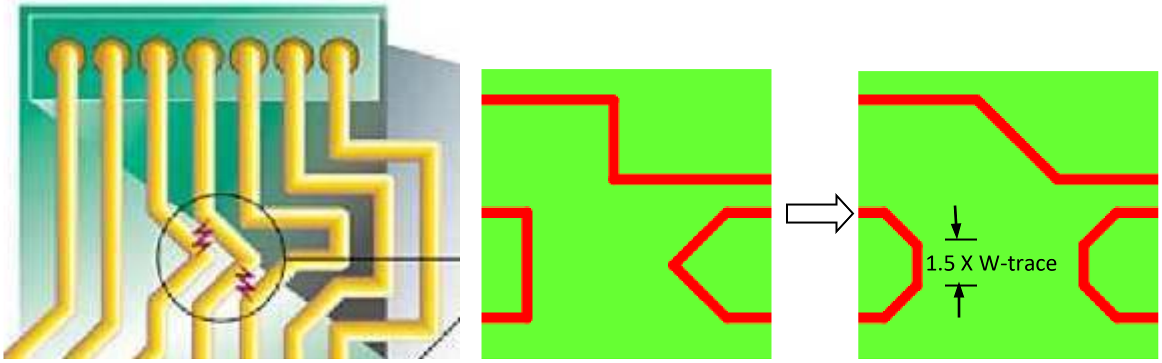
(b)

Fig 6.20 Correct method of placement of (a) Decoupling capacitors and (b) ferrite beads

Source: https://www.analog.com/media/en/training-seminars/design-handbooks/Basic-Linear-Design/Chapter12.pdf

http://www.ti.com/lit/an/szza009/szza009.pdf

Sharp bends on signal lines lead to radiations and cross-talks between the lines. This is avoided by using obtuse angles in the layouts; see Fig 6.21.



(a) Cross-talk (b) potential for cross talks (C) minimal cross-talk

Fig 6.20 Cross talk is minimized with the use of angle of 135^0

Source for illustrations: https://docs.toradex.com/102492-layout-design-guide.pdf

For high speed signals, the path delay between the signal and the return line causes distortion of the signals. This delay is compensated by introducing a meander on the traces, see Fig. 6.22.

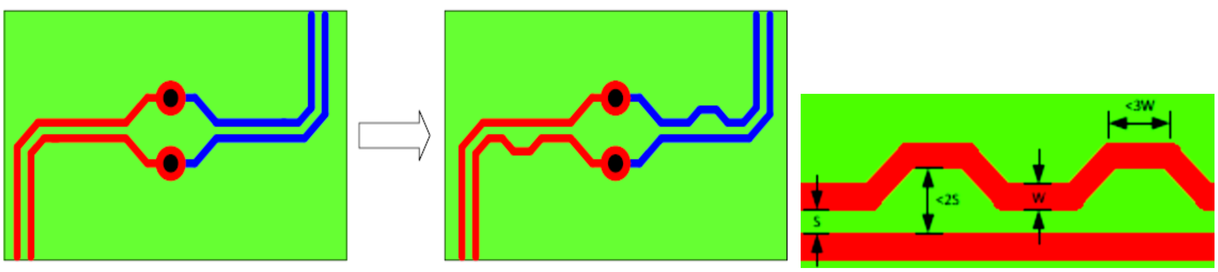


Fig 6.20 Introducing a meander for path compensation and dimensional guidelines

Source for illustrations: https://docs.toradex.com/102492-layout-design-guide.pdf

In current times, all these EMI/ EMC aspects can be analysed by software tools having signal-integrity capabilities. The link "https://www.ipc.org/ContentPage.aspx?pageid=Signal-Integrity-Vendor-List" gives the list of leading vendors.

6.5 Numerical problems

Chapter-7

Biological Effects of Electromagnetic Radiation

All the living creatures on earth are continuously getting exposed to different kind or electromagnetic (EM) radiations. These radiations could be from any part of electromagnetic spectrum. EM waves alternating at different frequencies are generated on the earth and human body gets exposed to these EM radiations. Modern science is able to detect and measure EM frequencies from a fraction of Hertz ($\approx 10^{-1}$) to Zetta Hertz ($\approx 10^{21}$). Fig 7.1 shows the electromagnetic spectrum for the radiating frequencies. We also have lower frequencies in up to TLF band. According to the contemporary understanding, EM radiation between frequencies 10^{1} to 10^{19} shows biological effects on humans. This chapter shall discuss these effects of EM radiation on humans, prevailing safety standards and precautionary measures and so on.

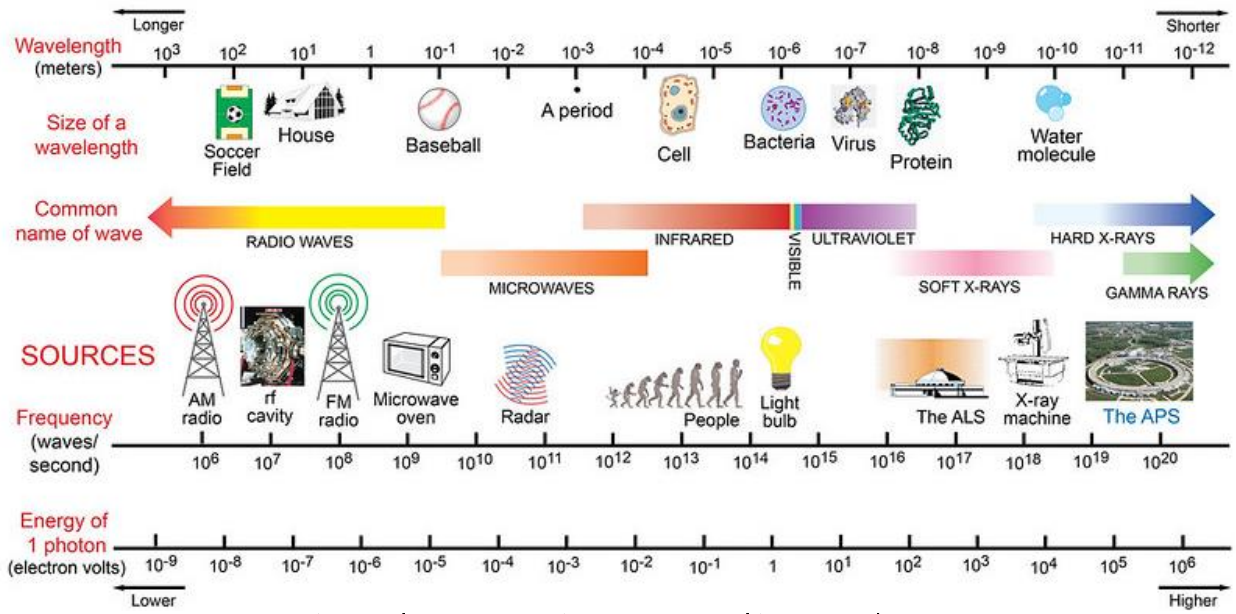


Fig 7.1 Electromagnetic spectrum and its general usage
Source: https://www.flickr.com/photos/advancedphotonsource/5940581568

The term 'radiation' is generally associated with nuclear radiation. This is mainly due to the fact that the development in nuclear technology happened in first half of 20th century and the world witnessed the human sufferings. The term 'thermal radiation' or 'heat radiation' is also in common usage. However, we shall restrict the discussion of this chapter to 'electromagnetic (EM) radiation'. We shall include all types of energy emissions in the form of EM waves. It is known that these EM emissions have biological effects on human beings. Therefore, the EM radiations are used in 'weaponry'. Fig 7.2 presents the EM spectrum with gross segregation of frequency bands considering the safety in it usage.

