8

External Noise

> “Though this be madness, yet there is method in’t”
>
> (W. Shakespeare)

■ **Objective.** The purpose of this chapter is to present external noise sources and to detail the interference coupling mechanisms.

■ **Basic Terms.** In this section, the term *system of interest* denotes the ensemble of electronic circuits whose noise performance is under investigation. For example, the sensor together with its preamplifier or the transmitter-receiver ensemble of a communication system may both be regarded as systems of interest.

Considering the location of the noise source with respect to the system of interest, the noise may be *internal* or *intrinsic* (source located inside the system), or *external* (noise source outside the system). Often external noise is called *interfering signals.*

External noise sources are either natural (such as solar noise, galactic noise, atmospheric noise) or man-made (which include industrial noise, electric motors, arc welders, switches, broadcast communication systems, mobile phones, etc.).

■ **Comparison.** Compared to intrinsic noise, whose main feature is its randomness, many external noise sources are rather deterministic in nature.

A typical example is crosstalk: signals which are deterministic (and useful) in one communication channel can couple into another channel, where they are unwanted, and mask the content of the signals there, so they are treated as external noise.

Another example is high-voltage power lines, which can induce 50-Hz (60-Hz) signals and their harmonics into the systems exposed to their electromagnetic fields. These signals are also deterministic in nature, the only unknowns being their amplitude and phase, which largely depend on the coupling between the noise source and the victim.

In communication systems operating at frequencies up to 50 MHz, external noise picked up by the receiving antenna is generally greater than the internally generated noise, and it therefore represents the main limiting factor. Above this limit, the situation is reversed, and internal noise becomes the limiting factor.

8.1 External Noise Sources

■ **Classification.** External noise sources can be grouped into two categories:

1. Natural noise sources,
2. Man-made noise sources.

Each category includes several items, which are detailed in Table 8.1, where "ISM equipment" stands for "Industrial, Scientific, and Medical equipment".

8.1.1 Natural Noise Sources

■ **Comment.** For convenience, atmospheric noise, precipitation static, solar noise, Galactic noise and hot-Earth noise are all grouped together under "Sky noise." In practice, all quoted noise sources combine with the celestial background in the radiation pattern of the receiving antenna.

Magnetic storms induced by solar flares have the ability to induce damaging surges in power-line voltage, destroying electrical equipment over a huge area. They also dramatically affect signal propagation and sky noise.

■ **Atmospheric Noise.** This is defined as *noise having its source in natural atmospheric phenomena, mainly lightning discharges in thunderstorms.* Their location is time-variable, depending on time of the day, season of the year, weather, altitude, and geographical latitude. As a general rule, they are more frequently encountered in the equatorial region than at temperate latitudes and above. However, the electromagnetic waves produced by thunderstorms propagate at thousands of kilometers via ionospheric skywave.

In the time domain, this noise is characterized by large spikes against a background of short random pulses.

Its frequency spectrum extends up to 20 MHz and the spectral density is proportional to 1/f. Consequently, it mainly affects long-range navigation systems (maritime radio), terrestrial radio broadcasting stations (LW, MW, and SW) and to a considerably lesser extent, FM and TV reception.

■ **Precipitation Static.** *This kind of noise is encountered in rain, snow, hail, and dust storms in the vicinity of the receiving antenna.* Its frequency

Table 8.1. Miscellaneous external noise sources

Natural noise sources	Sky noise	atmospheric noise solar noise Galactic noise hot-Earth noise precipitation static
	Magnetic storms	
	Telluric currents	
Man-made noise sources	Industrial (electromagnetic) noise sources	spark plugs in ignition systems arc welders electric motors and switches high-voltage transmission lines 220 V / 50 Hz supply lines neon signs radio and TV broadcast services ISM equipment cellular telephones mobile radios household appliances
	Electrostatic noise sources	triboelectric effect piezoelectric effect
	Non-electric noise sources	galvanic action electrochemical effect Seebeck effect contact noise

spectrum peaks below 10 MHz. It can be substantially reduced by eliminating sharp metallic points from the antenna and its surroundings, and by providing paths to drain static charges that build up on an antenna and in its vicinity during storms.

■ **Galactic Noise.** According to [141], this is defined as *noise at radio frequencies caused by disturbances that originate outside the Earth or its atmosphere.*

Galactic noise sources can be grouped into two classes: discrete sources and distributed sources.

In the former category the chief source is the Sun, together with thousands of known discrete sources, such as supernova remnant Cassiopeia A, one of the most intense sources of cosmic radio emission as viewed from Earth. The Sun is the most powerful noise source, with its temperature of about 6000°C and its proximity to Earth. Its energy is radiated in a continuous mode, and the frequency spectrum mainly covers the range from several MHz up to several GHz. During quiescent periods, the Sun's noise temperature is about

700,000 K at 200 MHz, and about 6000 K at 30 GHz. However, during sunspot and solar-flare activity these values are considerably higher.

Also belonging to this category are the quasars, which emit copious quantities of energy (usually as powerful radio waves), often in a continuous mode, although the signals arriving at Earth are perceptible only by sensitive radiotelescopes.

The *distributed noise sources* are the ionized interstellar gas clouds in our Galaxy and a considerable number of extragalactic sources known as radio galaxies. Depending on emission mechanisms, the distributed noise sources are thermal or nonthermal [142]. So-called thermal noise sources are associated with random encounters of electrons and ions in gas clouds, mostly ionized hydrogen. Nonthermal noise sources (also called synchrotron radiation) involve electrons moving in magnetic fields. This is a general galactic phenomenon, encountered even in interstellar space.

As a general rule, cosmic radio noise covers the frequency range from 15 MHz up to 100 GHz, with a predominance between 40 MHz and 250 MHz. It is observed that it reaches a maximum when the receiving antenna points toward the center of the Milky Way.

■ **Sky Noise.** This term lumps the effects of all previous noise sources. Experimentally, it has been found that for a receiving antenna pointing toward the zenith (elevation angle of 90°), the typical variation of the sky noise temperature versus frequency looks like the plot of Fig. 8.1. Two peaks appear: the first is situated near 22 GHz (where the atmospheric absorption of radio waves reaches a maximum, as a consequence of water vapor), and the second is located at about 60 GHz, due to oxygen absorption. (It is well known that both oxygen and water vapor can absorb energy from a radio wave due to the permanent electric dipole moment of their respective molecules.)

