Chapter 1

Introduction

1.1 What is EMC?

Electromagnetic interference (EMI) is a serious and increasing form of environmental pollution. Its effects range from minor annoyances due to crackles on broadcast reception, to potentially fatal accidents due to corruption of safety-critical control systems. Various forms of EMI may cause electrical and electronic malfunctions, can prevent the proper use of the radio frequency spectrum, can ignite flammable or other hazardous atmospheres, and may even have a direct effect on human tissue. As electronic systems penetrate more deeply into all aspects of society, so both the potential for interference effects and the potential for serious EMI-induced incidents increases.

Electromagnetic *compatibility* (EMC), then, is the absence of effects due to EMI. The definition of EMC, as it appears in the International Electrotechnical Vocabulary [152], is:

> The ability of a device, equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbance to anything in that environment.

Some reported examples of electromagnetic *in*compatibility are:

- in Norfolk, various makes of car would “go crazy” when they passed a particular air defence radar installation – dashboard indicators dropping to zero or maximum, lights and engines cutting out;
- on one type of car, the central door locking and electric sunroof would operate when the car’s mobile transmitter was used;
- new electronic push-button telephones installed near the Brookmans Park medium wave transmitter in North London were constantly afflicted with BBC radio programmes;
- interference to aeronautical safety communications at a US airport was traced to an electronic cash register a mile away;
- the instrument panel of a well-known airliner was said to carry the warning “ignore all instruments while transmitting HF”;
- electronic point-of-sale units used in shoe, clothing and optician shops (where thick carpets and nylon-coated assistants were common) would experience lock up, false data and uncontrolled drawer openings;
- when a piezo-electric cigarette lighter was lit near the cabinet of a car park barrier control box, the radiated pulse caused the barrier to open and drivers were able to park free of charge;

- lowering the pantographs of electric locomotives at British Rail's Liverpool Street station interfered with newly installed signalling control equipment, causing the signals to "fail safe" to red;
- a digital TV set-top box initiated an air–sea rescue operation in Portsmouth harbour by creating an emission on the distress frequency;
- two Navy warships nearly collided when the radar transmissions of the frigate HMAS Anzac disabled the steering of the minehunter HMAS Huon, Huon passing ahead of Anzac "at close range".

Many other examples have been collected over the years; the "Banana Skins" column in the *EMC Journal*, collated by Keith Armstrong, is a fruitful source, and the EMC group of the former UK Radiocommunications Agency commissioned an EMC Awareness web page introducing the subject [203], which also contains a number of examples. Here are a few issues in more detail.

1.1.1 Portable electronic devices in aircraft

Mobile cellular telephones are rapidly establishing themselves, through their sheer proliferation, as a serious EMC threat. Passengers boarding civil airliners are now familiar with the announcement that the use of such devices is not permitted on board. They may be less familiar with why this is regarded as necessary. The IFALPA International Quarterly Review reported 97 EMI-related events due to passenger "carry-on" electronic devices since 1983. To quote the Review:

> ... By 1990, the number of people boarding aeroplanes with electronic devices had grown significantly and the low-voltage operation of modern aircraft digital electronics were potentially more susceptible to EMI.
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> A look at the data during the last ten years indicates that the most likely time to experience EMI emissions is during cruise flight. This may be misleading, however. During the last three years, 43% of the reported events occurred in cruise flight while an almost equal percentage of events occurred in the climb and approach phases.
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> Of particular note: during the last three years the number of events relating to computers, compact disc players, and phones has dramatically increased and these devices have been found to more likely cause interference with systems which control the flight of the aircraft.
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> Recognising an apparent instrument or autopilot malfunction to be EMI related may be difficult or impossible in many situations. In some reported events the aircraft was off course but indications in the cockpit displayed on course. Air traffic controllers had to bring the course deviations to the attention of the crews. It is believed that there are EMI events happening that are not recognised as related to EMI and therefore not reported.

Particular points noted by the Review were that:

- events are on the rise;
- all phases of flight are exposed (not just cruise);
- many devices may cause EMI (phones, computers, CD players, video cameras, stereos);
- often there will be more than one device on a flight;
- passengers will turn on a device even after being told to turn it off[†];
- passengers will conceal usage of some devices (phones, computers);
- passengers will turn devices on just after take-off and just prior to landing;
- phones are a critical problem;

- specific device type and location should be recorded and reported by the crew;
- when the emitting EMI device is shut off, the aircraft systems return to normal operation (in the case of positioning errors a course change may be necessary);
- flight attendants should be briefed to recognize possible EMI devices.

In 2000, the Civil Aviation Authority carried out tests on two aircraft parked at Gatwick, which reinforces the ban on the use of mobile phones while the engine is running [64]. The tests revealed that interference levels varied with relatively small changes in the phone's location, and that the number of passengers on the flight could affect the level, since they absorbed some of the signal. Further testing has been done since, publicly reported in [198], which showed that at the GSM mobile frequencies it was possible to create the following interference effects:

- compass froze or overshot actual magnetic bearing;
- instability of indicators;
- digital VOR (VHF Omnidirectional Ranging, an aeronautical navigation aid using the VHF spectrum) navigation bearing display errors up to 5 degrees;
- VOR navigation To/From indicator reversal;
- VOR and ILS (Instrument Landing System, an aeronautical navigation aid using the VHF spectrum) course deviation indicator errors with and without a failure flag;
- reduced sensitivity of the ILS Localiser receiver;
- background noise on audio outputs.

Nevertheless, there is considerable public pressure to allow use of cellphones on board, and the fact that more often than not interference *doesn't* actually create problems has led to the perception that there *isn't* a problem. To deal with both of these issues, some airlines are trialling a system which actually allows cellphones to be used via a pico-cell base station on the aircraft, communicating via satellite with the ground networks. The EMC implication of this is that because the base station is very local, the phones are able to transmit at their minimum power, thus (hopefully) eliminating EMC interactions. Even so, there will almost certainly be restrictions on use, only above 10,000 feet and not during takeoff and landing.

1.1.2 Interference to medical devices

Another critical area with potentially life-threatening consequences is the EMC of electronic medical devices. A 1995 review article [122] described three incidents in detail and listed more than 100 EMI problems that were reported to the US Food & Drug Administration between 1979 and 1993. It states bluntly that:

> EMI-related performance degradation in electronic medical devices has resulted in deaths, serious injuries, and the administration of inappropriate and possibly life-threatening treatment.

† Especially if they regard their need for personal communication as more important than a mere request from the crew. [64] reports that an aircraft carrying a German foreign minister had to make an emergency landing "after key cockpit equipment cut out". It was claimed that mobile phone transmissions could be the only explanation and it was said that, "despite repeated requests from the crew, there were still a number of journalists and foreign office personnel using their phones".

