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Dipoles, Unintentional Antennas and EMC

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Abstract: Radiated emissions from equipment commonly originate from electronic circuits that act as electric dipoles created by the signal voltage between the signal conductors or as magnetic dipoles formed by the signal current flowing in a loop. Direct emission is mostly small, but circuits often couple to long conductors or large wiring loops which act as antennas and are efficient radiators.
A comparable situation exists when short dipole antennas or small wiring loops receive ambient noise (susceptibility).
Usually the amplitude of noise sources or the susceptibility of circuits is an invariable. The dipole strength increases with the distance between the conductors and the area. Shielding and proper grounding decreases the interaction via unintentional antennas. Short-circuiting and the insertion of lossy ferrite cores reduce the efficiency of unintentional antennas.

Keywords: Dipoles, Antennas, Emission, Immunity.

1 Introduction

Small electronic circuits behave as combinations of electric and magnetic dipoles. The electric dipole strength is proportional to the signal voltage and to the distance between the signal conductors. The magnetic dipole strength depends on the signal current and the loop area between the conductors. The emission of dipoles follows from the dipole equations. However, an adjacent conductor influences the emission, even without physical contact between the dipole and the conductor – see Fig. 1. Electric and magnetic field coupling induce currents in the conductor. The emission decreases for parallel (side-by-side) constructions, as the field from the current in the conductor cancels part of the electric and magnetic field. The emission increases for co-linear or co-planar constructions, as the current induced in the conductor now flows across a larger distance or a greater area. The increase can be dramatic if the length of the conductor is an appreciable part of the wavelength.

Reception of noise by small dipole antennas and wiring loops increases through the influence of nearby conductors too (reciprocity).

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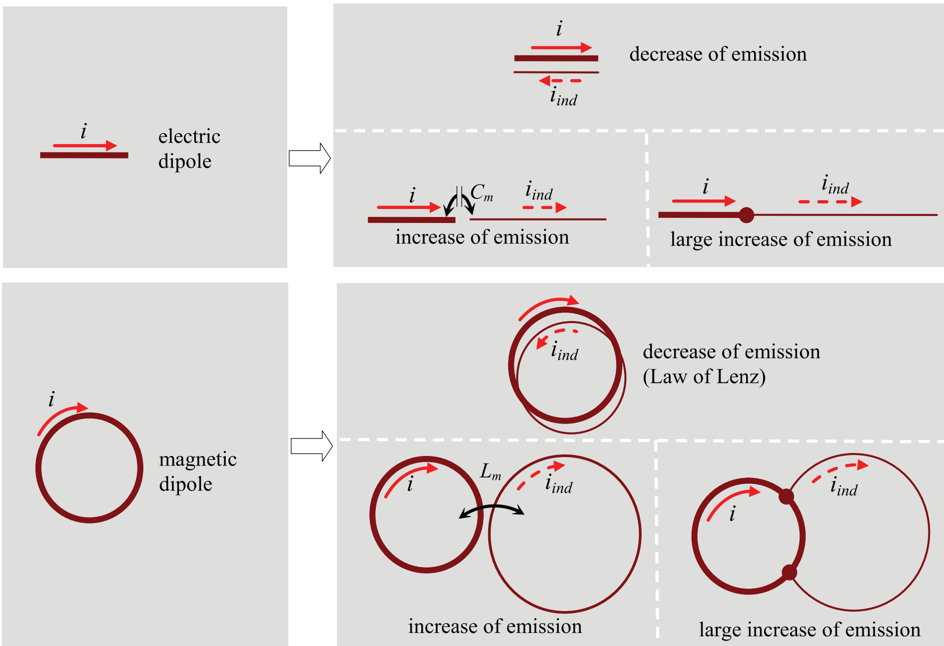

Fig. 1 – *Adjacent conductors influence the dipole emission.*

2 Electric dipoles

2.1 Direct emission of short conductors

High-impedance circuits like liquid crystal displays, CMOS logic, switched-mode power supplies and fluorescent lamps that have small dimensions behave as electric dipoles. The ratio between voltage and current in such circuits is much larger than 377Ω, the impedance of plane waves. The emission is mainly determined by the dipole strength (the product of dipole length and dipole current; the latter being proportional to the signal voltage). The dipole length of most circuits is about equal to the distance between the two signal conductors.