Considering the safety of use, the EM radiations are grossly in two categories; ionizing radiation and non-ionizing radiation.

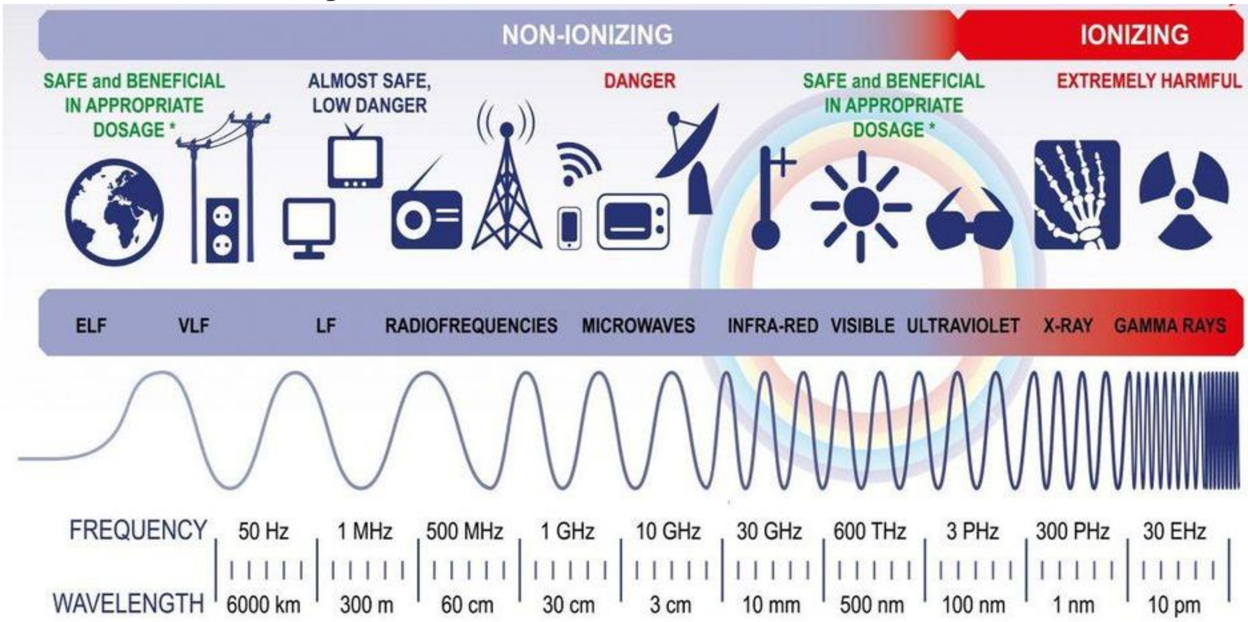


Fig 7.2 Electromagnetic spectrum with the consideration of safety of use

Source: https://www.forbes.com/sites/cognitiveworld/2019/04/12/the-weaponization-of-the-electromagnetic-spectrum/#47a733ee699e;JayashreePandya: The weaponization of the electromagnetic spectrum

Radiation from sources external to the earth: Earth receives nuclear particles and high energy and heat wave-EM radiation from celestial objects, generally termed as cosmic radiation. The nuclear particles and high energy radiation impact on the atmospheric layers and give rise to secondary EM radiation. This secondary radiation is called terrestrial radiation. It presents itself as long wave radiation. Additionally, there are man-made radiations and radiations due to earth's magnetic field and volcanic activities. Fig 7.3 shows the penetration of various frequency bands of EM radiation to different heights in atmospheric layers.

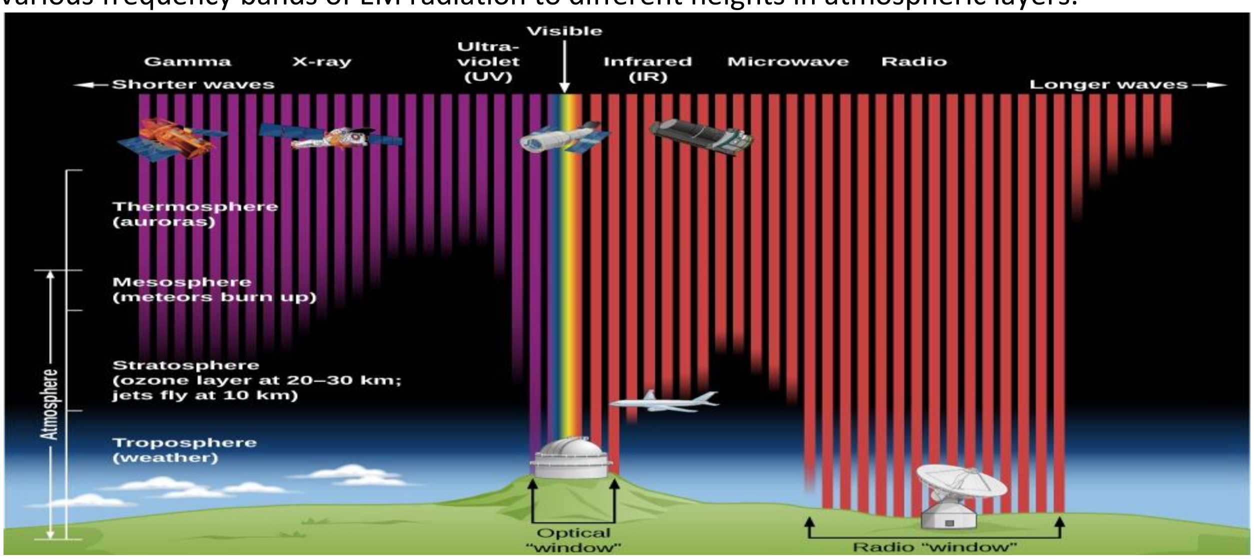


Fig 7.3 Frequency bands of extra-terrestrial EM radiations and their penetration in atmospheric layers

Source: https://courses.lumenlearning.com/astronomy/chapter/the-electromagnetic-spectrum/

7.1 Ionizing and Non-ionizing Radiation:

While considering the biological effects, it is important to understand the mechanism of interaction between the EM radiation and matter. Based on its reaction with matter, the radiation is classified in to two types, namely:

1. Ionizing radiation:

Ionizing radiation has photon energy, enough to dislodge an electron from a molecule. The action of removing electron creates 'free radicals' or 'atoms with unpaired electrons'. These atoms/ molecules are unstable and aggressively seek electron for pairing. This is known as 'oxidative stress'. In live organisms it is known and scientifically established that it causes 'tissue damage', 'aging' and multiple diseases like, diabetes, atherosclerosis (hardening of the blood vessels), inflammatory conditions, hypertension, heart disease, Parkinson, Alzheimer's and cancer.