The detailed case studies were as follows:

- apnea monitors: the essential function of an apnea monitor is to sound an alarm when breathing stops; the devices are used in hospitals and frequently prescribed for home use in the case of infants who either have exhibited or are at risk of experiencing prolonged apnea. After numerous reports of unexplained failure on the part of apnea monitors to alarm even upon death, their susceptibility to radiated RF was evaluated by the US Center for Devices and Radiological Health (CDRH). Most commercial apnea monitors were found to erroneously detect respiration when exposed to relatively low field strengths, a situation that could result in failure to alarm during apnea. Most monitors were found to be susceptible above 1V/m; one particular model was susceptible to pulsed fields above 0.05V/m.
- anaesthetic gas monitor: the CDRH received several reports of erroneous displays and latch-up of an anaesthetic gas monitor during surgery. None of the reports mentioned EMI as a possible cause. FDA investigators found that the manufacturer had a list of 13 complaint sites, and his own investigations revealed that interference from certain types of electrosurgery units disrupted the communication link between the monitor and a central mass spectrometer, causing the monitor to fail to display the concentration of anaesthetic gas in the operating room during surgery.
- powered wheelchairs: a QA manager at a large wheelchair manufacturer had received reports of powered wheelchairs spontaneously driving off kerbs or piers when police or fire vehicles, harbour patrol boats, or CB or amateur radios were in the vicinity. Though CDRH databases showed reports of unintended motion – in several cases involving serious injury – none of these incidents had been attributed to EMI. When CDRH investigated the EMI susceptibility of the motion controllers on various makes of powered wheelchairs and scooters, they discovered susceptibilities in the range of 5 to 15V/m. At the lower end of the range, the electric brakes would release, which could result in rolling if the chair happened to be stopped on an incline; as the field strength at a susceptible frequency was increased, the wheels would actually begin turning, with the speed being a function of field strength.

Another issue is the effect on hearing aids:

> The problem of interference to hearing aids has been known for some time. Digital mobile phones use a form of radio transmission called Time Division Multiple Access (TDMA), which works by switching the radio frequency carrier rapidly on and off. If a hearing aid user is close to a digital mobile telephone, this switching of the radio frequency carrier may be picked up on the circuitry of the hearing aid. Where interference occurs, this results in a buzzing noise which varies from very faint to maximum volume of the aid... [A specialist standards panel] has determined that, although digital mobile telephones are being looked at as the source of likely interference, all radio systems using TDMA or similar transmissions are likely to cause some interference.
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> *BSI News December 1993*

These are all examples of the lack of a product's "fitness for purpose": that is, to operate correctly and safely in its intended environment, which includes the electromagnetic environment. There are clear safety implications in the reports.

1.1.2.1 Hospital and emergency service radio management

Many types of hospital equipment are susceptible to RF radiation from hand-portable mobile radio transmitters – diagnostic equipment such as ECGs, EEGs, pulse oximeters and other physiological monitoring equipment; and therapeutic equipment such as infusion pumps, ventilators and defibrillators. Physiological (patient-coupled) monitoring equipment is very sensitive and hence very susceptible, although for every device type, some models consistently perform better than average (they exhibit good EMC design). The type of modulation employed by the mobile transmitter can be significant. For example, an external pacemaker withstood a GSM signal (modulated at 217Hz) at 30V/m field strength, but TETRA modulation (17Hz) caused interference at 3V/m.

This is of particular concern for ambulances, which in Europe are mandated to use the TETRA system for emergency communications, but which also carry an array of patient-coupled instrumentation for life support purposes. This has led to the UK's Medicines and Healthcare Products Regulatory Agency (MHRA) recommending as follows [199]:

- the use of portable handsets and cellphones inside ambulances should be restricted;
- special precautions are needed if a patient with an external pacemaker is being transported;
- displaying warning notices, providing staff training, and relocating parking bays are possible actions if risks of interference prove unacceptable when emergency vehicles are parked immediately outside patient treatment areas;
- caution should be exercised when treating patients with medical devices at the scene of an accident if an emergency vehicle is nearby;
- mobile data terminals should be subjected to any restrictions which are locally applied to cellphones.

Various studies have tested medical devices and recommend that a distance of 1 to 1.5m be maintained between typical hand-portable transmitters and medical equipment. The MHRA tested 178 different models of medical device using a wide range of radio handsets. Overall, in 23% of tests medical devices suffered electromagnetic interference (EMI) from handsets. 43% of these interference incidents would have had a direct impact on patient care, and were rated as serious. Only 4% exhibited effects with cellphones at 1m distance, although at that distance emergency and security handsets had much greater effects [200].

The difficulty with controlling the use of radio communications in hospitals and other medical situations is well illustrated in the MHRA's guidance document [201], which itself refers to an ISO technical report on the subject [170]:

> Overly-restrictive policies may act as obstacles to beneficial technology and may not address the growing need for personal communication of patients, visitors and the workforce. At the other extreme, unmanaged use of mobile communications can place patients at risk.

The guidance stresses the need for an effective policy for healthcare providers to manage the use of the radio frequency spectrum in their own sites. This includes considering areas where medical devices will not be affected and therefore no restrictions apply, and other areas where authorized staff can use communication devices authorized by the hospital. Incidents should be reported when a medical device is suspected to have suffered electromagnetic interference.

1.1.2.2 Diathermy and electrosurgery

As well as radio communications, medical diathermy and electrosurgery are well known as a source of significant interference problems that most surgeons simply learn to cope with. Medical diathermy (tissue heating) used for physiotherapy typically operates at 27MHz with RF powers up to 400W, although modern pulsed diathermy uses average RF powers around 40W; but these levels are more than enough to interfere with many kinds of electro-medical equipment, particularly monitors.

1.1.3 Thermostats

Thermostats and other automatic switching contacts of all sorts are a major source of noise complaints, particularly when they are faulty. The former UK Radiocommunications Agency dealt with many cases of interference caused by thermostats or the radio-suppression components fitted to them. In about 90% of these cases, the interference is attributable to thermostats in gas boilers. It seems that, as these operate in a heat-stressed environment, they are prone to more rapid deterioration than other domestic thermostats such as room thermostats, cylinder thermostats and diverter switching valves. Sometimes the offending thermostat is found in the house that is suffering the interference, although there have been cases where the source of the interference has been found some distance away.

New domestic appliances are required to pass tests for "discontinuous disturbance" emissions (the current harmonized standard is EN 55014-1), but this does not guarantee that such products will remain noise-free after many years of operation. The limits for RF emissions are related in a complex way to the repetition rate and duration of the automatic switching event.

An example is the interference signal generated from a boiler gas control valve and its associated thermostat switching from stand-by to ON and vice versa. The low power single-phase arc causes a short burst of radiation. When the thermostat is malfunctioning this burst of radiation can be heard as a rough rasping noise which typically lasts for a few seconds but may last for 20 seconds or more. It repeats typically every 10 minutes but in some cases, a faulty thermostat may arc several times per minute. This kind of interference, which is intermittent in nature, is mostly noticed in relation to the reception of analogue TV signals at 470 to 850 MHz and sometimes on FM radio at 88–108 MHz.