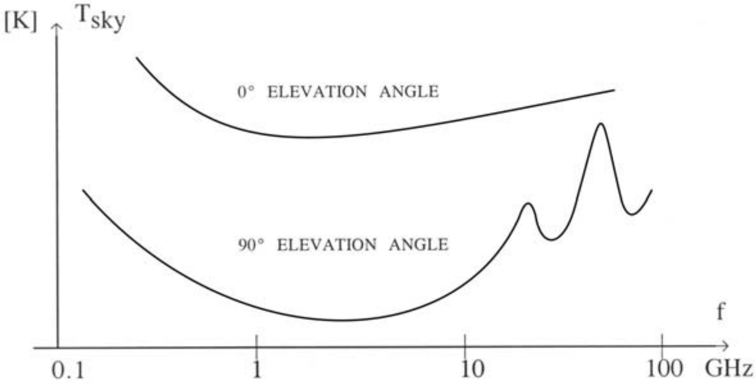

Fig. 8.1. Sky noise temperature versus frequency

Table 8.2. Approximate limits of sky noise temperature

	Maximum	Average	Minimum
Sky noise temperature	$1450\,\lambda^2$	$100\,\lambda^{2.4}$	$58\,\lambda^2$

Globally, in the frequency range $1-10\,\mathrm{GHz}$ the received noise power is at a minimum (this is also called the "space communication window").

Of course, the sky temperature depends strongly on antenna orientation: if the elevation angle is low (approaching zero), the sky temperature increases because the antenna looks through much more atmosphere.

According to various publications, Table 8.2 groups the approximate limits of sky noise temperature for the VHF range (30 MHz to 300 MHz), where λ denotes the corresponding wavelength, expressed in meters.

■ **Remark.** In microwave communication systems, the actual noise power received by the antenna is more important than the value predicted by Table 8.2. To understand why, consider a steerable dish antenna pointing toward a satellite.

Ideally (Fig. 8.2a), the beamwidth of the antenna should exactly cover the angular diameter of the satellite, to avoid noise picked up from regions outside the target.

However, in practice, the beamwidth of any single practical ground based antenna is far larger then the minuscule angular extent of the target satellite (Fig. 8.2b). In this case the antenna "sees" more sky noise than in the ideal situation and this explains why the values predicted by Table 8.2 are lower limits.

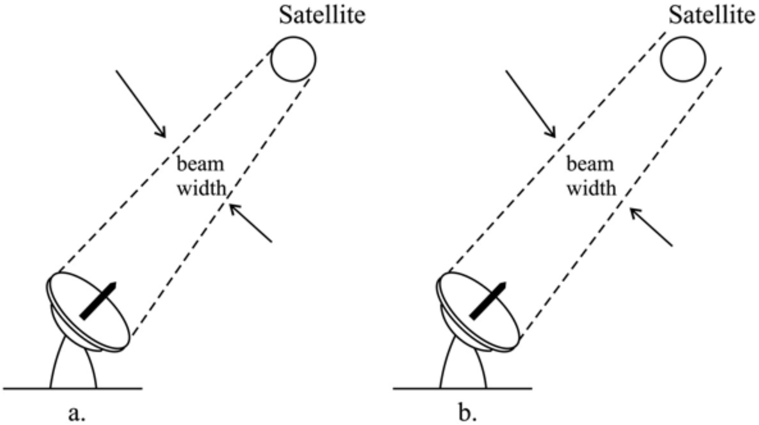

Fig. 8.2. Beamwidth of an antenna relative to the angular diameter of a satellite: **a** ideal case; **b** real case

8.1.2 Man-Made Noise Sources

■ **Classification.** Depending on origin, these noise sources are grouped in three categories:

1. Electromagnetic sources,
2. Electrostatic sources,
3. Non-electric sources.

■ Electromagnetic Noise Sources

☐ **Automotive Ignition Systems.** There are two major sources: spark plugs and the current flowing through the ignition system. Both are responsible for radiated electromagnetic energy, which comes in bursts of short duration pulses (nanoseconds), the burst width ranging from microseconds to milliseconds. The frequency of the bursts depends on the number of cylinders in the motor and the angular motor speed (RPM). It can be reduced by using spark plugs with a built-in interference suppressor and shielding the entire ignition system (when possible).

☐ **Arc Welders.** Typically, arc welders use an RF arc whose fundamental frequency is around 2.8 MHz [143]. Their spectrum covers the 3 kHz to 250 MHz frequency range, but the fundamental remains at a significant level even at a distance of several hundred meters. In radio receivers, this noise is perceived as a “frying” noise. The emission is considerably reduced by improving welder grounding, using short welding leads, shielding wiring, and avoiding proximity to power lines.

☐ **Electric Motors.** All high-power motors involved in electric transport systems (underground, trains, conveyor belts, elevators, etc.) generate noise when switched, but also do so in steady-state operation. Switching produces transients which can reach several hundred volts as a result of current interruption in an inductive load. In the steady state, motor brushes are responsible for arc production, which increases with aging. Besides radiation, these sparks generate spurious signals that are conducted and distributed to nearby systems by the power supply lines. The same problem (although less aggressive) appears in all household appliances that use electric motors (washing machines, vacuum cleaners, ventilators, etc.). This noise can be reduced by inspecting the motor brushes and changing them when necessary, as well as by adding a capacitor of about 1 μF in parallel, to suppress sparks. Note that massive introduction of microprocessors to control the operation of equipment has also a favorable effect on noise generation.

☐ **High-Voltage Transmission Lines.** Noise from transmission lines peaks at 50 (60) Hz, and it can cause interference at distances of several hundred meters. It is especially perceptible in AM receivers. Transients associated with switching of loads occur in bursts, and have rise times of a few nanoseconds; amplitude spikes larger than 2 KV are seldom observed. Another major source of noise is the Corona effect, which consists in a large number of discharges around the conductors of a power line. This occurs when the electric field around the conductor exceeds the value required to ionize the ambient gas (air), but is insufficient to cause a spark. Discharges are initiated by the presence of small irregularities in the conductor surface (like dust, pollen, snow, ice crystals, etc.) and the resulting noise mainly affects AM communication systems.

