EMC for Product Designers

Third edition

Tim Williams

Newnes

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Preface

The most popular TV programme in the UK over Christmas 1991 was *Auntie's Bloomers*. Millions of viewers watched a selection of clips from the BBC's archives, showing various well known television personalities at embarrassing moments while the camera was running, clips that never made it to the final programme. For a significant fraction of these viewers, their enjoyment would have been spoilt by a bloomer of another kind. In the first half of 1985, before a service charge was introduced, the UK's Radio Investigation Service was receiving an average of 1900 complaints a month relating to broadcast reception, and about 80% of the RIS's resources were devoted to domestic radio and TV reception problems. Spots, hash, snowstorms, colour and vision distortion and occasionally complete loss of picture are all symptoms of the same cause – electromagnetic interference.

It is irritating for the viewer when the picture flickers or is wiped out during a crucial programme, just as it is irritating for a music lover who has carefully taped an important broadcast on FM radio only to find that the quiet passages are ruined by the intrusion of the neighbour's electric drill. It is far more critical when the emergency services are unable to communicate within a city centre because their radio signals are obscured by the electromagnetic "smog" emitted by thousands of computer terminals in the buildings around them.

The coexistence of all kinds of radio services, which use the electromagnetic spectrum to convey information, with technical processes and products from which electromagnetic energy is an undesirable by-product, creates the problem of what is known as *electromagnetic compatibility* (EMC). The solution is a compromise: radio services must allow for a certain degree of interference, but interfering emissions may not exceed a certain level, which normally involves measures to limit or suppress the interference energy. There is an economic tradeoff inherent in this compromise. A lower level of interference would mean that less powerful transmitters were necessary, but the suppression costs would be higher. Alternatively, accept high power transmitters – with the attendant inefficient spectrum usage – in return for lower suppression costs. This economic balance has been tested over the past decades with the establishment of various standards for allowable levels of interference.

The problems of EMC are not limited to interference with radio services. Increasingly, electronic equipment of all kinds is becoming more susceptible to malfunctions caused by external interference. This phenomenon is more and more noticeable for two reasons: the greater pervasiveness and interaction of electronic products in all aspects of daily life, and the relatively worse immunity of modern equipment using plastic cases and microprocessors. Susceptibility to interference is now an issue for many kinds of electronic device, especially those whose continued correct operation is vital for safety or economic reasons. Automotive and aviation control systems are examples of the former category, banking and telecommunication networks are examples of the latter.

There is now an urgent need for mandatory measures to be taken to protect and ensure equipment's EMC. Various national administrations have taken ad hoc measures in the past to impose restrictions on some of the electromagnetic properties of some types of product. These measures have often come to be seen as implementing back-door methods of protectionism, with the technical inadequacy of some of the requirements allowing effectively different standards to be applied to imported and indigenous products.

In an heroic effort to recognize the need for EMC protection measures and at the same time to eliminate the protectionist barriers to trade throughout the European Community, the European Commission adopted in 1989 a Directive "on the approximation of the laws of the Member States relative to electromagnetic compatibility", otherwise known as the EMC Directive. It is discussed in detail in Chapter 1 of this book.

The adjective "heroic" is used above because the eventual implementation of the requirements of the EMC Directive is proving to be a task worthy of any Hercules. Both the scope of the Directive and the EMC phenomena it covers are exhaustive, but it is framed in extremely general terms. The interpretation of these terms is taking considerable effort, as is the generation of standards against which compliance with the Directive can be judged. As an example of the latter, CENELEC (the European standards body) was mandated to produce several new standards within two years, when the normal process for generating international standards takes at least five years.

Practically speaking, the new standards started appearing in a steady stream during 1992 and succeeding years, and they will undoubtedly be subject to continual revision as experience is gained with their use. One consequence of the early lack of availability of these standards is that the Directive's initial timetable was extended to include a transitional period of four years during which its observance was optional.