Replacing the faulty thermostat will normally resolve the problem, but a better solution is to fit suppression to all such switching contacts. This prevents the arc forming at the instant of switching and if properly designed has the side effect of lengthening the contact life, but the added cost is usually viewed unfavourably by manufacturers.

1.1.4 The quacking duck

In a lighter vein, probably the least critical EMC problem this author has encountered is the case of the quacking duck: there is a toy for the under-fives, which is a fluffy duck with a speech synthesizer which is programmed to quack various nursery rhyme tunes. It does this when a certain spot (hiding a sensor) on the duck is pressed, and it shouldn't do it otherwise. Whilst it was in its Christmas wrapping in our house, which is not electrically noisy, it was silent. But when it was taken to our daughter's house and left in the kitchen on top of the fridge, next to the microwave oven, the Christmas present quacked apparently at random and with noone going near it. Some disconcerting moments arose before it was eventually explained to the family that this was just another case of bad EMC and that they shouldn't start to doubt their sanity!

1.2 Compatibility between and within systems

The threat of EMI is controlled by adopting the practices of electromagnetic compatibility (EMC), as defined earlier. The concept of EMC has two complementary aspects:

- it describes the ability of electrical and electronic systems to operate without interfering with other systems;
- it also describes the ability of such systems to operate as intended within a specified electromagnetic environment.

Thus it is closely related to the environment within which the system operates. Effective EMC requires that the system is designed, manufactured and tested with regard to its predicted operational electromagnetic environment: that is, the totality of electromagnetic phenomena existing at its location. Although the term "electromagnetic" tends to suggest an emphasis on high frequency field-related phenomena, in practice the definition of EMC encompasses all frequencies and coupling paths, from DC through mains supply frequencies to radio frequencies and microwaves. And "phenomena" is not restricted to radio-based phenomena but also transient events and power-related disturbances.

1.2.1 Intra-system EMC

There are two approaches to EMC. In one case the nature of the installation determines the approach. EMC is especially problematic when several electronic or electrical systems are packed into a very compact installation, such as on board aircraft, ships, satellites or other vehicles. In these cases susceptible systems may be located very close to powerful emitters and special precautions are needed to maintain compatibility. To do this cost-effectively calls for a detailed knowledge of both the installation circumstances and the characteristics of the emitters and their potential victims. Military, aerospace and vehicle EMC specifications have evolved to meet this need and are well established in their particular industry sectors.

This, then, can be characterized as an int*ra*-system approach: the EMC interactions occur between parts of the overall system, the whole of which is amenable to characterization. It may not be necessary or desirable to draw a boundary around individual products in the system, but rather to consider how they affect or are affected by other parts of the same system. Mitigation measures can be applied as easily, and sometimes more easily, at the system level as at the equipment level.

1.2.2 Inter-system EMC

The second approach assumes that the system will operate in an environment which is electromagnetically benign within certain limits, and that its proximity to other sensitive equipment will also be controlled within limits. This approach is appropriate for most electronics used in homes, offices and industry, and similar environments. So for example, most of the time a personal computer will not be operated in the vicinity of a high power radar transmitter, nor will it be put right next to a mobile radio receiving antenna. This allows a very broad set of limits to be placed on both the permissible emissions from a device and on the levels of disturbance within which the device should reasonably be expected to continue operating. These limits are directly related to the class of environment – domestic, commercial, industrial, etc. – for which the device is marketed. The limits and the methods of demonstrating that they have been met form the basis for a set of standards, some aimed at emissions and some at immunity, for the EMC performance of any given product *in isolation*. This makes it an int*er*-system approach rather than an int*ra*-system approach, and means that a necessary part of the process is defining the boundary of the product – easy for typical commercial electronic devices, harder when it comes to installations.

Note that compliance with such standards will not guarantee electromagnetic compatibility under all conditions. Rather, it establishes a probability (hopefully very high) that equipment will not cause interference nor be susceptible to it when operated under *typical* conditions. There will inevitably be some special circumstances under which proper EMC will not be attained – such as operating a computer within the near field of a powerful transmitter – and extra protection measures must be accepted.

1.2.3 When intra-system meets inter-system

Difficulty arises when these two approaches are confused one with the other, or at the interface where they meet. This can happen when commercial equipment is used in other environments, for instance on vehicles or in aircraft, and we get the issues referred to earlier, for instance with passenger electronic devices; the PED might be compliant with its normal requirements but that isn't necessarily relevant to its use in these different surroundings. Military projects might require commercial-off-the-shelf (COTS) products to be procured, but their EMC performance requirements are substantially mismatched to military needs. Grounding and bonding techniques which are necessary and appropriate for intra-system requirements can be misapplied to attempt to meet the EMC Directive.

From the product designer's point of view, many of the necessary techniques are similar or common to both approaches, but there are instances where they diverge and so we need to be clear about which approach is being considered in any given case.

1.3 The scope of EMC

1.3.1 Malfunction of control systems

Solid state and especially processor-based control systems have taken over many functions which were earlier the preserve of electromechanical or analogue equipment such as relay logic or proportional controllers. Rather than being hard-wired to perform a particular task, programmable electronic systems rely on a digital bus-linked architecture in which many signals are multiplexed onto a single hardware bus under software control. Not only is such a structure more susceptible to interference, because of the low level of energy needed to induce a change of state, but the effects of the interference are impossible to predict; a random pulse may or may not corrupt the operation depending on its timing with respect to the internal clock, the data that is being transferred and the program's execution state. Continuous interference may have no effect as long as it remains below the logic threshold, but when it increases further the processor operation will be completely disrupted. With increasing functional complexity comes the likelihood of system failure in complex and unexpected failure modes.

Clearly the consequences of interference to control systems will depend on the value of the process that is being controlled. In some cases disruption of control may be no more than a nuisance, in others it may be economically damaging or even life threatening. The level of effort that is put into assuring compatibility will depend on the expected consequences of failure.

1.3.1.1 Phenomena

Electromagnetic phenomena which can be expected to interfere with control systems are:

- supply voltage interruptions, dips, surges and fluctuations;
- fast transient overvoltages (spikes and surges) on supply, signal and control lines;
- radio frequency fields, both pulsed (radar) and continuous, coupled directly into the equipment or onto its connected cables;
- electrostatic discharge (ESD) from a charged object or person;
- low frequency magnetic or electric fields.

The stress levels that can occur for each of these phenomena depend largely on the local environment, with industrial areas expected to be more stressful than, say, residential or commercial. Special environments such as military, automotive and aerospace can be expected to have even higher levels of some phenomena. The levels are reflected in the standards for immunity testing, which are covered in later chapters.

Note that we are not directly concerned with the phenomenon of component damage due to ESD, which is mainly a problem of electronic production. Once the components are assembled into a unit they are protected from such damage unless the design is particularly lax. But an ESD transient can corrupt the operation of a microprocessor or clocked circuit just as a transient coupled into the supply or signal ports can, without actually damaging any components (although this may also occur), and this is properly an EMC phenomenon.