☐ **AC Supply Lines.** The 220 (or 110) V supply lines connect all the rooms of a building in a power distribution network, as well as all nearby buildings. Besides its proper 50 (or 60) Hz fields and the transients caused by switching various loads, the mains wiring constitutes an excellent antenna, which picks up noise radiated in one room from perturbing equipment and delivers it to all other rooms sharing the same line. Hence, it propagates perturbations from one site to another. In order to protect sensitive equipment, filters and surge suppressors must be provided so that the bulk of energy is absorbed before it claims victims. Various types of surge suppressors exist, such as gas-discharge devices (which can handle high power, but are slow) and semiconductor devices (using Zener diodes).

☐ **Fluorescent Lamps and Neon Signs.** Noise is generated in two distinct areas:

1) In the ionized gas column, which presents a small but fluctuating resistance when the light is on.
2) In the associated circuitry, which includes a starter. Usually, the starter is made of a bimetallic strip, which bends when the temperature changes and abruptly breaks the current flowing through an inductor. A voltage spike occurs, which is used to trigger the discharge; however, this spike is also a source of interference for nearby systems.

☐ **ISM Equipment.** This category includes industrial equipment (such as relay-controlled devices, electrical switching gear, laser cutters, microwave ovens, etc.), scientific equipment (for instance, all sorts of computer facilities), and medical equipment for intensive care units, physical therapy facilities, electrosurgical units, diathermy, CAT scanners, etc. The frequency spectrum of these noise sources can extend up to several megahertz or even gigahertz.

☐ **Radio, Television, and Radar Transmitters.** These are intentional emitters of electromagnetic waves that can interfere with systems not intended for any form of reception. All such transmitters have considerable power, since they must cover a large area. Less powerful (but no less harmful) are electromagnetic waves emitted by CB transmitters, cellular phones, mobile radios, portable computers, and so forth.

☐ **Power Supplies.** The major noise sources belonging to this category are DC/DC converters and switching-mode power supplies. Both employ switching transistors operating at frequencies up to 100 kHz (but with actual V-MOS devices, the tendency is to increase the switching frequency, for higher efficiency). The frequency spectrum is dominated by the fundamental and its harmonics, but it extends well above the switching frequency fundamental.

■ Electrostatic Noise Sources

☐ **Triboelectric Effect.** This entails *generating electrostatic charges of opposite sign when two materials are rubbed together and separated*, leaving one positively charged and the other negatively charged [144]. The term *triboelectricity* refers to electricity produced by friction of two dissimilar solids (as by sliding). In practice, this phenomenon affects mainly the dielectric material within a coaxial cable. When the cable bends, the metallic conductors slide along the dielectric used to separate them (if the dielectric does not maintain permanent contact with the metallic parts). A charge accumulation appears in the equivalent capacitor formed between the metallic shield and the inner conductor, separated by the insulator. This charge fluctuates according to the rhythm of mechanical flexing of the cable and hence acts as a noise source. This phenomenon is especially pertinent when the coaxial cable is used to connect a generator with high internal impedance to a high-value load (like an electrometer). In this situation, the discharge of the equivalent capacitor through the terminal impedances is slow, and additional flexing of the cable causes additional charge to accumulate. For instance, a coaxial cable terminated by 10-MΩ resistances generates noise voltages by intermittent flexing which fluctuate during 50% of the monitoring time around a few millivolts; however, if the terminal resistances are lowered to 1 MΩ, the noise voltage level decreases to several hundred microvolts. If the cable is terminated by low impedances, triboelectricity is no longer a factor.

This kind of noise is critical in cables employed in vehicles, satellite or airborne instruments, rockets, and military applications, where vibration is unavoidable. The best solution is to reduce vibration whenever possible; otherwise, special low-noise cable can be used, where friction is reduced by an additional layer of graphite (Fig. 8.3).

☐ **Piezoelectric Effect.** This is defined as *the generation of a potential difference in a crystal when a strain is introduced.* In piezoelectric materials the converse effect is also observed, namely that a strain results from the application of an electric field [145]. In practice, some circuit board materials exhibit this effect. Consequently, they are vibration-sensitive, and noise voltages can

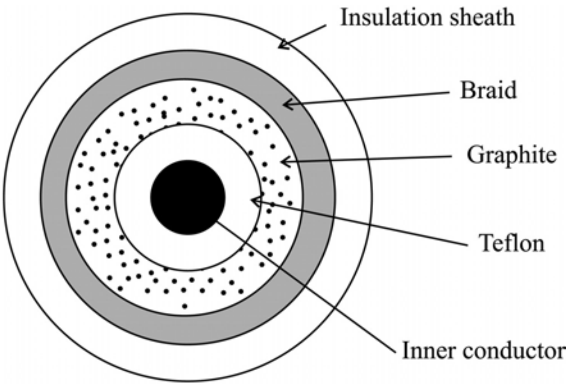

Fig. 8.3. Low-noise coaxial cable (cross-section)

appear between conductors connected to opposite sides, or between tracks situated on opposite sides. To avoid this kind of noise, the only solution is to carefully select circuit boards employing insulators that do not exhibit the piezoelectric effect.

■ **Noise of Non-electrical Origin.** Under this label are grouped non-electric phenomena that generate voltage or current fluctuations. Among them, the most important ones are:

□ **Galvanic Action.** Whenever two dissimilar metals are used in the same connecting path, *an e.m.f. at the contact area appears due to the electrochemical action of the two metals.* This e.m.f. will normally keep a constant value determined by the position of the metals in the galvanic series. However, in the presence of water vapor or moisture (that penetrates the contact region), the metal surface (especially at the anode) is degraded by corrosion. The rate of corrosion depends on the relative positions of the metals in the galvanic series (the closer they are, the slower the corrosion), the moisture level and temperature. As a consequence, the e.m.f. fluctuates according to external conditions, and this noise can corrupt the useful signal.

□ **Electrochemical Contamination.** This phenomenon is chiefly encountered on printed circuit boards, where *fluctuating voltages can appear across two metallic tracks separated by a contaminated insulating material* (which as an electrolyte). Often the contamination is the result of poorly cleaning the flux from a circuit board after soldering, although small particles of oxides and abrasives can also contaminate the surface during fabrication. The remedy is to carefully clean the circuit board after soldering to remove all residues. Sealing and coating the assembly with a protective film represents the final step in circuit board fabrication.