2. Non ionizing radiation:

Non-ionizing radiations are lower frequency radiations having lower photon energy, not sufficient to knock out and electron from atomic orbits. This radiation interacts with live tissue in different mechanisms; heat, voltage gradient induced current and electromagnetically induced biological effects. The heat generation and the physical damage due to induced currents are well understood. On the other hand the 'stimulative' effects of EM waves is a topic of research. Some of the early work in this field is referenced as follows:

(i) Non-ionizing radiation, Part II: Radiofrequency electromagnetic fields / IARC Working Group on the Evaluation of Carcinogenic Risks to Humans, 2013;102 (Pt 2):1-460. PMID:24772662 PMCID: PMC4780878

(ii) Van Leeuwen GM, Lagendijk JJ, Van Leersum BJ, Zwamborn AP, Hornsleth SN, Kotte AN., "Calculation of change in brain temperatures due to exposure to a mobile phone", *Physics in Medicine and Biology*. 1999; Oct 44(10):2367-2379.

(iii) Bernardi P, Cavagnaro M, Pisa S, Piuzzi E., "Specific absorption rate and temperature increases in the head of a cellular-phone user", *IEEE Trans. Microwave Theory Tech, 2000;* 48:1118-1126.

A brief description is as follows:

(a) Heating: The best-known proven effect of non-ionizing radiation is heating of tissue. This effect occurs mainly in the range of 30MHz to 300 GHz (radio frequency). This heating effect of this interaction is perceptible on tissue-material with polar molecules. The alternating magnetic field of the incident radiation induces oscillatory motion of the polar molecules. This oscillatory motion of molecules leads to temperature rise. Depending on the molecular weight and moment of inertia of the molecule, the vibrations are set. Resonance is achieved at specific frequencies where the molecules vibrate with maximum displacement. Consequently, at resonant frequencies, the heat generation is at maximum. This mechanism is known as 'dielectric heating'. Domestic microwave ovens and some of the industrial processes work on this principle.

The tissue can usually cope with a slight increase of its temperature, by increasing the blood flow to the area that absorbed the radiation. If the temperature increase is high the body cannot overcome and dispel the excess heat, and the tissue may be damaged (e.g. a burn).

However, at the power with which most personal devices emit electromagnetic radiation, the heating effect is observed to be minimal and does not carry the risk of significant damage! For instance, exposure to a power of 600 mW for 50 minutes would raise brain temperature by 0.08 ^{0}C - 0.19 ^{0}C, whereas nerve cell damage would be observed only after an increase of 4.5^{0}C for 30 minutes. Most modern cell phones transmit maximum 250mW. On the other hand Citizen Band radio (CB radio) sets transmit maximum of 5 watts of power. These numbers (temperature rise, heating time etc) are likely to vary for individual persons.

(b) Voltage gradient induced currents: This effect is observed at frequencies below 3 KHz. This is generally grossly referred as 'ELF (extremely low frequencies). It may be noted that the classical/ formal definition of the frequency bands are VLF (3-30 kHz), ULF (300Hz-3kHz), SLF (30Hz-300Hz), ELF (3Hz-30Hz) and TLF(300mHz-3 Hz). Such voltage induced currents induce biological stimulations. If the induced very high it may cause burning to electrocution.

(c) Non-thermal effects: it is observed that EM waves create stimulation signals. These signals are believed to prompt biological actions/ activities in living organisms. Such effects studied under the research areas known as 'bio-electromagnetism', 'electromagneto-biology' and 'electromagnetic bio-informatics. The contention behind these research areas is that the living cells in the body are able to 'sense' non-ionizing radiation and react to it without getting heated. To verify this hypothesis, the effects of different frequencies of non-ionizing radiation on intracellular processes in tissue cultures of various cell types were studied. Though the effect of non-ionizing radiation on the DNA sequence or structure could not be established conclusively, the effects on intracellular mechanisms of signal transduction, including free radical formation, phosphorylation (addition of phosphate to an organic compound) and protein breakdown were observed. In other word, the sensing by living organisms is established. Though no measurable physiological effect, structure change were established, a detailed study claims a weak positive correlation between microwave exposure and non-malignant brain tumers; meningioma and glioma. (Ref: Gabriele Berg1, Jacob Spallek1, Joachim Schuz, Brigitte Schlehofer, Eva Bohler, Klaus Schlaefer, Iris Hettinger, Katharina Kunna-Grass, Ju¨ rgen Wahrendorf, and Maria Blettner, "Occupational Exposure to Radio Frequency/Microwave Radiation and the Risk of Brain Tumors: Interphone Study Group, Germany*", American Journal of Epidemiology*, 2006 Vol. 164, No. 6, p-p- 538-348.)

7.2 Units of radiation measurement

Different units of measure are used depending on what aspect of radiation is being measured. This section presents the measurement units and the definitions. (https://www.cdc.gov/nceh/radiation/emergencies/measurement.htm). Most scientists in the international community measure radiation using the System Internationale (SI), a uniform system of weights and measures that evolved from the metric system. In the United States, however, the conventional system of measurement is still widely used.

(a) Measuring Emitted Radiation

Emitted radiation, or the amount of radiation being given off, by a radioactive material is measured using the conventional unit Curie (Ci), named for the famed scientist Marie Curie, or the SI unit Becquerel (Bq), named after Antoine Henri Bequrel. A radioactive atom gives off or emits radioactivity because one of the following reasons; Either, the nucleus has too many particles or too much mass to nucleus has too much energy to be stable. The nucleus breaks down, or disintegrates, in an attempt to reach a stable or nonradioactive state. As the nucleus disintegrates, energy is released in the form of radiation.