1.3.1.2 Software

Malfunctions due to faulty software may often be confused with those due to EMI. Especially with real-time systems, transient coincidences of external conditions with critical software execution states can cause operational failure which is difficult or impossible to replicate, and the fault may survive development testing to remain latent for years in fielded equipment. The symptoms – system crashes, incorrect operation or faulty data – can be identical to those induced by EMI. In fact you may only be able to distinguish faulty software from poor EMC by characterizing the environment in which the system is installed.

1.3.2 Immunity of data and programme processing

A very large class of EMC problems comes not with the impact of disturbance on electronic controls, but on various types of system which process audio, video material or data – telecomms and consumer applications being the main areas. Interference here manifests as corruption of data or degradation of the audio or video programme that is being enjoyed.

The phenomena which cause the effects are the same as those discussed above in section 1.3.1.1. In the worst case these can cause complete loss of function; as before, in digitally-based systems this is usually a result of transient interference interrupting the processor program control. But before that level is reached, lower levels of transients and continuous radio frequency disturbances can affect the analogue sections of the equipment and cause annoying effects on the programme material itself, particularly demodulation effects which appear as distortion of the video picture or extraneous audible noise on an audio programme. The buzzing noise that occurs when you place a mobile cellphone next to your radio or TV set, which warns you that it is about to ring, or when you are engaged on a call, is an example of this phenomenon. Other examples which were more prevalent in the days before RF immunity requirements became well established are the pickup of taxi mobile transmitters on your home hi-fi, or the susceptibility of early electronic telephones to the programmes of high power local broadcasting transmitters.

Because of the heavy reliance of developed societies on data communications, the impact of interference on telecommunications networks is a critical issue and the network equipment itself must be capable of withstanding the full range of phenomena at quite substantial levels; for instance the lightning surge immunity of exchange equipment and mobile phone base stations, both at the equipment and the system level, is carefully specified by the network operators.

1.3.3 Interference with radio reception

Bona fide users of the radio spectrum have a right to expect their use not to be affected by the operation of equipment which is nothing to do with them. Typically, received signal strengths of wanted signals vary from less than a microvolt to more than a millivolt, at the receiver input. If an interfering signal is present on the same channel as the wanted signal then the wanted signal will be obliterated if the interference is of a similar or greater amplitude. The acceptable level of co-channel interference (the "protection factor") is determined by the wanted programme content and by the nature of the interference. Continuous interference on a high fidelity broadcast signal would be unacceptable at very low levels, whereas a communications channel carrying compressed voice signals can tolerate relatively high levels of impulsive or transient interference.

Analogue sound and TV broadcasting are being replaced by digital broadcasting like Digital Radio Mondial (DRM) which is intended to replace the AM radio in the MF and HF bands, Digital Audio Broadcasting (DAB or T-DAB) operated in the VHF and UHF bands, and Digital Video Broadcasting Terrestrial (DVB-T) operated in the UHF bands. These digital radio services require lower RF protection ratios (17dB for DRM, 20dB for DVB-T and 28dB for DAB) than radio services with analogue modulation (which need protection ratios of about 27dB for AM, about 48dB for FM and about 58dB for TV). On the other hand, the transition between no interference and unacceptable interference is narrower than for analogue modulation: digital systems do not fail gracefully.

1.3.3.1 Setting the limits

Radiated interference, whether intentional or not, decreases in strength with distance from the source. For radiated fields in free space, the decrease is inversely proportional to the distance provided that the measurement is made in the far field (see section 10.1.4.2 for a discussion of near and far fields). As ground irregularity and clutter increase, the fields will be further reduced because of shadowing, absorption, scattering, divergence and defocussing of the diffracted waves. Annex D of CISPR 11

[161] suggests that for distances greater than 30m over the frequency range 30 to 300MHz, the median field strength varies as $1/d^n$ where n varies from 1.3 for open country to 2.8 for heavily built-up urban areas (n = 1 for ideal, far field, free-space propagation). An average value of n = 2.2 can be taken for approximate estimations; thus, increasing the separation by ten times would give a drop in interfering signal strength of 44dB. In the near field – for a frequency of 30MHz the transition distance is 1.6m, extending further away proportionally as the frequency decreases – the factor n depends also on the detailed characteristics of the emitting source and cannot be generalized, but remains theoretically in the range 2 to 3.

Below 30MHz the dominant method of coupling out of the interfering equipment is via its connected cables, and therefore the radiated field limits are translated into equivalent voltage or current levels that, when present on the cables, correspond to a similar level of threat to HF and MF reception. Electric or magnetic field coupling to nearby antennas in this frequency range is in most cases of minor importance compared with conduction coupling to the mains input of the affected receiver.

Limits for unintentional emissions are based on the acceptable interfering field strength that is present at the receiver – that is, the minimum wanted signal strength for a particular service modified by the protection ratio – when a nominal distance separates it from the emitter. This will not protect the reception of very weak wanted signals nor will it protect against the close proximity of an interfering source, but it will cover the majority of interference cases and this approach is taken in all those standards for emission limits that have been published for commercial equipment by CISPR (see Chapter 4). CISPR 16-4-4 gives an account of how such limits are derived, including the statistical basis for the probability of interference occurring.

Historically, the rationale for particular limits has relied upon statistics of interference complaints. A draft amendment to CISPR 16-4-4 [168] points out that with the advent of digital communications this is becoming harder to rely on:

> If a digital mobile phone or a wireless LAN receiver cannot receive the signal from the nearest base station or access point because of an unwanted emission from a nearby equipment, the user will never suspect this equipment and will even not consider the possibility of an interference to occur. He will assume that the coverage of the network is poor and will move to another place to make his call or to get his connection. Furthermore, as these systems are generally frequency agile, if one channel is interfered with, the system will choose another channel, but if all other channels are occupied, then the phone will indicate that the network is busy, and once again, the user will think the network capacity is not large enough to accommodate his call, but he will never suspect an EMC problem.
>
> Generally for analogue systems, one can hear the interference. With digital and mobile systems, interference is much less noticeable† (muting in audio reception, or frozen images on the TV set for DVB). In addition, modern digital modulations implement complex escape mechanisms (data error correction, frequency agile systems...) so that the system can already be permanently affected from an EMC point of view before an interference case actually is detected.
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> The evolutions detailed above – generalisation of mobile use of radio receivers and move from analogue to digital radio services – will not reduce the number of interference situations, but continues to decrease the probability of getting significant numbers of interference complaints indicating an existing EMC problem.