☐ **Seebeck Effect.** According to [146], *this is the production of an e.m.f. in a circuit comprising two dissimilar metals when the two sides of the junction are at different temperatures.* Assume a junction of two metals, denoted by 1 and 2, such that metal 2 is at higher temperature than metal 1. The junction voltage difference appearing is proportional to $(T_2 - T_1)$. Fluctuation in $(T_2 - T_1)$ can result from turbulent convection of air or from local variations in temperature. As a result, fluctuation in the voltage difference is also observed, which becomes a noise source.

Two types of metal junctions are commonly encountered in electronic circuits:

- gold plating on connectors and copper traces on a circuit board;
- a copper trace with tin solder applied. The latter might be locally overheated, for instance by a lead from a power device connected (soldered) to the point in question.

Since it is impossible to avoid junctions between dissimilar metals, it is recommended that they be selected so that the Seebeck effect is as small as possible. For instance, a junction of copper and a tin-lead solder alloy has a Seebeck voltage in the range $1 - 3\,\mu\mathrm{V}/^\circ\mathrm{C}$. However, if a tin-cadmium alloy is used instead, this value drops to only $0.3\,\mu\mathrm{V}/^\circ\mathrm{C}$. Finally, good ventilation of the equipment and better heat evacuation has a favorable effect on this noise source.

☐ **Poor Mechanical Contacts.** Typically, such contacts are parts of a relay, switch, or connector that is engaged or disengaged to open or close some electrical circuit [146]. Heavy-duty operation of such devices leads to oxidation and mechanical deterioration of the contact surfaces. The contact pressure becomes lower and moisture and dust accumulate, forming thin films on the surface. Finally the contact resistance increases, and even worse, fluctuates. Consequently, the current flowing through the contact in question also fluctuates. The only remedy is to periodically clean the contact surface, or to completely replace the contacts whenever necessary.

☐ **Poor Solder Joints.** Most insidious are solder joints, which despite their normal appearance, can either contain flux/paste residues or be affected by defects (formation of voids which contain flux, micro-cracks, etc.). As a consequence, the distributed electrical resistance inside the joint is nonuniform, the current density varies locally from one micro-region to another, and the area which supports the maximum current density risks overheating. Hence, the current becomes even more non-uniformly distributed, etc. Finally, fluctuating resistance is associated with the poor solder joint, at a level that depends on the current, temperature, aging, vibrations, etc.

Detecting eventual poor solder joints on a circuit board is a difficult task; once they are found, the only remedy is to resolder them manually.

8.2 Glossary of Terms

■ **Absorber.** According to [147], *a material that causes the irreversible conversion of the energy of an electromagnetic wave into another form of energy (normally heat) as a result of interaction with the absorbed material.*

■ **Absorption.** *The loss of electromagnetic energy due to conversion into heat or other forms of energy, as a result of interaction with matter.*

■ **Attenuation.** *Decrease in signal energy, usually expressed in decibels.*

■ **Balun.** *A device for transforming an unbalanced voltage to a balanced voltage or vice versa* [147]. The term "balun" is an acronym for "BALanced-to-UNbalanced".

■ **Bond.** *A reliable connection to assure the required electrical conductivity between conductive parts, to maintain a common electrical potential* [145].

■ **Bonding.** *A process of connecting metal structures together in order to achieve a low resistance contact* [143].

■ **Bus.** *A conductor, or group of conductors, that serve as a common connection for two or more circuits* [145].

■ **Crosstalk.** *Undesired energy (disturbance) appearing in a transmission path by mutual coupling with other transmission paths.*

■ **Electromagnetic Compatibility (EMC).** *The capability of electronic systems, equipment or devices to operate in their intended electromagnetic environment without suffering or causing unacceptable degradation of performance as a result of electromagnetic interference.* Note that EMC has two aspects: the *emission* of perturbations and the *susceptibility* to perturbations.

■ **Electromagnetic Environment.** *The totality of electromagnetic phenomena existing at a given location.* This term is pertinent to the electromagnetic energy which is *unintentionally* conducted/radiated away.

■ **Electromagnetic Gasket.** *A conductive insert usually between flanges, intended to provide electrical continuity across a joint and to prevent intrusion of electromagnetic waves.*

■ **Electromagnetic Immunity.** *A relative measure of a device or system's ability to withstand EMI exposure while maintaining a predefined performance level.*

■ **Electromagnetic Interference (EMI).** *EMI is the degradation of the performance of a device, circuit, or system caused by an electromagnetic perturbation.*

■ **Electromagnetic Perturbation.** *Any electromagnetic phenomenon able to alter the performance of an electronic device, circuit, or system.*

■ **Electromagnetic Susceptibility.** *A relative measure of a device or system's inability to perform without degradation in the presence of an electromagnetic perturbation.* Lack of electromagnetic immunity.

■ **Emission.** *The propagation of electromagnetic energy liberated by a source, by radiation, or conduction.*

■ **Far-Field Region.** *The region of the field of a transmitting antenna where the angular field distribution is essentially independent of the distance from the antenna* [147].

■ **Ground (Earth).** *A conductive system whose potential is taken as reference for all voltages in the circuit.* This may or may not be an actual connection to earth, but it could be connected to earth without disturbing the operation of the circuit in any way. Note that an electronic system may have several grounds, and some of them can even float (for instance, a TV receiver has 3 different grounds, so-called "signal grounds" or "local grounds"). The signal grounds may or may not be at earth potential. In contrast, the ground connected to earth is called "safety ground."

■ **Ground Plane.** According to [145,147], *a conducting flat surface or plate used (1) as a common reference point for circuit returns, as well as for electric or signal potentials; and (2) to reflect emitted electromagnetic waves.* Note that a ground plane can bend and follow a curved surface.

■ **Interfering Signal.** *A signal that impairs the reception of a useful signal.*

■ **Isolation.** *Separation of one section of a system from undesired influences of other sections.* This may be achieved either by galvanic separation, or by inserting a high impedance between the sections in question.

■ **Near-Field Region.** *The region of the field of a transmitting antenna wherein the angular field distribution is dependent on the distance from the antenna* [147].