In electronic circuits like digital circuits and switched-mode power supplies, the fundamental and harmonics between frequencies of 30 MHz and 1000 MHz have amplitudes of about 1V. A voltage source connected in series with a short conductor (representing a capacitive load to the source) simulates an electric dipole. The field strength at a distance of 3 m from a dipole of 2×10 mm that is excited in its centre by a voltage source of 1V is shown in Fig. 2. For most frequencies, it is below the mandatory limits of Class B. Compare this with the emission of a tuned dipole antenna when driven by a source of 1V; it now far exceeds the limits.

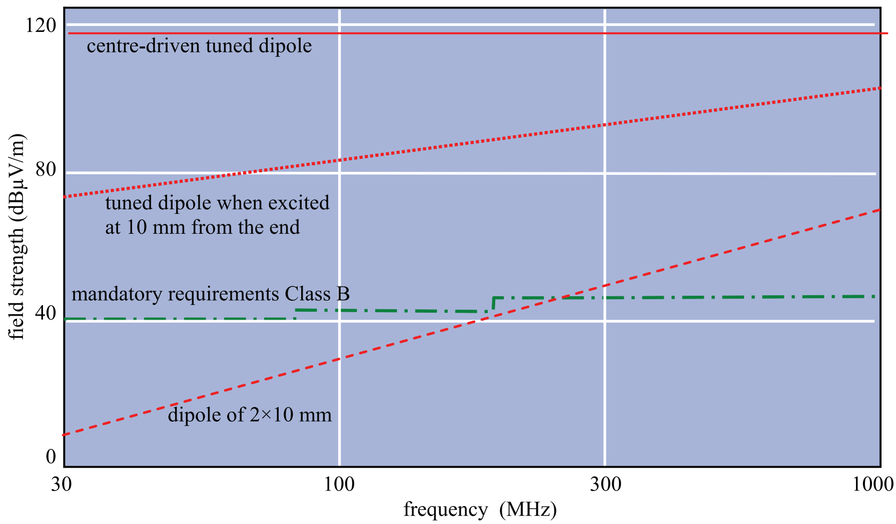

Fig. 2 – *Radiated fields of different dipole antennas at a distance of* 3m; *excitation* 1V.

2.2 Indirect emission of short conductors via unintentional antennas

A large increase of emission can occur through excitation of a long conducting object (for example interface wiring). When this object is connected in series with the short dipole, an asymmetrically excited antenna, a hybrid form of monopole and dipole, is created. Examples are leads to webcams, shavers, hand-held telephones and fluorescent lighting; these leads are excited by noise sources inside the product. One half of the dipole in Fig. 3 is formed by the active pin of an integrated circuit on a printed wiring board, the interface wiring forms the other half and an asymmetric dipole (a non-ideal monopole) is created.

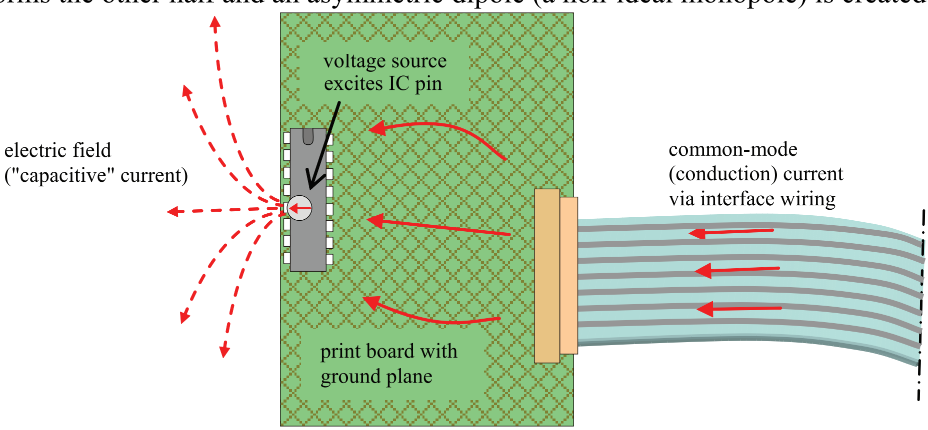

Fig. 3 – *Common-mode excitation of long wiring.*

The voltage induces a current into the antenna, which flows across a greater distance compared to the current via the short dipole. The emission increases, particularly when the long wiring is tuned to the noise frequency. Compare it to plucking near the end the string of a guitar. See Fig. 4.