The units, Ci or Bq is used to express the number of disintegrations of radioactive atoms in a radioactive material over a period of time. For example, one Ci is equal to 37 billion (37 X 10^9) disintegrations per second. The Ci is being replaced by the Bq. Since one Bq is equal to one disintegration per second (dps), one Ci is equal to 37 billion (37 X 10^9) Bq. The units, Ci or Bq are generally used to refer to the amount of radioactive materials released into the environment; e.g. during the Chernobyl power plant accident that took place in the former Soviet Union, an estimated total of 81 million Ci of radioactive cesium (a type of radioactive material) was released.

$$Ci = 37 \times 10^9 \, Bq(dps) \qquad \dots \quad (7.1)$$

(b) Measuring Radiation Dose

When a person is exposed to radiation, energy is deposited in the tissues of the body. The amount of energy deposited per unit of weight of human tissue is called the absorbed dose. Absorbed dose is measured using the conventional rad or the SI unit Gray (Gy). The rad, which stands for radiation absorbed dose, was the conventional unit of measurement, but it has been replaced by the **Gy**. One Gy is equal to 100 rad.

$$rad = 100 erg.gm^{-1} \quad \text{and} \quad 100 rad = 1Gy \qquad \dots \quad (7.2)$$

(c) Measurement of Biological risk

A person's biological risk (that is, the risk that a person will suffer health effects from an exposure to radiation) is measured using the conventional unit rem (Roentgen equivalent man), named after Wilhelm Konrad Roentgen or the SI unit Sievert **(Sv).** To determine a person's biological risk, scientists have assigned a number to each type of ionizing radiation (alpha and beta particles, gamma rays, and x-rays) depending on that type's ability to transfer energy to the cells of the body. This number is known as the Quality Factor (Q). Quality factor for x-rays, β and γ radiation is 1, for α particles, it is 20 and for neutrons it is 10. When a person is exposed to radiation, scientists can multiply the dose in rad by the quality factor for the type of radiation present and estimate a person's biological risk in rems.

$$rem = rad \times Q \quad \text{and} \quad Sv = 100 rad = Gy \times Q \qquad \dots \quad (7.3)$$

It is clear that all the above units are used for the ionizing radiations. The effect of these radiations on Human body is indicated in table 7.1

(Source: http://www.atomicarchive.com/Effects/radeffectstable.shtml)

Table 7.1: Effects of Radiation Levels on the Human Body

Dose (rem)	Effects
5-20	Possible late effects; possible chromosomal damage.
20-100	Temporary reduction in white blood cells.
100-200	Mild radiation sickness within a few hours: vomiting, diarrhoea, fatigue; reduction in resistance to infection.
200-300	Serious radiation sickness effects as in 100-200 rem and haemorrhage; exposure is a Lethal Dose to 10-35% of the population after 30 days (LD 10-35/30).
300-400	Serious radiation sickness; also marrow and intestine destruction; LD 50-70/30.
400-1000	Acute illness, early death; LD 60-95/30.
1000-5000	Acute illness, early death in days; LD 100/10.

The amount of radiation received in some of the medical examinations and treatments is given in tables 7.2 to 7.4. (Source: https://www.slideshare.net/RavishwarNarayan/biological-effects-of-radiation-17243436; original NCRP report no 160(2009) on www. NCRPpublications.org

Table 7.2 Diagnostic X-ray, single exposure

Exam	Effective Dose mSv (mrem)[1]	Exam	Effective Dose mSv (mrem)[2]
Chest (LAT)	0.04 (4)	Mammogram (four views)	0.7 (70)
Chest (AP)	0.02 (2)	Dental (lateral)	0.02 (2)
Skull (AP)	0.03 (3)	Dental (panoramic)	0.09 (9)
Skull (Lat)	0.01 (1)	DEXA (whole body)	0.0004 (0.04)
Pelvis (AP)	0.7 (70)	Hip	0.8 (80)
Thoracic Spine (AP)	0.4 (40)	Hand or Foot	0.005 (0.5)
Lumbar Spine (AP)	0.7 (70)	Abdomen	1.2 (120)

Table 7.3 Other investigation on ionizing radiations:

Complete Exams	Effective Dose mSv (mrem) [1]
Intravenous Pyelogram (kidneys, 6 films)	2.5 (250)
Barium Swallow (24 images, 106 sec. fluoroscopy)	1.5 (150)
Barium Enema (10 images, 137 sec. fluoroscopy)	7.0 (700)
CT Head	2.0 (200)
CT Chest	8.0 (800)
CT Abdomen	10.0 (1,000)
CT Pelvis	10.0 (1,000)
Angioplasty (heart study)	7.5 (750) - 57.0 (5,700)[3]
Coronary Angiogram	4.6 (460) - 15.8 (1,580)[3]

Table 7.4 Effective doses of nuclear medicines examinations

Nuclear Medicine Scan	Radiopharmaceutical (common trade name)	Effective Dose mSv (mrem)^2
Brain (PET)	^{15}O water	1.0 (100)
Brain (perfusion)	^{99m}Tc HMPAO	6.9 (690)
Hepatobiliary (liver flow)	^{99m}Tc Sulfur Colloid	2.8 (280)
Bone	^{99m}Tc MDP	4.2 (420)
Lung Perfusion/Ventilation	^{99m}Tc MAA & ^{133}Xe	2.0 (200)
Kidney (filtration rate)	^{99m}Tc DTPA	3.6 (360)
Kidney (tubular function)	^{99m}Tc MAG3	5.2 (520)
Tumor/Infection	^{67}Ga	18.5 (1,850)
Heart (rest)	^{99m}Tc sestimibi (Cardiolite)	6.7 (670)
Heart (stress)	^{99m}Tc sestimibi (Cardiolite)	5.85 (585)
Heart	^{201}Tl chloride	11.8 (1,180)
Heart (rest)	^{99m}Tc tetrofosmin (Myoview)	5.6 (560)
Heart (stress)	^{99m}Tc tetrofosmin (Myoview)	5.6 (560)
Various PET Studies	^{18}F FDG	14.0 (1,400)

However, the radiation due to the electronic systems is almost always non-ionizing. Therefore we shall concentrate on the biological effects of non–ionizing radiations. The radiation strength of non-ionizing radiation is measured in power density ($W.m^{-2}$) or the specific absorption rate (SAR) measured in $W.kg^{-1}$.

The standards applicable in India are discussed in the next, section (7.3).

7.3 Safety standards for non-ionizing radiation

Some of the relevant events and findings regarding Non-ionizing radiations are as follows.
Source for the information and figures: https://www.inae.in › img › FInal Report on Non-Ioninzing Radiation effects)

1. Cosmic Microwave Background Radiation (CMBR) was discovered in 1964 and earned 1978 Nobel Prize for American radio astronomers Arno Penzias and Robert Wilson. The CMBR has a thermal black body spectrum at a temperature of 2.72548±0.00057 ^0K; the spectral radiance dE_v/dv peaks at 160.2 GHz (wavelength of 1.9 mm), or at wavelength of 1.063 mm (frequency 283 GHz) if spectral radiance is defined as $dE_\lambda/d\lambda$ (spectral radiance is a measure of the quantity of radiation that passes through or is emitted from a surface and falls within a given solid angle in a specified direction. The units of Spectral radiance are Watts per steradian per square meter per Hz ($W.Sr^{-1}.m^{-2}Hz^{-1}$). And for the wavelength spectrum it is $W\cdot Sr^{-1}\cdot m^{-3}$.