■ **Plane Wave.** *A wave whose equiphase surfaces form a family of parallel planes.*

■ **Radiation.** *The propagation of energy through space or through a material in the form of electromagnetic waves.* Usually classified according to frequency, e.g., Hertzian, microwaves, infrared, visible, ultraviolet, X rays, gamma rays, etc.

■ **Reflection.** *The phenomenon in which a wave that strikes a medium of different characteristics is returned to the original medium with the angles of incidence and reflection equal and lying in the same plane* (for instance, at the air-metal interface of a shield, or more generally, at any abrupt discontinuity of refractive index).

■ **Relative Conductivity (σ_r).** *A material constant which indicates (relative to copper) the electrical conductivity of the material.*

■ **Relative Permeability (μ_r).** *A material constant which indicates (relative to copper) the ability of the material to concentrate magnetic field lines.*

■ **Shield.** *A conducting barrier separating sources from receptors to reduce the effects of source electromagnetic fields upon receptors* [147].

■ **Shielding Effectiveness.** *An insertion loss measure of the ability of a shield to exclude or confine electromagnetic waves, usually expressed as a ratio (in the frequency domain) of the incident to penetrating signal amplitudes, in decibels* [147].

■ **Shielding Enclosure.** As stated in [147], *a metallic mesh, sheet housing, or continuous conductive layer designed expressly for the purpose of separating the internal and external electromagnetic environments.*

8.3 Interference Problem

■ **Physical Approach.** Electromagnetic perturbations are present everywhere, and they are a constitutive part of our industrial civilization. Interference occurs when the situation depicted in Fig. 8.4 is encountered.

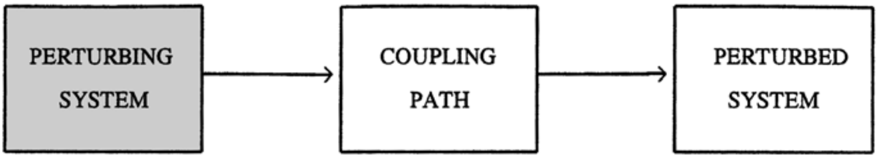

Fig. 8.4. Overview of the electromagnetic interference problem

Three conditions are simultaneously required: the presence of a source of perturbations (perturbing or aggressor system), the presence of a perturbed system (victim), and at least one coupling path to transmit the noise from source to victim.

It is important to know how the aggressor is coupled to the victim, since in many practical situations, reducing the coupling coefficient is the only way to fight interference.

■ **Classification.** Two main situations are encountered:

1) Both aggressor and victim belong to the same system or facility. In this case, the interference is *inside* the system of interest.
2) The source of perturbation belongs to one system and the victim to another (for example, the aggressor is a mainframe computer and the victim is a radio receiver). The interference then appears between two distinct systems.

Note that in some situations the same equipment is both aggressor and its own victim.

■ **Solution.** To reduce interference, there are three possible approaches:

- reduce the emission of perturbations at the source,
- reduce the electromagnetic susceptibility of the victim,
- reduce the coupling between aggressor and victim.

Each will be detailed in a distinct chapter.

8.4 Coupling Paths

■ **Background.** Accurate modeling of coupling paths requires solving Maxwell's equations, which are differential equations containing the derivatives of the electric and magnetic fields with respect to time and with respect to three orthogonal spatial variables. The main difficulty arises from complicated boundary conditions affecting these equations, since at the interface between two media, the E and H fields can be discontinuous. To overcome this difficulty, the space dependency of E and H is often neglected, analysis being carried out only in the time domain (which is accurate for systems of small electrical length). In this way, approximate solutions (as functions of time) are delivered. From a conceptual point of view, this approach is equivalent to adopting the following assumptions [148]:

- all electric fields are confined inside capacitors,
- all magnetic fields are confined inside inductors,
- dimensions of the circuit are small compared to the signal wavelength(s).

Hence, the coupling paths (which are actually distributed elements) are represented by means of their lumped equivalents. Besides a considerable simplification of the problem, the expected benefit is clarify how interference depends on the system parameters, layout, or package. This information is not available from the solution of Maxwell's equations, even if accurately solving them were possible.

Of course, the drawback of this approach is the limited accuracy of the solution (but it should be remembered that the ultimate goal of analysis is to check that the perturbation does not exceed an imposed threshold, rather than finding an exact solution!).

8.4.1 Methods of Noise Coupling

■ **Coupling Paths.** Coupling paths can be grouped under two categories: conduction paths and radiation paths. The electrical power lines represent the traditional example of conductive coupling, especially when both the aggressor and victim share the same power line. An illustration of both categories is shown in Fig. 8.5, where the perturbations generated by the motor are transported by the distribution network to the victim (radio receiver). The radiation path transports the perturbation produced by the ignition system of a nearby car engine to the antenna of the receiver through free-space.

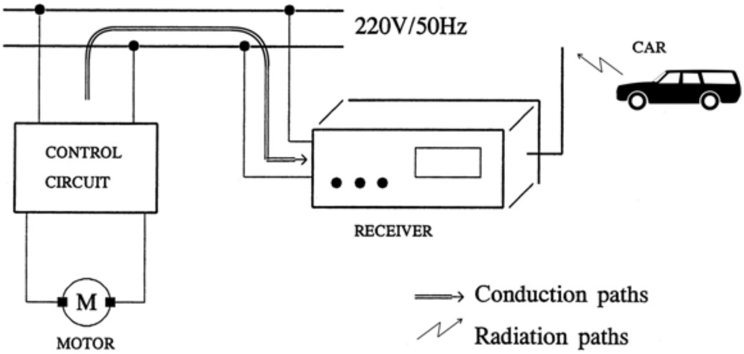

Fig. 8.5. Coupling paths in industrial environment

■ **Conducted Noise.** This kind of noise (also called conducted interference) is due to interfering signals that can propagate from source to victim via a conductive path. Depending upon the kind of conductive path involved, the commonest practical situations include:

☐ **AC Power Lines.** Consider the typical situation in which two different pieces of equipment connected to adjacent outlets share the same AC line