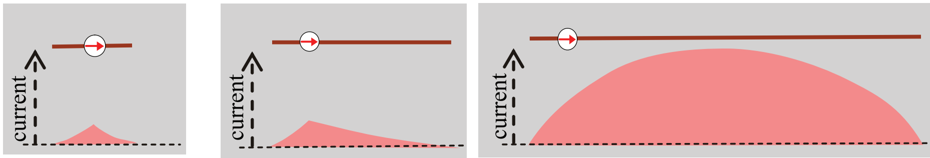

Fig. 4 – *Current along symmetric and asymmetric dipoles.*

For a radiation resistance of 73 Ω in the centre and a sinusoidal current distribution, the resistance at the location of the source is $R_A = 73/[\sin^2(2\ell\pi/\lambda)]$ (Krauss p. 182). When excited with $U_A = 1\,\mathrm{V}$ at $\ell = 10\,\mathrm{mm}$ mm from the end, the radiation increases dramatically – see Fig. 2.

The radiation can also be estimated as follows: Consider a dipole as a circuit with distributed quantities: a capacitance between the two sections, a series inductance and a series resistance – see Fig. 5.

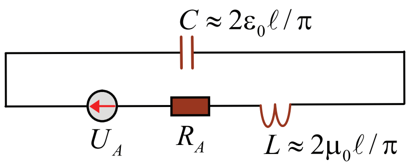

Fig. 5 – *Approximation of equivalent diagram of dipole driven by voltage source.*

C represents the electric flux per unit of voltage and L the magnetic flux per unit of current; both depend on the diameter of the conductor and the current distribution along the dipole. For practical constructions $C \approx 2\varepsilon_0\ell/\pi$, where $\varepsilon_0 = 8.85\cdot10^{-12}$ F/m is permittivity of free space and ℓ is the length of one section of the dipole; $L \approx 2\mu_0\ell/\pi$, where $\mu_0 = 4\pi\cdot10^{-7}\,\mathrm{H/\mu}$ is permeability of free space. For a tuned dipole $\ell = \lambda/4$, so $C \approx \varepsilon_0\lambda/(2\pi)$ F and $L \approx \mu_0\lambda/(2\pi)$ H. R_A represents losses and radiation; it is about 73 Ω for a tuned dipole. See Fig. 6. The capacitance of the 10 mm end is $C \approx 2\varepsilon_0\ell/\pi = 0.056\,\mathrm{F}$. Based on this “circuit”, the radiation found is slightly smaller than calculated before.

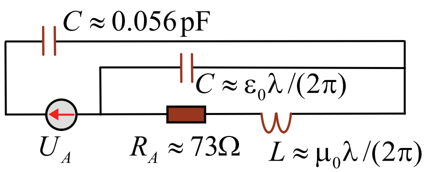

Fig. 6 – *Approximate equivalent diagram of tuned dipole exited at* 10mm *from the end.*

2.3 Direct reception of noise fields by short conductors

A series voltage, so a current, is induced in a conductor when immersed in an electric field. The current in a short conductor follows from the field strength E, the effective length ℓ_{eff} and the distributed capacitance C between the two conductor sections. The current along the conductor is triangular-shaped; the current I_s in the centre is $I_s = E2\pi fC$. This induced "antenna" current determines the reception of noise by a circuit connected in series with the conductor.

Fig. 7 shows the current I_s in the centre of a 2×10 mm dipole, induced by an ambient field of 1 V/m. This small current usually gives no EMC problems. Compare it with the current induced in a (tuned) dipole with a length of $\lambda/2$, where λ is wavelength of the ambient noise field, also shown in Fig. 7.

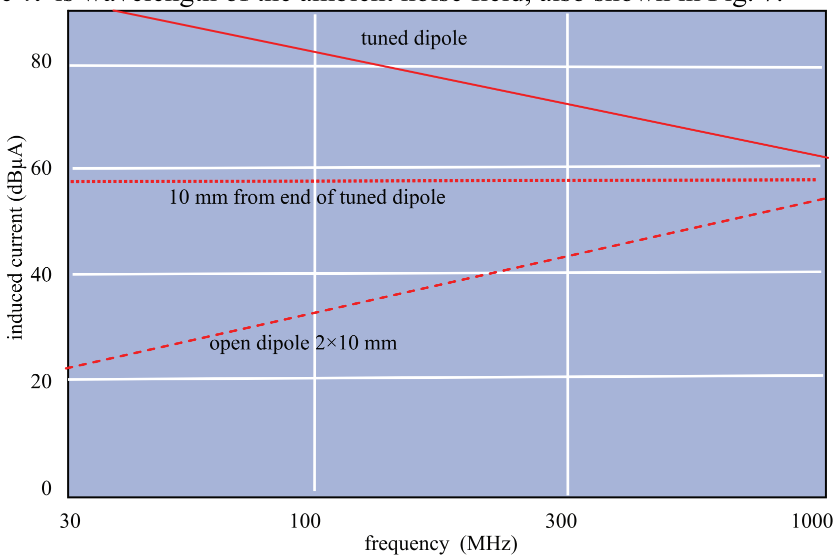

Fig. 7 – *Current induced in centre of conductor immersed in field of* 1 V/m.