1.3.3.2 Malfunction versus spectrum protection

It should be clear from the foregoing discussion that RF emission limits are not determined by the need to guard against malfunction of equipment which is not itself a

† It's questionable that the interference is less "noticeable"; on the other hand it is harder to attribute the noticeable effects unequivocally to interference.

radio receiver. As discussed in the last section, malfunction requires fairly high energy levels – RF field strengths in the region of 1–10 volts per metre for example. Protection of the spectrum for radio use is needed at much lower levels, of the order of 10–100 microvolts per metre – ten to a hundred thousand times lower. RF incompatibility between two pieces of equipment neither of which intentionally uses the radio spectrum is very rare. Normally, equipment immunity is required from the local fields of intentional radio transmitters, and unintentional emissions must be limited to protect the operation of nearby intentional radio receivers. The two principal EMC aspects of emissions and immunity therefore address two different issues.

1.3.3.3 Free radiation frequencies

Certain types of equipment, collectively known as industrial, scientific and medical (ISM) equipment, generate high levels of RF energy but use it for purposes other than communication. Medical diathermy and RF heating apparatus are examples. To place blanket emissions limits on this equipment would be unrealistic. In fact, the International Telecommunications Union (ITU) has designated a number of frequencies specifically for this purpose, and equipment using only these frequencies (colloquially known as the "free radiation" frequencies) is not subject to emission restrictions. Table 1.1 lists these frequencies.

Centre frequency, MHz	Frequency range, MHz	
6.780	6.765 – 6.795	*
13.560	13.553 – 13.567	
27.120	26.957 – 27.283	
40.680	40.66 – 40.70	
433.920	433.05 – 434.79	*
2,450	2,400 – 2,500	
5,800	5,725 – 5,875	
24,125	24,000 – 24,250	
61,250	61,000 – 61,500	*
122,500	122,000 – 123,000	*
245,000	244,000 – 246,000	*

* maximum radiation limit under consideration

The frequency range 902 – 928MHz is also allowed in Region 2 only (the Americas, Canada and Greenland).

Table 1.1 ITU designated industrial, scientific and medical free radiation frequencies (Source: CISPR 11 [161])

1.3.3.4 Co-channel interference, spurious emissions and blocking

A further problem with radio communications, often regarded as an EMC issue although it will not be treated in this book, is the problem of co-channel interference from unwanted transmissions. This is caused when two radio systems are authorized to use the same frequency on the basis that there is sufficient distance between the systems, but abnormal propagation conditions increase the signal strengths to the point at which interference is noticeable. This is essentially an issue of spectrum utilization.

A transmitted signal may also overload the input stages of a nearby receiver which is tuned to a different frequency and cause desensitization or distortion of the wanted signal. Transmitter outputs themselves will have spurious frequency components present as well as the authorized frequency, and transmitter type approval has to set limits on these spurious levels. This is more properly viewed as a spectrum management concern and is sometimes called "mutual interference".

Although this book doesn't consider the subject further, it is important particularly for interactions between systems on the same platform, such as telecommunication installations sharing one mast, or multiple transmitter/receiver installations in one vehicle. Issues which have to be addressed are:

- spurious and harmonic emissions from the transmitters: emissions of any frequency which is not intended;
- correct frequency and power control of transmitters;
- spurious responses of the receivers: reception of any frequency which is not intended;
- adjacent channel blocking of receivers: unintended deafness induced by loud signals on nearby channels;
- sidelobe antenna patterns of both transmitters and receivers;
- intermodulation effects in transmitters, receivers and nearby structures, which create different frequencies from the interaction of existing ones.

1.3.4 Disturbances of the mains supply

Mains electricity suffers a variety of disturbing effects during its distribution. These may be caused by sources in the supply network or by other users, or by other loads within the same installation. A pure, uninterrupted supply would not be cost-effective; the balance between the cost of the supply and its quality is determined by national regulatory requirements, tempered by the experience of the supply utilities. Typical disturbances (see also section 10.3.5) are:

- *medium-term voltage variations*: the distribution network has a finite source impedance and varying loads will affect the terminal voltage. Not including voltage drops within the customer's premises, an allowance of ±10% on the nominal voltage will cover normal variations in Europe.
- *voltage fluctuations*: short-term (sub-second) fluctuations with quite small amplitudes are annoyingly perceptible as flicker on electric lighting, though they are comfortably ignored by electronic power supply circuits. Generation of flicker by high power load switching is subject to regulatory control.
- *voltage dips and interruptions*: faults on power distribution systems cause up to 100% voltage drops but are cleared quickly and automatically by protection devices, and throughout the rest of the system the voltage immediately recovers. Most consumers therefore see a short voltage dip. The frequency of occurrence of such dips depends on location and seasonal factors.
- *waveform distortion*: at source, the AC mains is generated as a pure sine wave but the reactive impedance of the distribution network together with the harmonic currents drawn by non-linear loads causes voltage distortion. Power converters and electronic power supplies are important contributors to non-linear loading. Harmonic distortion may actually be worse at points

remote from the non-linear load because of resonances in the network components. Not only must non-linear harmonic currents be limited but equipment should be capable of operating with up to 10% total harmonic distortion in the supply waveform.

- *transients and surges*: switching operations generate transients of a few hundred volts as a result of current interruption in an inductive circuit. These transients normally occur in bursts and have risetimes of no more than a few nanoseconds, although the finite bandwidth of the distribution network will quickly attenuate all but local sources. Rarer high amplitude spikes in excess of 2kV may be observed due to fault conditions. Even higher voltage surges due to lightning strikes occur, most frequently on exposed overhead line distribution systems in rural areas.

All these sources of disturbance can cause malfunction in systems and equipment that do not have adequate immunity.

Mains signalling

A further source of incompatibility arises from the use of the mains distribution network as a telecommunications medium, or mains signalling (MS). MS superimposes signals on the mains in the frequency band from 3kHz to 150kHz and is used both by the supply industry itself and by consumers. Unfortunately this is also the frequency band in which electronic power converters – not just switch-mode power supplies, but variable speed motor drives, induction heaters, fluorescent lamp inverters and similar products – operate to their best efficiency. There are at present very few pan-European standards which regulate conducted emissions on the mains below 150kHz, although EN 50065-1 sets the frequency allocations and output and interference limits for MS equipment itself. Overall, compatibility problems between MS systems and such power conversion equipment can be expected to increase.

1.3.5 Power line telecoms

Power Line Telecommunication (PLT or PLC, Power Line Communications, or Broadband over Power Line, BPL, in the USA) is a means of transmitting broadband data over the installed base of mains electricity supply cables. It can be used in two ways:

- Access to the home, to deliver the data connection from the service provider;
- Networking within the home, for data interconnection between mains-connected devices.

The two applications use different frequency ranges: low frequency (1.6–10MHz) for access, and high frequency (10–30MHz) for in-home, as specified for Europe in ETSI TS 101 867. The generally accepted power level for adequate operation of a PLT system is −50 to −40dBm/Hz. Measured in a 9kHz bandwidth, as is the normal method for interference measurements at these frequencies, this implies a power level of around −10 to 0dBm, which across the differential 100 ohm resistance of the power network is 100−110dBμV (0.1−0.32V). This compares with the allowed levels for conducted emissions in the domestic environment, with which most if not all electronic product designers are familiar, of 60dBμV in a comparable frequency range – one hundred times lower.