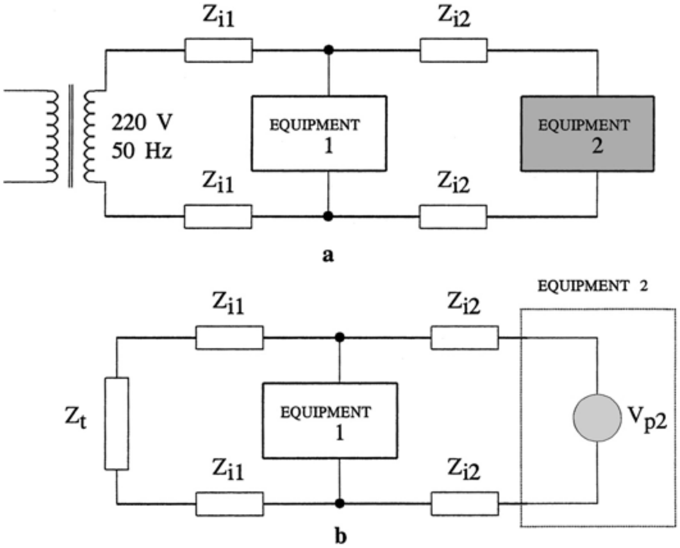

Fig. 8.6. **a** Conductive coupling through AC power supply; **b** equivalent circuit

(Fig. 8.6a). Let EQUIPMENT 2 be the source of perturbations and EQUIPMENT 1 the victim.

The equivalent circuit is shown in Fig. 8.6b, where Z_{i1}, Z_{i2} represent the impedances of the mains lines, which can on the average be approximated by 50 Ω resistances in parallel with 50 µH inductances [149]. Z_t is the impedance seen in the secondary of the transformer and V_{p2} represents the perturbations produced by the source. Applying the voltage divider formula, the amount of perturbing voltage reaching EQUIPMENT 1 is

$$V_{p1} = V_{p2} \frac{2Z_{i1} + Z_t}{2(Z_{i1} + Z_{i2}) + Z_t} \tag{8.1}$$

Note that V_{p1} increases when Z_{i2} is reduced (i.e., when the separating distance between the two units decreases). When $Z_{i2} \ll Z_{i1}$, $V_{p1} \cong V_{p2}$ and there is no attenuation of perturbations reaching the victim. The only remedy is to insert filters at the AC terminals of EQUIPMENT 1.

☐ **Common Ground Impedance.** Another type of conductive coupling is by means of a common ground impedance. Consider the circuit detailed in Fig. 8.7 involving two amplifiers, where M1, M2 are respectively a signal ground and the ground plane of the equipment. The connection between them is achieved by a short wire (or strip), which, at low frequency, acts like a short circuit. However, at higher frequencies the parasitic self inductance (L) of this wire and its associated resistance (R) give rise to an impedance which is no longer negligible.

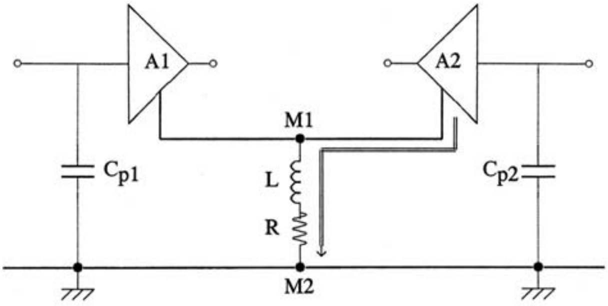

Fig. 8.7. Undesired coupling due to ground return impedance

Suppose that C_{p1} and C_{p2} are the stray capacitances between each input and ground; due to the current injected by the amplifier A2 into ground, a voltage drop appears on the series combination of L and R:

$$v = Ri + L\frac{di}{dt}$$

Despite the low value of L, the second term of the sum becomes dominant, especially when fast switching currents are flowing. This voltage transient is transmitted through C_{p1} and C_{p2} to the inputs and is then amplified, just like any useful signal.

■ **Radiated Noise.** Radiated noise is usually in the form of electromagnetic fields that escape from the source and reach the victim via propagation. This noise is transmitted by:

- *Capacitive coupling* (through the stray capacitances between wires or tracks on the circuit board), when electric field induction is dominant.
- *Inductive coupling* (mainly between cables or circuit board tracks), when magnetic field induction is dominant.
- *Electromagnetic coupling*, through the wires, cables, and circuit board traces of the victim system, which all act like small receiving antennas. Note that at the usual power levels, all involved fields drop off rapidly with distance, and are significant only close to the source.

□ **Capacitive Coupling.** This mechanism is illustrated in Fig. 8.8, where the load Z_L is connected to the amplifier output by a wire (or a trace on the circuit board), which passes close to the wire (or trace) connected to the input of amplifier A2. The coupling capacitance between wires is distributed (Fig 8.8a); however, for simplicity it is represented in Fig. 8.8b as a lumped capacitor, labeled C_p.

The flow of current I_L through Z_L charges the left "plate" of C_p and as a consequence, the same amount of electric charge (but of opposite sign) will be induced on the right "plate". This is equivalent to a parasitic voltage V_p appearing at the input of amplifier A2, such that

$$V_p = C_p \frac{dV_L}{dt} (Z_{in} \parallel R_g) \tag{8.2}$$

where Z_{in} represents the input impedance of A2 and R_g is the resistance of the signal generator V_g. Of course, reducing C_p (by increasing the separation between wires or traces) can help to reduce V_p, but the unexpected conclusion from (8.2) is that *a low input impedance of the victim circuit increases immunity to perturbations transmitted via capacitive coupling.*

If either of the grounds M1 or M2 is floating, the only difference is that the stray capacitance between the point in question and ground will be seen in series with C_p. Finally, the best solutions to reduce this type of interference are:

- decrease the coupling capacitance C_p by increasing the separation of traces or by shielding (for instance, introduce a ground trace between the traces in question);
- reduce the input impedance of the victim circuit (when possible).