2.4 Indirect reception of noise fields via unintentional antennas

Comparable to the emission, the reception of ambient noise also increases when a short conductor to a susceptible circuit forms, in combination with for example a long ground conductor, a tuned dipole antenna, as a large current is now induced in this antenna. The amplitude of the noise induced across the susceptible circuit depends of course on the impedance of the susceptible circuit and on the internal impedance of the antenna at the location of the circuit – see Fig. 4. Fig. 7 also shows the current at 10 mm from the end of a tuned open dipole, assuming that the susceptible circuit does not influence this current. Examples of high-impedance circuits are sensors such as the read diode in a compact disk player, CMOS input circuits and the input of audio amplifiers.

3 Magnetic dipoles

3.1 Emission of small wiring loops

When low-impedance circuits such as AC rectifier circuits and DC supply lines to integrated circuits have small dimensions, they act as magnetic dipoles. The emission is determined by the current and the loop area, therefore the length of the signal conductors and their mutual distance. Noisy loop areas in properly designed equipment are usually small enough to avoid EMC problems. The calculated emission at frequencies between 30 MHz and 1000 Hz from a current loop of 100 mm^2 carrying a current of 1 mA is given in Fig. 8.

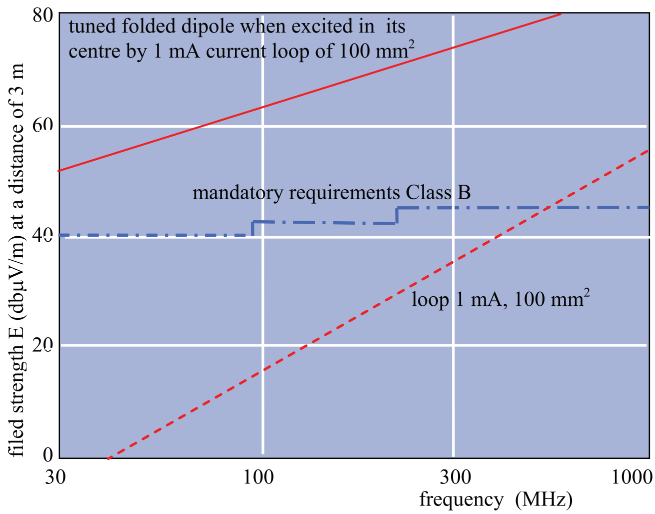

Fig. 8 – *Direct radiation of loop of* 1cm^2 *and indirect emission via tuned dipole antenna.*

3.2 Indirect emission via unintentional antennas

The emission of current loops increases when coupled to other wiring loops: currents are induced in the other loops and large loops are more efficient radiators compared to small loops. Examples are the ground pattern on a printed wiring board and the DC decoupling loop of integrated circuits.

When a small current loop and a large ground loop are connected in parallel, part of the current flows via the ground loop; this part flows via a larger loop area and this increases the dipole strength, so the emission increases. When one of the dimensions of the ground loop is equal to (a multiple of) one half of the wavelength of the noise signal, the emission increases dramatically as then the ground loop forms a tuned folded dipole antenna. An example is a personal computer connected to a printer and both their mains cords connected to the same wall outlet – see Fig. 9.