1.3.5.1 The politics of PLT

Because it can deliver domestic broadband access as an alternative to other providers such as cable and telephone companies, PLT is viewed favourably by regulators on the grounds of extending competition. The local loop, or the "last mile" (delivery of the broadband data finally into the home or office), appears as a bottleneck in the process of liberalizing the competitive environment for the telecommunications infrastructure, particularly in breaking the perceived stranglehold of the "incumbents" (pre-existing telecom providers). Hence any technology which promises to unblock this bottleneck is encouraged by the European authorities. PLT is clearly such a technology.

But meanwhile, some European nations have implemented regulations which would allow them to control it if there was any threat of interference becoming widespread. In Germany, the standard NB30 put down radiated emissions limits in the 1.6–30MHz range. In the UK, the Radiocommunications Agency standard MPT1570 was also published, though it covered a lower frequency range. Naturally, this put a brake on PLT activity in these countries, since investors were wary of supporting systems which might quickly turn out to be illegal, and it also meant that there were differences in approach across the European Union.

In 2001 the European Commission placed a mandate on the standard bodies ETSI and CENELEC (mandate M/313) to create a standard for the EMC of Telecommunications Networks. This was addressed by a Joint Working Group of the two bodies but the difficulties involved, particularly that of finding agreement on a set of limits for radiated emissions from the network which would satisfy all participants, meant that the work on it eventually stalled. The Commission subsequently issued a Recommendation in April 2005 [191] which includes the following wording:

> 2. ... Member States should remove any unjustified regulatory obstacles, in particular from utility companies, on the deployment of broadband powerline communications systems and the provision of electronic communications services over such systems.
>
> 3. Until standards to be used for gaining presumption of conformity for powerline communications systems have been harmonised under Directive 89/336/EEC, Member States should consider as compliant with that Directive a powerline communications system which is:
>
> – made up of equipment compliant with the Directive and used for its intended purpose,
>
> – installed and operated according to good engineering practices designed to meet the essential requirements of the Directive.
>
> The documentation on good engineering practices should be held at the disposal of the relevant national authorities for inspection purposes as long as the system is in operation.

We will meet the phrase "good engineering practices" elsewhere (section 2.2.5.4) in the context of fixed installations.

1.3.5.2 The use of the HF spectrum

The slice of spectrum from about 1 to 30MHz (MF and HF) is unique in that it can support long distance communication, and so it is important to broadcasters and many other users. Sky-wave propagation in the HF bands enables an international broadcaster to reach a target country without having a transmitter within the target area. This has political consequences, since it means that an audience can be reached without the co-operation of that country's authorities – which cannot be said for other kinds of access, including any kind of internet delivery. The BBC's World Service, for instance, is broadcast on several HF frequencies and is heard by many people in countries that have no free media of their own.

As well as broadcasting, aeronautical and marine communications use the HF band for long-distance communication when the mobile station is out of reach of ground-based VHF stations, which is a large proportion of their journeys.

1.3.5.3 PLT's interference capability

Interference from PLT systems stands outside the general regime of interference control, which as we will see applies limits to the amount of noise injected onto the mains supply. The principal emissions are deliberately injected onto the supply wiring, rather than accidentally as is the case with other sources such as fluorescent light inverters or computer power supplies. From access-PLT systems, the interference will be largely continuous rather than intermittent, and will potentially affect all households being supplied from a substation in a PLT-active zone, whether they are a subscriber or not. Even in-home systems could interfere with other parties connected to the same service entrance.

The interference signal will stretch broadband across the whole of the spectrum occupied by the modem's output, and within a given region of spectrum it will be impossible to tune it out. In the quiescent state some systems will create a pulsing type of signal which may or may not be subjectively less annoying than the continuous noise which occurs when the system is actually passing data. Some systems may use low-frequency carriers such that a continuous audible tone is present across the spectrum.

Dependence on quality of wiring

The mains supply wiring both to and within a domestic house was never intended to carry high frequencies. At some frequencies the signal may be transmitted with little loss, but at others the attenuation can be severe, and this characteristic can change with time as users plug various appliances into the mains supply. This means that in order to work at all, the amplitude of the signal must be high enough to ride over any interference already present on the network, and must adapt to time-dependent changes in this interference and the network attenuation. Current-generation PLT systems are designed to do this.

A critical parameter which determines the amount of radiation that the mains wiring creates is the "Longitudinal Conversion Loss" (LCL) of the cable, discussed in section 13.1.9.1. Simply put, this is the ratio between the signal level which appears across the wires, intentionally, due to the desired data transmission, and which to a first order does not radiate; and the signal level in common mode – all wires together – which represents the leakiness of the cable and which contributes the lion's share of the radiation. Data cables which carry broadband signals, of which Ethernet is the most typical example, are very tightly specified for good LCL, which ensures that the RF leakage from the data signal is kept low. This is not the case for mains wiring. The most important aspect of cable design which affects LCL is the physical balance of the two wires that make up the cable. Each conductor must be tightly coupled to the other so that they cancel each other's interaction with the environment. Data cables are tightly twisted in a controlled way to achieve this. Not only is mains wiring not controlled in this way, it is commonly installed in direct contravention of this principle.

1.3.5.4 Is PLT the same as other interferers?

PLT supporters propose that there should be parity (at least) between the emissions compliance requirements that a PLT system has to meet, and those applied to other devices such as information technology, lighting, or household appliances. CISPR conducted limits, it is said, have been adequate to protect the HF spectrum so far and therefore any system limits should be no more onerous than levels derived from these. This argument overlooks a number of important points:

- a victim won't be able to get away from PLT interference. When a whole street or a whole building is wired for PLT, it will be pervasive and re-positioning the victim will not work. CISPR limits assume that mitigation by separation from a local interferer is possible;
- PLT is always on. CISPR limits incorporate a relaxation which takes into account the probability of non-coincidence in time of source and victim. For PLT, this relaxation must be ignored;
- EMC engineers know that most products which comply with CISPR conducted limits do so with a good margin, often at least 20dB, in the frequency range above 2MHz. If CISPR limits do indeed protect HF reception, this factor should not be overlooked, since such a margin will not be enjoyed by a PLT product.

In fact, PLT modems are unable to operate anywhere near the mains conducted emissions limits in force in CISPR at the moment.

1.3.5.5 Cumulative effects

The threat to victim receivers in close proximity to the PLT system is not the only one that concerns radio administrations. If PLT were to be widely implemented within any country, the total radiated power available would be sufficient to increase the radio noise floor at distances remote from the source, potentially even in other countries. If, say, an entire city was to be wired for PLT, this could form an aggregate transmitter whose RF energy was reflected from the ionosphere and illuminated a continent. In addition, an aircraft flying over such a city might find that its ability to receive HF signals was curtailed. The UK's Civil Aviation Authority has expressed its concern that “aeronautical services are under threat from cabled telecommunications services.” Established HF propagation models exist for this phenomenon and a number of studies have been carried out to try and model the possible outcome. The problem with any such study is that for the time being it must remain theoretical, since it's impossible to validate the radiation (as opposed to propagation) models used for prediction until there are sufficient installed systems to be statistically acceptable; but by then the roll out may be so advanced that it will be impossible to stop it.