2. BAUBIOLOGIE MAES (Building Biological measurements) developed the Standard for biology measurement (SBM-2008), have listed background fields as
   (i) Low frequency AC Electric field: <0.001 V/m, magnetic field: <-0.0002nT,
   (ii) High Frequency RF: <0.000001 µW/m^2,
   (iii) DC Electric: <100 V, DC Magnetic: Earth's magnetic 25-65 µT,
   (iv) Background magnetic fields for sensitive organs; namely, for eye 0.0001 nT, brain 0.001 nT, , heart 0.05 nT, animal navigation 1 nT.
3. Generally accepted 'safe levels' vary from 1 µW/m^2 for sleeping areas and 10 µW/m^2. They would vary to as much as 1000 µW/m2.

With this background, the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and the Federal Communication Commission (FCC) of USA have come up with most comprehensive standards. They are generally accepted documents followed by most countries

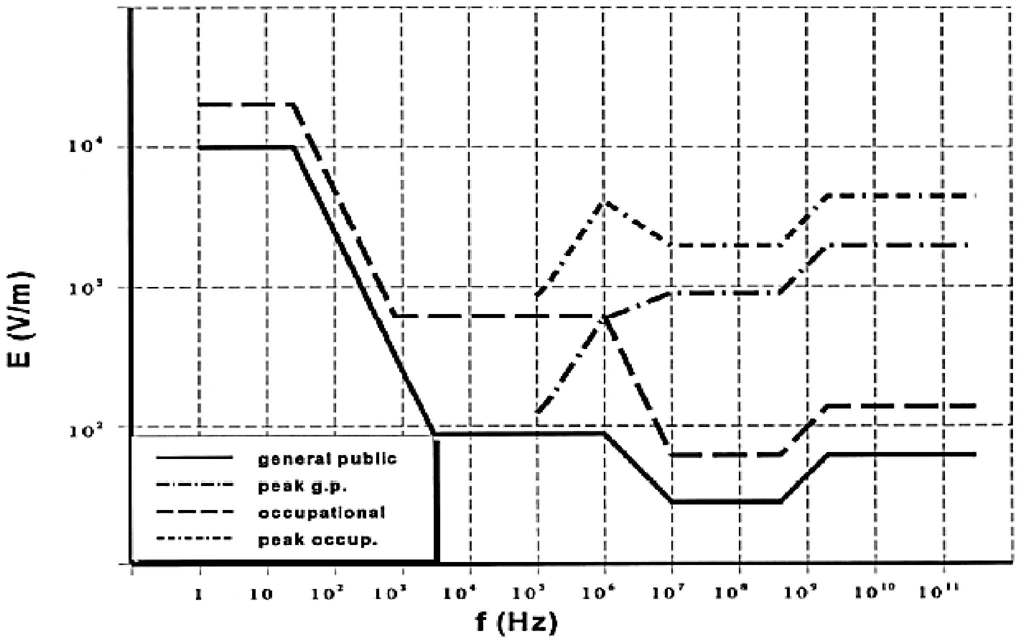
We shall see some of the representative standards. Table 7.4 gives the basic of electric and magnetic fields up to 10 GHz; (Other agencies have may have different SAR levels).

Table 7.5 Basic restrictions on electric and magnetic fields (

Exposure characteristics	**Frequency range**	**Current density for head and trunk (mA m^{-2}) (rms)**	**Whole-body average SAR (W kg^{-1})**	**Localized SAR (head and trunk) (W kg^{-1})**	**Localized SAR (limbs) (W kg^{-1})**
Occupational exposure	up to 1 Hz	40	—	—	—
	1–4 Hz	40/f	—	—	—
	4 Hz–1 kHz	10	—	—	—
	1–100 kHz	f/100	—	—	—
	100 kHz–10 MHz	f/100	0.4	10	20
	10 MHz–10 GHz	—	0.4	10	20
General public exposure	up to 1 Hz	8	—	—	—
	1–4 Hz	8/f	—	—	—
	4 Hz–1 kHz	2	—	—	—
	1–100 kHz	f/500	—	—	—
	100 kHz–10 MHz	f/500	0.08	2	4
	10 MHz–10 GHz	—	0.08	2	4

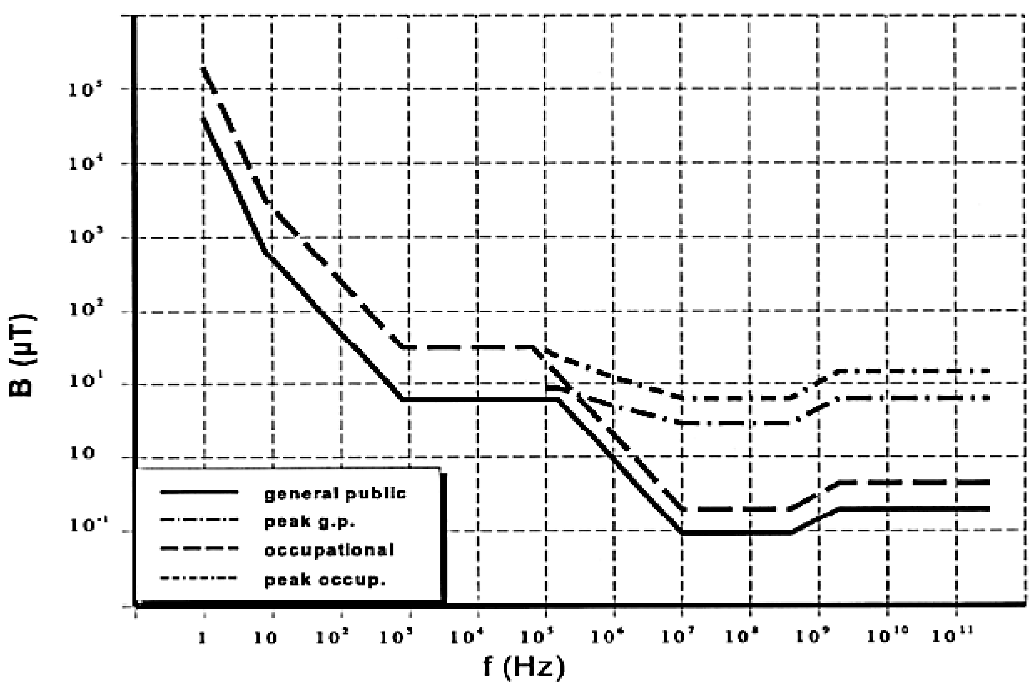
Fig. 7.4 gives the reference levels for time varying electric fields. Fig. 7.5 gives the reference levels for time varying magnetic fields. Fig. 7.6 presents maximum permissible exposure for plane wave equivalent power density. Fig 7.7 shows the instantaneous time averaged exposure of electric field strengths. Fig. 7.8 shows the instantaneous time averaged exposure of magnetic field strengths.