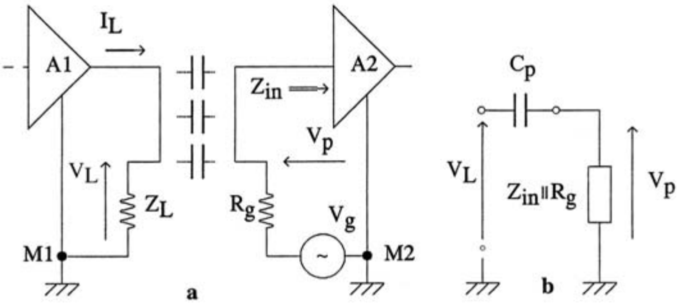

Fig. 8.8. **a** Capacitive coupling between wires; **b** Equivalent circuit

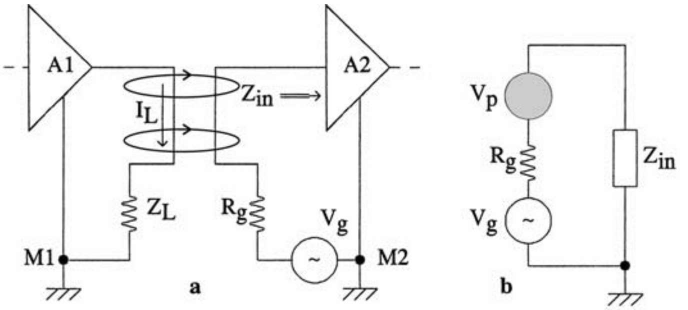

Fig. 8.9. **a** Magnetic coupling; **b** equivalent circuit

□ **Magnetic Coupling.** This kind of coupling is illustrated in Fig. 8.9, where the current flowing through the output loop of amplifier A1 produces a magnetic field whose lines intersect the input loop of amplifier A2 [149].

Consequently, an induced parasitic voltage V_p appears in the input loop, which can be evaluated as

$$V_p = -M \frac{dI_L}{dt} \tag{8.3}$$

M being the mutual inductance between the loops (which depends on both loop areas, their orientation, and their separation). In the equivalent circuit, the perturbing voltage V_p is in series with the signal generator V_g, hence the noise is added to the useful signal. Note that V_p is unaffected by whether or not M1 and M2 are floating or connected to ground.

To decrease the noise induced by magnetic coupling, three solutions may be considered:

- limit the area of the victim loop by properly designing the layout;
- reduce the magnetic field by shielding or by decreasing the output current in the aggressor circuit;
- when possible, modify the loop orientations so that their planes become perpendicular.

□ **Electromagnetic Coupling.** Traditionally, this term refers to coupling between an electromagnetic plane wave and a transmission line (recall that a plane wave has both fields perpendicular to the direction of propagation and perpendicular to each other). In the present case, the electromagnetic coupling appears between the intentionally emitted waves (like TV and broadcast services, radars, etc.) and each wire of the circuit, which acts like a receiving antenna.

■ **Concluding Remark.** In practice, whenever the emitting source is close to the victim circuit (near-field condition), the E and H fields can be dissociated and treated separately. However, if the aggressor and the victim are far from each other (far-field condition), the two fields must be simultaneously considered (electromagnetic coupling).

8.4.2 Coupling Modes

■ **Comment.** Whenever a non-random perturbation contaminates the useful signal, it seems natural to ask what the phase difference is between them, in order to appreciate the damage. Thus, differential-mode coupling and common-mode coupling will not have the same effect on the resulting interference.

Since both modes have their origin in the theory of differential amplifiers, it is important to recall some basic concepts.

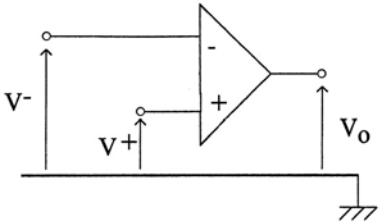

Fig. 8.10. Differential amplifier

■ **Ideal Differential Amplifier.** *An ideal differential amplifier is defined as a symmetrical circuit with two inputs and one output* (Fig. 8.10) *that amplifies the difference between two input signals.*

Let us denote by V^+ and V^- the input signals with respect to ground; according to the given definition, the output voltage is

$$V_o = A_d(V^+ - V^-) \tag{8.4}$$

where A_d is called the *differential gain.* Typical values for A_d lie between 10^4 and 10^6.

Note that if the same voltage is simultaneously applied to V^+ and V^-, the output of the ideal differential amplifier is unaffected. Hence, the output voltage V_o is the same, regardless of the value of input signals, as long as their difference is the same. For instance, $V^+ = 10\,\mu V$, $V^- = -10\,\mu V$ would yield the same output as $V^+ = 1010\,\mu V$, $V^- = 990\,\mu V$.

■ **Actual Amplifier.** In practical amplifiers, the output depends not only on the difference between the input voltages, *but also on the average value of the input signals.* Briefly, this is due to the impossibility of achieving a perfect symmetry.

Of course, the average value of the input signals (called *common-mode voltage*) does not exert a significant influence, but nevertheless it can modify the expression (8.4):

$$V_o = A_d(V^+ - V^-) + A_c\left(\frac{V^+ - V^-}{2}\right) \tag{8.5}$$

where A_c is called the *common-mode gain.* Typical values of A_c are between some fraction of unity and some small multiple; the greater the value of A_c, the more important the asymmetry of the amplifier.

As a figure of merit indicating amplifier symmetry, the *common-mode rejection ratio* (CMRR) is defined to be

$$\mathrm{CMRR} = 20\log\frac{A_d}{A_c} \quad [\mathrm{dB}] \tag{8.6}$$

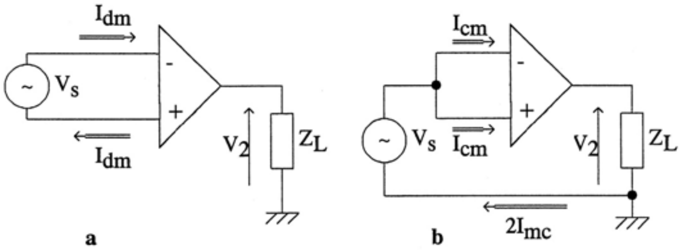

Fig. 8.11. a Differential-mode operation; **b** Common-mode operation

■ **Modes.** An operational amplifier operates in the differential mode (Fig. 8.11a) when the signal is applied between its inputs ($V_s = V^+ - V^-$). It is important to note that differential-mode input currents (denoted by I_{dm}) have *opposite directions.*

Common-mode operation occurs (Fig. 8.11b) when the voltage signal is *common* to both inputs. In this case the input currents have the *same direction.* Note that the return current (carried out by the ground) is twice as great and flows in the opposite direction.

■ **Coupling Modes.** In this section, the concept of coupling mode refers instead to the coupling between a radiated field and a victim circuit (although the same concepts may apply to conducted perturbations also). Each mode will be next detailed.