1.3.5.6 Compliance status of PLT devices

The EC's Recommendation on PLT quoted above refers to a system being “made up of equipment compliant with the Directive”. Here is the nub of the question: how can PLT modems be made compliant with the EMC Directive? It is the case that some PLT modems are already on the market in Europe and are CE Marked, which means that their manufacturers believe that they meet the essential requirements of the EMC Directive. But there are no standards specifically for such devices and for now, no such device could actually meet the usual standards. In fact, existing products appear to use the Technical Construction File route (under the first EMC Directive, see section 2.1.3) which implies that a Competent Body has issued a certificate of compliance with the essential requirements. It is difficult to know how this has been justified.

1.3.5.7 Opening the floodgates

It must be assumed that the mains supply already carries noise from other apparatus which may approach the usual conducted emission limits, even if everything connected is in full compliance with the EMC Directive. For PLT to operate at all, its signals must be greater than this minimum noise level, almost by definition; and so it must breach these limits, again by definition. This is indeed so, by several tens of dB, and if it were not, PLT could not operate. Yet all other mains-connected equipment, such as ITE, medical products, household appliances, lighting and so forth, is subject to the standard limits.

What is to prevent the manufacturers of such equipment, which after all forms the vast bulk of products placed on the market within the EU, from demanding to know why PLT has received such special treatment? If PLT can flagrantly flout the limits, they would say, so can we. But of course, were they to do that, it would open the floodgates to an uncontrolled escalation of interference on the mains wires. More bluntly, it would drive a horse and cart through the principles of interference control established over decades.

This exposes a contradiction at the core of the case for PLT. It can only operate if it is indeed granted special status to apply RF disturbances to the mains lines. It must, in fact, be regarded as a special case in the context of the EMC Directive. It cannot possibly comply with the requirement not to generate an electromagnetic disturbance exceeding "a level allowing radio and telecommunications equipment and other apparatus to operate as intended" because, since the limits are set to achieve this requirement, it must itself exceed those limits and therefore breach the requirement.

In fact, it seems at the time of writing that PLT is losing its attractiveness both to the regulators and to its hopeful operators, mainly because of the regulatory EMC problems rehearsed above. Probably, it will be relegated to a curiosity in years to come, superseded by less polluting, more reliable and more effective wired and wireless ways of delivering broadband internet access.

1.3.6 Other EMC issues

The issues discussed above are those which directly affect product design to meet commercial EMC requirements, but there are some other aspects which should be mentioned briefly.

1.3.6.1 EEDs and flammable atmospheres

The first is the hazard of ignition of flammable atmospheres in petrochemical plant, or the detonation of electro-explosive devices in places such as quarries, due to incident RF energy. A strong electromagnetic field will induce currents in large metal structures which behave as receiving antennas. A spark will occur if two such structures are in intermittent contact or are separated. If flammable vapour is present at the location of the spark, and if the spark has sufficient energy, the vapour will be ignited. Different vapours have different minimum ignition energies, hydrogen/air being the most sensitive. The energy present in the spark depends on the field strength, and hence on the distance from the transmitter, and on the antenna efficiency of the metal structure. BS 6656 [173] discusses the nature of the hazard and presents guidelines for its mitigation.

Similarly, electro-explosive devices (EEDs) are typically connected to their source of power for detonation by a long wire, which can behave as an antenna. Currents induced in it by a nearby transmitter could cause the charges to explode prematurely if the field was strong enough. As with ignition of flammable atmospheres, the risk of premature detonation depends on the separation distance from the transmitter and the efficiency of the receiving wire. EEDs can if necessary be filtered to reduce their susceptibility to RF energy. BS 6657 [174] discusses the hazard to EEDs.

1.3.6.2 Data security

The second aspect of EMC is the security of confidential data. Low-level RF emissions from data-processing equipment may be modulated with the information that the equipment is carrying – for instance, the video signal that is fed to the screen of a VDU. These signals could be detected by third parties with sensitive equipment located outside a secure area and demodulated for their own purposes, thus compromising the security of the overall system. This threat is already well recognized by government agencies and specifications for emission control, under the Tempest scheme, have been established for many years. Commercial institutions, particularly in the finance sector, are now beginning to become aware of the problem.

1.3.6.3 Electromagnetic weapons

The idea that an intense broadband radiated pulse could be generated intentionally, and used to upset the operation of all potentially susceptible electronics within a certain range, is gaining credence. Because of the almost universal social reliance on electronic systems, an attack that simultaneously crashed many computer networks could indeed have substantial consequences. It is known that US and other military researchers are working on such technology, but we can also imagine less sophisticated devices being within reach of many other organizations or individuals.

The more sensationalist press, of course, has a field day with this idea – phrases such as “frying computer chips” are used with abandon. Realistically, the amount of energy needed to generate a wide-area pulse would be so enormous that only disruption, not damage, is at all likely. This is precisely the effect of a high altitude nuclear explosion, which generates a sub-nanosecond nuclear electromagnetic pulse (NEMP) that is disruptive over an area of hundreds of square kilometres. The idea that attracts military researchers now is to do this more discreetly. The limitation of any such weapon is its uncertainty. Unless you know exactly what kind of electronics you are attacking, and how well protected it is, it is hard to predict the damage that the weapon will cause. Equipment that is immune to a local electrostatic discharge (ESD, as described in these pages) is likely to have good immunity to electromagnetic warfare.

On the other hand, radio communications are easy to disrupt by jamming transmissions and this subject is well established in the military canon; there are military aircraft that are specifically designed to carry high power broadband jammers and it is not hard to imagine that they are used with some enthusiasm in “theatres of war” (it is said that one such aircraft suffered an engine shutdown when its jammers were turned on in earnest). Under such circumstances, the issue of the commercial application of radiated emission limits is of no more than academic interest.

1.3.7 The compatibility gap

The increasing susceptibility of electronic equipment to electromagnetic influences is being paralleled by an increasing pollution of the electromagnetic environment. Susceptibility is a function partly of the adoption of VLSI technology in the form of microprocessors, both to achieve new tasks and for tasks that were previously tackled by electromechanical or analogue means, and the accompanying reduction in the energy required of potentially disturbing factors. It is also a function of the increased penetration of radio communications, and the greater opportunities for interference to radio reception that result from the co-location of unintentional emitters and radio receivers.