It is seen that the standards for various situations are specified to good details. In order to avoid unwanted biological effects, the strategy is exactly same for the compliance of RE and RS which was followed in chapter 4. The user entities are expected to follow the techniques for the RS compliance and the manufacturers will have to follow the techniques that are used for RE compliance.



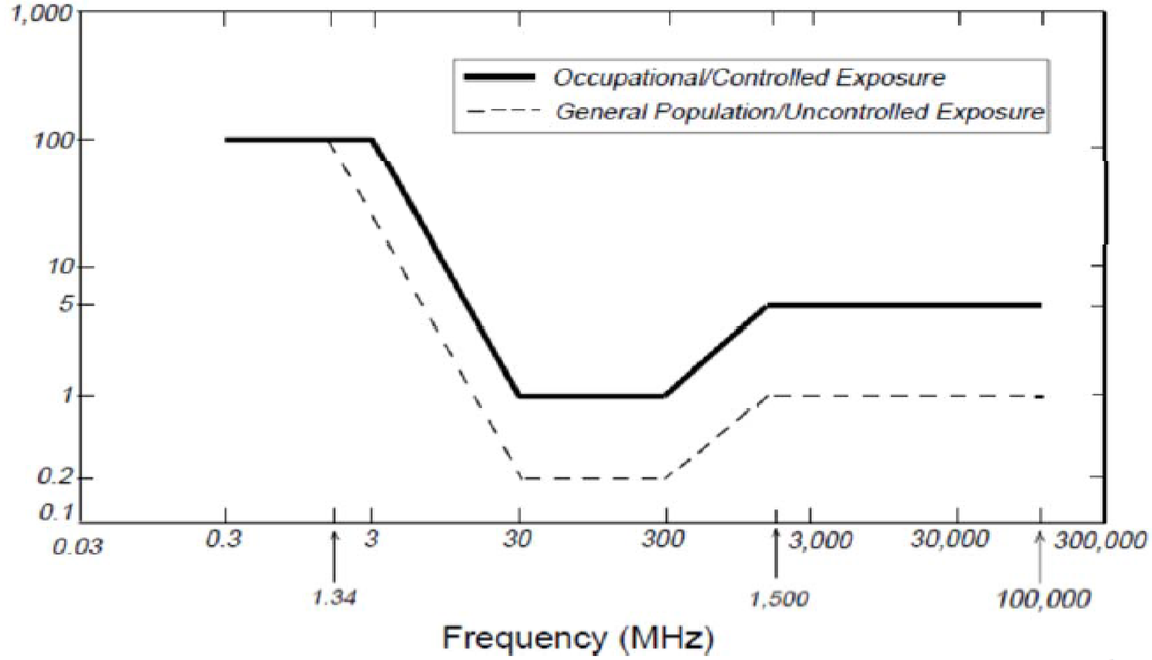
ICNIRP Reference levels for exposure to time varying electric fields

Fig 7.4 Field levels of exposure for time varying electric fields
Source: https://www.inae.in › img › FInal Report on Non-Ioninzing Radiation effects



ICNIRP Reference levels for exposure to time varying magnetic fields

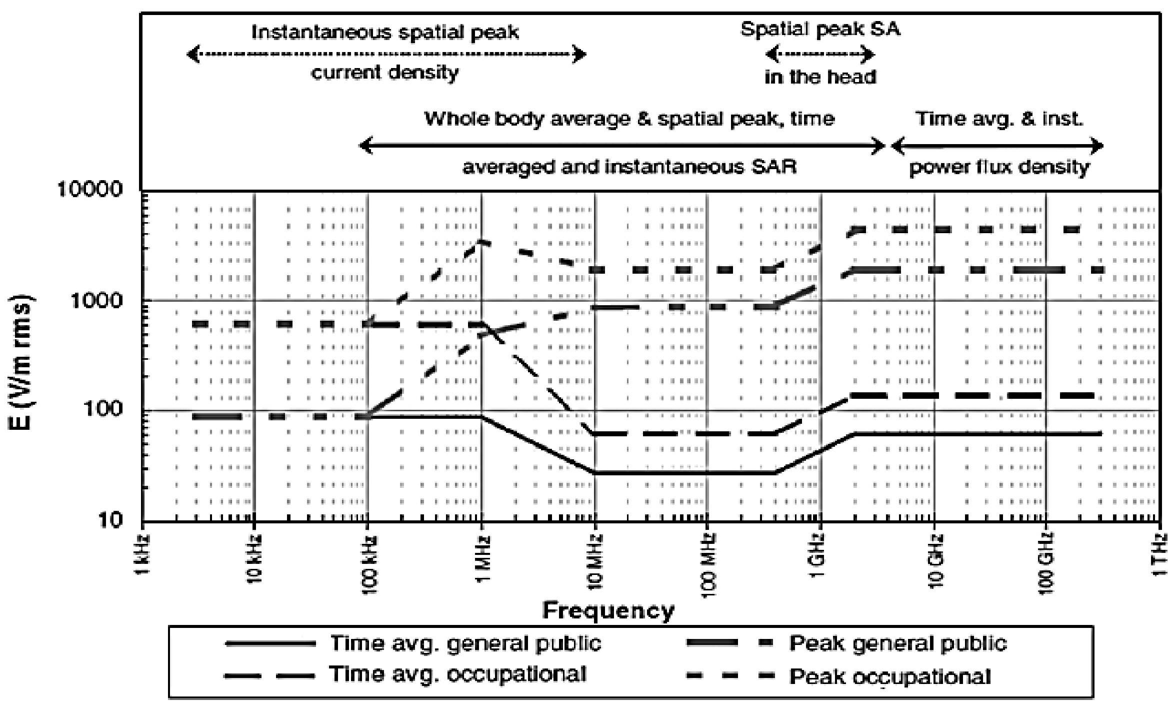
Fig 7.5 Field levels of exposure for time varying magnetic fields
Source: https://www.inae.in › img › FInal Report on Non-Ioninzing Radiation effects



FCC Limits for Maximum Permissible Exposure –Plane-Wave Equivalent Power Density (mW/cm^2)