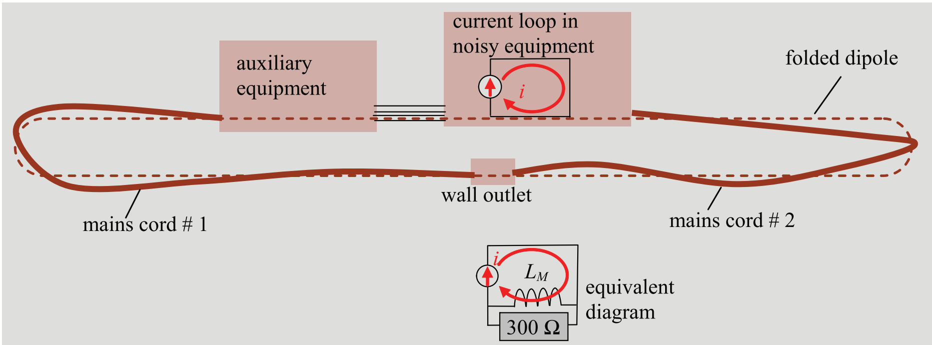

Fig. 9 – *Tuned folded dipole antenna excited by a current loop.*

The parasitic antenna might also consist of an open dipole antenna; an example is a notebook with webcam and external mouse. Usually frequencies are present to which the unintentional antenna is tuned, particularly in digital circuits, wide-band video amplifiers and switched-mode power supplies. The coupling mechanism occurs via mutual inductance (which is equal to the inductance of the common ground conductor) that in practical circuits on printed wiring boards is about 1 nH/mm. The emission of a 100 mm^2 square loop carrying 1 mA and coupled to the centre of a folded dipole antenna (see Fig. 9a) is also shown in Fig. 8 and far exceeds the mandatory limits.

3.3 Direct reception of magnetic noise fields by small wiring loops

The reception of ambient noise fields by a small wiring loop is proportional to the area, the field strength and the noise frequency. The direct reception of ambient noise by signal loops on well-designed print boards is usually small enough to guarantee EMC compliance – see Fig. 10.

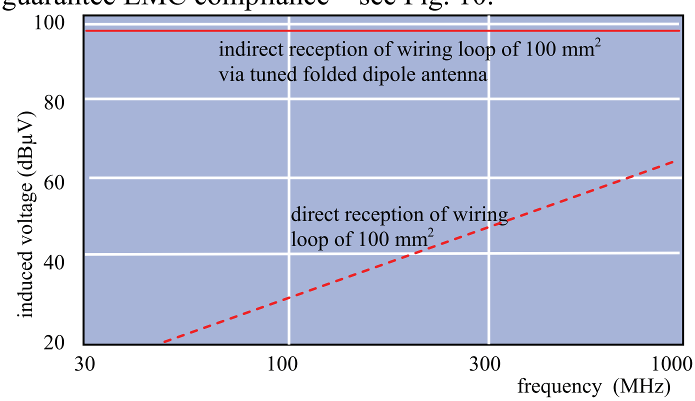

Fig. 10 – *Reception of ambient noise field of* 1 Volt/m.

3.4 Indirect reception of noise fields via unintentional antennas

Unintentional antennas formed by the wiring between equipment and the outside world are good receiving antennas too. Small susceptible wiring loops often couple with these antennas, for example via a ground loop or a DC supply conductor system – see Fig. 9. Ambient noise fields induce currents in such antennas and these in turn induce noise in the signal loop too – see Fig. 10. This indirectly induced noise can be much larger than the directly induced voltage and cause immunity problems, when the wiring forms a tuned antenna.

It follows from Figs. 8 and 10 that problems arise, even if only 1% of the noise couples from or into the parasitic antenna!

4 Solutions to EMC problems caused by unintentional antennas

1) Eliminate the unintentional antenna:
   - Apply optical fibre or "Bluetooth" signal connections,
   - Split power planes into small sections, interconnected via stop-band filters;
2) Short-circuit the field of the antenna – see Fig. 1:
   - Interconnect metalware (brackets, profiles, ground planes, etc); mount noisy or susceptible cables close to it; ground both ends of these cables,
   - Connect heat sinks and metal encasings to ground,
   - Design a ground plane under noisy or susceptible wiring loops,
   - Do not mount integrated circuits close to the edge of printed wiring boards;
3) Decrease efficiency of unintentional antennas with lossy toroid ferrite cores;
4) Decrease the coupling to the "antenna": apply under IC's a ground plane that acts as a common conductor for DC loops carrying large noise currents;
5) Decrease the dipole strength. Apply microstrips with thin isolation, low-profile integrated circuit encapsulations ("BGA", "Flip-chip") with on-chip or built-in DC decoupling capacitors, low-profile connectors; restrict the area of current loops in switched-mode power supplies;
6) Shield the relevant circuit: mount noisy or susceptible wiring loops inside a metal box or under a grounded metal plate.

5 Conclusion

A better understanding of the coupling between small electronic circuits and free space can lead to better EMC designs without risk of overkill.

The treatment in technical courses of the dipole theory should include the non-ideal behaviour of dipoles caused by the influence of adjacent conductors.

6 References

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