At the same time more radio communications mean more transmitters and an increase in the average RF field strengths to which equipment is exposed. A study has been reported [30] which quantified this exposure for a single site at Baden, Switzerland, for one year; this found the background field strength in the shortwave band regularly approaching, and occasionally exceeding, levels of 1V/m. Also, the proliferation of digital electronics means an increase in low-level emissions which affect radio reception, aptly described as a form of electromagnetic "smog".

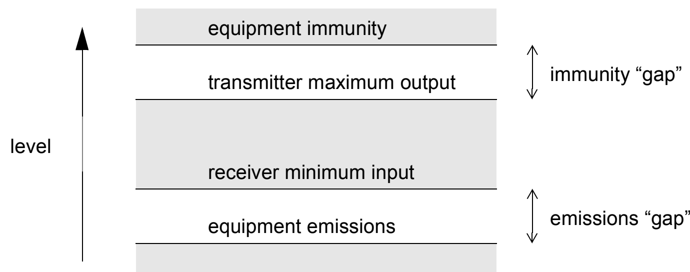

Figure 1.1 The EMC gap

These concepts can be graphically presented in the form of a narrowing electromagnetic compatibility gap, as in Figure 1.1. This "gap" is of course conceptual rather than absolute, and the phenomena defined as emissions and those defined as immunity do not mutually interact except in rare cases. But the maintenance of some artificially-defined gap between equipment immunity and radio transmissions on the one hand, and equipment emissions and radio reception on the other, is the purpose of the application of EMC standards, and is one result of the enforcement of the EMC Directive.

1.4 Electromagnetic fields and human health

This book is about EMC in electronic products, but one subject which any EMC engineer is regularly quizzed about is the related issue of the direct health hazards of electromagnetic fields. Apart from its application under the R&TTE Directive and relevance to radiated RF immunity tests at high levels, it's not a subject that will take up a lot of space in this book.

It is undoubtedly the case that high levels of electromagnetic energy can create effects in human tissue. This then implies that below some level the EM energy can be regarded as "safe" and above it as "hazardous", and that exposure to it should be controlled. The exposure levels to which most if not all regulatory limits adhere are laid down in the ICNIRP Guidelines [196].

1.4.1 ICNIRP basic restrictions

The International Commission on Non-Ionising Radiation Protection is a non-governmental expert body and its guidance document refers to the known short-term and immediate health effects. These are:

- stimulation of peripheral nerves and muscles;
- shocks and burns through touching conducting parts;
- tissue heating due to energy absorption.

For absorption of energy, EM fields can be divided into four frequency ranges:

- frequencies from about 100kHz to less than about 20MHz, at which absorption in the trunk falls rapidly with decreasing frequency, and significant absorption may occur in the neck and legs;
- frequencies in the range from about 20MHz to 300MHz, at which relatively high absorption can occur in the whole body, and to even higher values if partial body (e.g. head) resonances are considered;
- frequencies in the range from about 300MHz to several GHz, at which significant local, non-uniform absorption occurs;
- frequencies above about 10GHz, at which energy absorption occurs primarily at the body surface.

The ICNIRP guidelines' levels are set on the following basis:

> Available experimental evidence indicates that the exposure of resting humans for approximately 30 minutes to EMF producing a whole-body SAR of between 1 and 4 W kg^{-1} results in a body temperature increase of less than 1°C. Animal data indicate a threshold for behavioral responses in the same SAR range. Exposure to more intense fields, producing SAR values in excess of 4 W kg^{-1}, can overwhelm the thermoregulatory capacity of the body and produce harmful levels of tissue heating.
>
> Many laboratory studies with rodent and non-human primate models have demonstrated the broad range of tissue damage resulting from either partial-body or whole-body heating producing temperature rises in excess of 1–2°C. The sensitivity of various types of tissue to thermal damage varies widely, but the threshold for irreversible effects in even the most sensitive tissues is greater than 4 W kg^{-1} under normal environmental conditions. These data form the basis for an occupational exposure restriction of 0.4 W kg^{-1}, which provides a large margin of safety for other limiting conditions such as high ambient temperature, humidity, or level of physical activity.

SAR stands for Specific Absorption Rate, quoted in watts per kilogram, and is a measure which is given as a Basic Restriction in the ICNIRP guidelines. Depending on frequency, the physical quantities used to specify the basic restrictions on exposure to EMF are current density, SAR, and power density. Protection against adverse health effects requires that these basic restrictions are not exceeded.

1.4.1.1 Reference levels

"Reference levels" of exposure are provided for comparison with measured values of physical quantities (electric or magnetic field strength); compliance with all reference levels given in the ICNIRP guidelines will ensure compliance with basic restrictions.

In many circumstances actually measuring SAR is either not feasible (because it would imply invasive measurements in a human body) or would not be economically justified. In these cases the fields to which people are actually exposed can be measured directly and compared to the reference levels. It is important to note that these are not limits but levels above which you should investigate the exposure regime: provided that basic restrictions are met and adverse indirect effects can be excluded, these field strength values can be exceeded. Typical circumstances in which the reference levels are applied are in exposure of the public or workers to fields from base station transmitter installations (though not in evaluation of hand-held transmitters). For EMC test labs, the radiated RF immunity test also provides an opportunity to consider them (see section 7.1.3.5).

1.4.1.2 SAR measurement

Reference levels are not relevant for handheld transmitters since the coupling takes place in the near field of the transmitting antenna. For this situation, it is necessary to measure SAR directly using a phantom of a human head or body, filled with a tissue-simulating liquid (actually a mixture of sugar, salt and water) which gives the correct dielectric properties at the relevant frequency, and allows a specialized E-field probe to be positioned inside the head cavity. This method is now well established for mobile phones and is being extended to other types of radio transmitter which are used close to the body. It has some similarities to EMC measurements but also many more differences; relatively few generalist test labs can do it, and it is mostly carried out by the mobile phone manufacturers themselves.

1.4.2 Athermal effects

Effects at much lower levels of RF that may be experienced by some people but are not based on tissue heating (athermal effects) are still controversial and disputed, and are not covered by the ICNIRP guidance or indeed any other officially published and recognized documents. ICNIRP itself says "available data are insufficient to provide a basis for setting exposure restrictions" and this position has been maintained for some years, although numerous studies have been published which purport to show one effect or another on biological systems of various frequencies and modulation schemes, including those used by mobile phone transmissions. It seems that there are two problems with this body of research:

- much of the experimental data is open to criticism and has been found difficult or impossible to replicate;
- the implication for radio transmitting authorities, if low-level EM energy is ever conclusively shown to have serious health hazards, is such that many radio-based systems would be shut down overnight, and this is a nettle that, unsurprisingly, noone in authority has seen fit to grasp.

Nevertheless, there is a substantial body of public opinion which believes that such a low-level hazard exists, and agitates against the continued extension of the radio transmitting infrastructure, particularly as evidenced by mobile phone base station installations. It is largely in (perhaps misplaced) response to this public opinion that standards for measuring the RF emissions of virtually any electronic apparatus have been drafted. Since these are essentially safety standards they are only relevant in the context of the R&TTE Directive.