Fig 7.6 FMaximum permissible exposure plane-wave equivalent power density

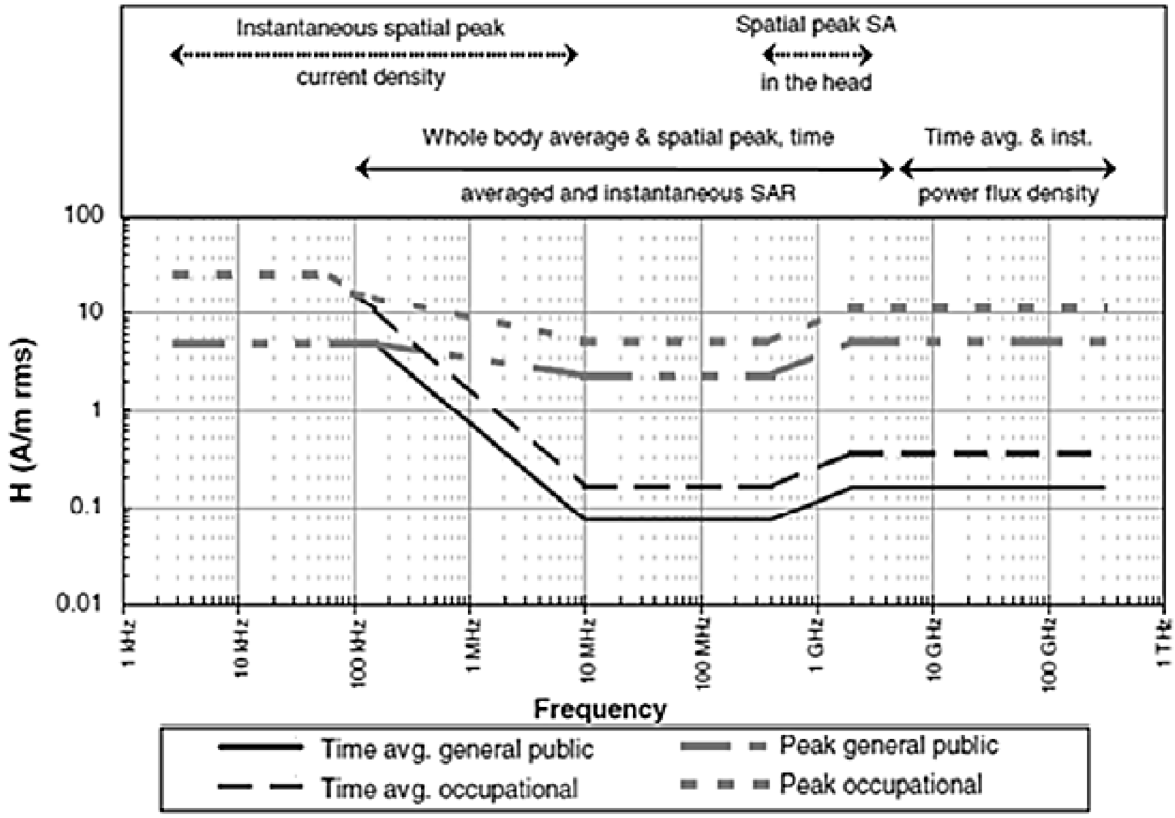
Source: https://www.inae.in › img › Final Report on Non-Ioninzing Radiation effects



Reference levels for instantaneous and time averaged rms exposure to electric fields

Fig 7.7 Reference level for instantaneous and time averaged rms exposure for electric field

Source: https://www.inae.in › img › Final Report on Non-Ioninzing Radiation effects



Reference levels for instantaneous and time averaged rms exposure to magnetic fields

Fig 7.8 Reference level for instantaneous and time averaged rms exposure for magnetic field

Source: https://www.inae.in › img › Final Report on Non-Ionizing Radiation effects

7.4 Relating SAR and exposure fields

Earlier section presented the limits of EM field exposure. These limits is in terms of Electric field intensity ($V.m^{-1}$), Magnetic field (B or H, T or Am^{-1}), or power density (Wm^{-2}). Knowing the design parameters of the source system and the environment around the human receiving the radiation, it is possible to determine whether the exposure is in prescribed limits.

However, the biological effects are dependent on the energy/ power absorbed by the human body. The extent of the hazard also depends on the age of the 'subject' (human receiving the radiation) and specific part of the body receiving the EM radiation.

In many of the cases, the standards assume certain environmental conditions and parameters. Sometimes these conditions are not explicitly mentioned. Due to these aspects, there is some amount of uncertainty in judging whether particular equipment is 'safe' for human usage. These conflicts could be resolved by interconverting the units or translating the essence of the standards to match the actual conditions of the usage. This section presents some of the methods of inter-conversions of the radiation limits. Mathematical expressions and the illustrations in this sections are sourced from C95.1-2005 safety standards of the IEEE; https://standards.ieee.org/standard/C95_1-2005.html.

Human body (or the body of any living organism) is always under energy exchange with the environment. As an example, there is always energy exchange between the living creatures and the environment. While considering the effect of EM radiation, additional of 'incremental energy (due to the EM radiation)' is considered. Also, the portion of the body tissue which absorbs the radiation is considered. With this understanding, the *specific absorption rate (SAR)* is defined as the time derivative of the incremental energy (dJ) absorbed by (dissipated in) an tissue mass (δm) contained in a volume element (δV) of given density (ρ); see (7.4). The SI unit is Watts per kilogram(W.kg^{-1}).

$$SAR = \frac{d}{dt}\left(\frac{\delta J}{\delta m}\right) = \frac{d}{dt}\left(\frac{\delta J}{\rho \delta V}\right) \quad \ldots \quad (7.4)$$

In terms of electric field, SAR can be computed if from the value of incident electric field (E)or by measuring the temperature rise (ΔT) in an interval of time (Δt). See (7.5)

$$SAR = \frac{\sigma |E|^2}{\rho} = \frac{c\Delta T}{\Delta t} \quad \ldots \quad (7.5)$$

Where, σ is the conductivity (Siemens per meter Sm^{-1}), ρ is the (mass-density kgm^{-3}), c is the specific heat capacity ($J.kg^{-1}.K^{-1}$)

(a) Induced and contact current hazard

Another mechanism that directly affects the humans is the flow of current. This current could be flowing through direct contact or by induction. However, the extent of damage depends on the actual path of current through human body. The presentation of the damage is different in different persons. In most cases, the currents of more than 10mA (>10mA) may result in painful to severe shock. While the currents more than 200mA (>200mA) causes severe burns, unconsciousness. Currents of 100-200mA above are considered lethal.

These varied results are observed on human body as different parts of the human body show different electrical resistances.

Electrical resistance of dry skin is more than 100kΩ (> 1,00,000Ω). On the other hand the internal resistance of the human body is approximately 300 Ω !

Table 7.6 shows current limits for RF frequencies. Please note that the standards differ depending on the working environment.