☐ **Differential Mode Coupling.** Similarly to the case illustrated in Fig. 8.11a, *an electromagnetic field is said to be coupled in differential mode if the induced currents flow in opposite directions.* Consider the situation depicted in Fig. 8.12, where the perturbing currents (I_p) are induced in the wires connecting two circuits belonging to the system of interest. The region of vulnerability is apparent.

Z_1 and Z_2 are the impedances to ground of circuits 1 and 2, respectively. They are either real impedances, or the equivalent impedances of the stray

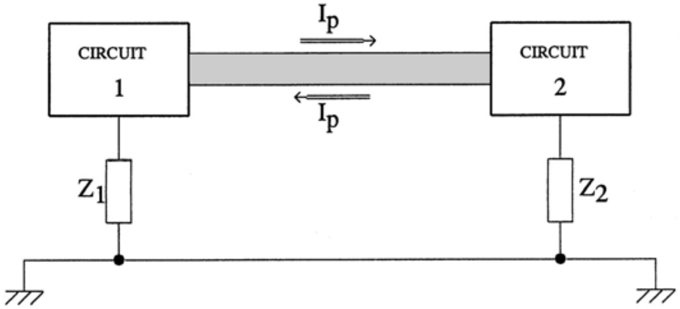

Fig. 8.12. Differential-mode coupling

capacitances to ground (when both circuits are floating), or the equivalent impedances of the bonding wires to ground. In any case, they have no influence on I_p.

☐ **Common-Mode Coupling.** Similarly to the general case shown in Fig. 8.11b, *a perturbing field is coupled in common mode if the resulting currents (apart from the return) all flow in the same direction.* This time the vulnerability area includes the ground plane; consequently, this time impedances Z_1, Z_2 affect both the amplitude and the spectrum of the induced currents (I_p).

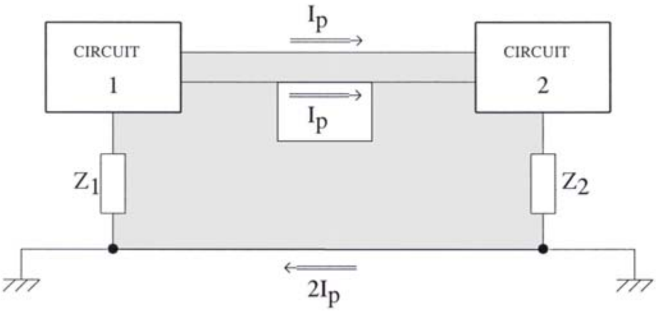

Fig. 8.13. Common-mode coupling

☐ **Antenna-Mode Coupling.** In this case, circuits 1 and 2, as well as the connecting wires (including the ground plane), all act as receiving antennas with respect to the perturbing field (Fig. 8.14). *The currents carried by the interconnecting wires and the ground plane all flow in the same direction.*

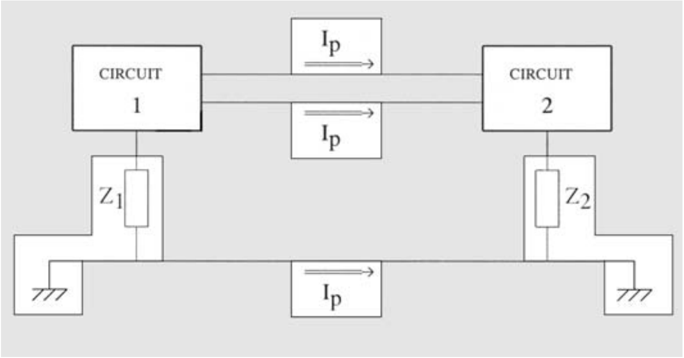

Fig. 8.14. Antenna-mode coupling

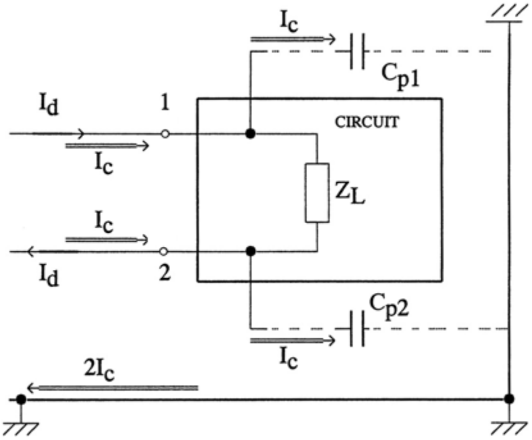

Fig. 8.15. Conversion between common- and differential-mode

■ **Conversion.** Interference may appear between the common-mode induced signals and the differential-mode signals (Fig. 8.15).

The useful signal is the voltage drop produced by the differential mode current I_d across the load impedance Z_L. However, due to the inherent stray capacitances to ground (C_{p1}, C_{p2}) which support the common mode currents (I_c), an additional differential-mode voltage may appear:

$$V_{ad} = I_c(Z_1 - Z_2) \tag{8.7}$$

where Z_1, Z_2 are the equivalent impedances of C_{p1}, C_{p2} respectively. Note that V_{ad} cancels if and only if the configuration is *perfectly balanced* (i.e., $Z_1 = Z_2$). The perfect balancing condition is not easily achieved in practice. Several solutions are proposed to ensure a well-balanced configuration:

- design a symmetrical layout (with identical trace configurations in the areas of C_{p1} and C_{p2});
- avoid the vicinity of any metallic body (shield, transformer etc.) that might introduce an asymmetry;
- whenever possible, add in parallel with C_{p1}, C_{p2} identical discrete capacitors (of higher value than the expected stray capacitances) to swamp the imbalance;
- use a common-mode choke.

■ **Remark.** The analysis of coupling between source and victim does not depend on the radiated or conducted nature of interfering signals.

Summary

- Noise sources can be grouped into three categories:
  1) intrinsic sources;
  2) man-made noise sources;
  3) environment noise sources.
- Sky noise includes cosmic noise, solar noise, and atmospheric noise.
- Electromagnetic perturbations are transmitted from source to victim either by radiation or conduction.
- There are three basic coupling modes:
  1) differential-mode coupling;
  2) common-mode coupling;
  3) antenna-mode coupling.
- Radiated noise can reach the victim in three ways:
  1) by capacitive coupling;
  2) by inductive coupling;
  3) by electromagnetic coupling.