(b) Age correction on SAR limits

It is known that for the same radiation exposure, the undesirable effects due to EM radiation differ for the persons in different age groups.

Multiple studies of EM wave exposure were conducted on monkeys, rodents and other animals. Based on these studies, the established SAR threshold for adverse effect is assumed to be a continuous/ long term whole body average(WBA) absorption rate of 4 W.kg^{-1}. Fig. 7.9

show different safety factor on this reference limits for different age groups for the frequencies of 10 MHz to 3 GHz.

Table 7.6: Induced contact and contact current limits for 100 kHz to 110 MHz (continuous sinusoidal waveforms). Source: https://standards.ieee.org/standard/C95_1-2005.html.

Condition	Action level[a] (mA)	Persons in controlled environments (mA)
Both feet	90	200
Each foot	45	100
Contact, grasp[b]	—	100
Contact, touch	16.7	50
NOTE 1—Limits apply to current flowing between the body and a grounded object that may be contacted by the person.		
NOTE 2—The averaging time for determination of compliance is 6 minutes.		
[a]MPE for the general public in absence of an RF safety program.		
[b]The grasping contact limit pertains to controlled environments where personnel are trained to make grasping contact and to avoid touch contacts with conductive objects that present the possibility of painful contact.		

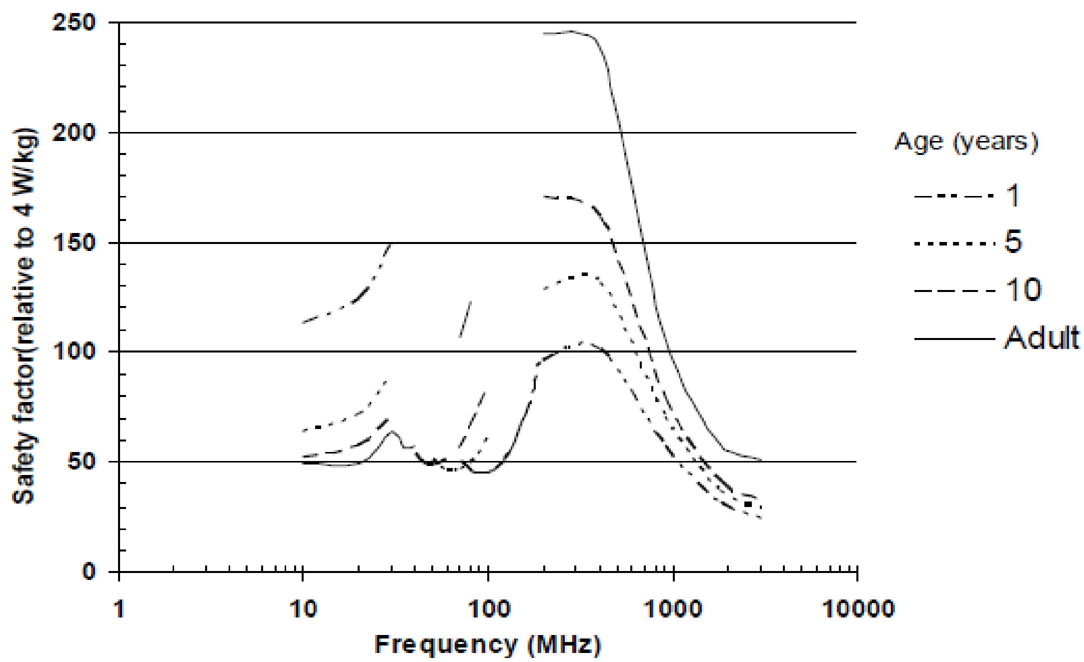


Fig 7.9 Safety factors on SAR limit of 4W/kg for different age groups
Source: : https://standards.ieee.org/standard/C95_1-2005.html

Applicable SAR limit can be calculated from this graph. As an example, the SAR limit at 300MHz for an adult will be 4/245=16.3 mW.kg^{-1}, long term whole body average exposure.

(c) Computing the Specic absorption rate

In most of the cases, the electrical parameters of the equipment and the relative position of the equipment during usage are known. From this it is possible to calculate the field strength (in V/m or Am) or the power density (Wm^{-2}) of the EM radiation. However in order to calculate its absorption rate, it is necessary to know the depth at which the EM radiation penetrates

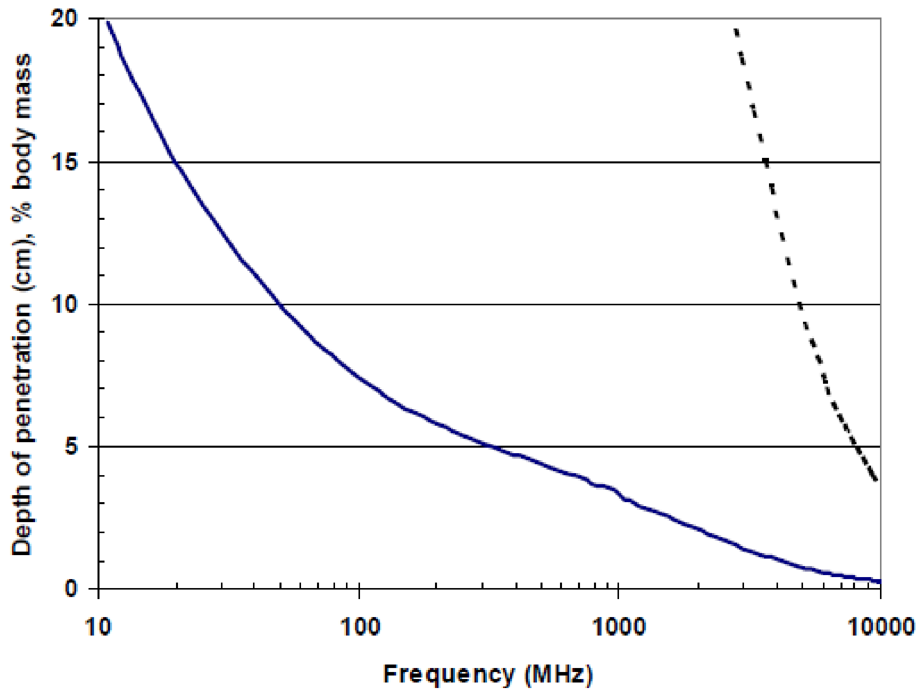


Fig 7.10 The depth of penetration (solid line) and percentage of the body mass (dashed line) in most RF energy is absorbed Source: : https://standards.ieee.org/standard/C95_1-2005.html

Knowing the depth and the exposure area, the volume of the body tissue which absorbs the radiation can be computed. Knowing the tissue density, it is possible to compute the SAR. Using this method the SAR and EM field parameters can be inter-converted.

7.5 Numerical problems