The task facing manufacturers who must comply with the Directive is, many feel, equally heroic. There is virtually no type of product for which the Directive's requirements were being met in their entirety already. Many manufacturers of data processing or household equipment already met emission standards required by American, German or previous EC legislation and for them it was, in the words of one commentator, "business as usual". But the Directive also requires equal attention to be given to a product's immunity. Few products which met emission standards had also been tested for immunity. There are some product sectors which already exercised immunity standards on a contractual basis – but few of these also tested for emissions. This is only pragmatic, since emissions legislation concentrates on protecting the innocent spectrum user while immunity standards are intended to safeguard the product's own end user, and it is still at present rare for these needs to co-exist in the same environment. For the first time, the Directive has brought together mandatory requirements for both emission suppression and immunity.

By the end of 1995, every company that manufactures or imports electrical or electronic products should have in place measures that will enable its products to comply with the Directive. This means that an awareness of EMC will have to penetrate every part of the enterprise. EMC is undoubtedly affected by the design of the product, and the design and development group is where the awareness normally starts. But it also depends on the way an individual product is put together, so it affects the production department; by the way it is installed, so it affects the installation and service technicians, and the user documentation; it needs to be assured for each unit, so it affects the test department; it impacts the product's marketing strategy and sales literature, so it affects the sales and marketing departments; and it ultimately affects the viability and liabilities of the company, so it must be understood by the senior management.

There are various means of implanting and cultivating this awareness. The many EMC training courses and awareness seminars are a good starting point. It would be possible to bring in consultants to handle every aspect of the EMC compliance process, but for many products this would be expensive and cumbersome and would not necessarily result in improved awareness and expertise within the company where it was really needed. It would also be possible to send every appropriate member of staff on a training course. This would certainly raise awareness but it may not prove so effective in the long run, since EMC techniques also need to be practised to be properly understood. It would also be expensive, but some of the larger companies with established in-house training programmes are capable of taking this route.

A good compromise is to nominate one person, or a group if the resources are available, to act as the centre of EMC expertise for the company. His, her or its responsibility should be to implement the requirements of the EMC Directive and any other EMC specifications to which the company may need to work. In the long term, it should also be to make the EMC centre redundant: to imbue a knowledge of EMC principles into each operating division so that they are a natural part of the functioning of that division. This, though, would take years of continuous oversight and education. Meanwhile, the tasks would include:

- reviewing each new product design throughout the development and prototyping stages for adherence to EMC principles, and advising on design changes where necessary;
- drawing up and implementing an EMC test and control plan for each product;
- supervising pre-compliance and compliance tests both in house and in liaison with external test houses;
- maintaining an intimate knowledge of the EMC standards and legislation that apply to the company's products;
- liaising with marketing, sales, production, test, installation and servicing departments to ensure that their strategies are consistent with EMC requirements.

There are probably more detailed tasks involved, but this serves as an indication of the breadth of scope of the EMC engineer's job. It is comparable to that of the quality department, and indeed can sometimes be incorporated within that department.

Preface to the third edition

The second edition of this book was published in 1996, and this third edition comes out five years later. In that time the EMC Directive has been fully functional and the vast majority of manufacturing companies have become familiar with it. But the EMC world has not stood still: new product standards have been published, new test methods have become established and much has been learned to improve old tests. Although Maxwell's laws haven't changed, there is more understanding of how best to apply them to maximize the compatibility of individual products. The onward and upward march of clock speeds and the shrinking of product, package and interconnect.xiv Preface dimensions has continued. And so, even if you were familiar with the second edition, you will find quite a lot of new material in this one.

This book is intended to help the work of the company's EMC centre. It seems to be serving its purpose: I have been pleasantly surprised by how widely it has been recommended. It can be used as a reference for the EMC engineer, as background reading for designers and technicians new to the subject, or as part of the armoury of the development group tackling a new project. It is structured into two parts. The first part (Chapters 1–4) discusses the European legislative framework now erected to encompass EMC, and the test techniques that are used to demonstrate compliance with that framework. The first two chapters are mainly non-technical in nature. Chapter 1 introduces the subject of interference, and goes on to discuss the provisions of the EMC Directive and the means of achieving compliance with it. Chapter 2 details the standards-making structure and describes the various harmonized standards that are now in existence and which are relevant for compliance with the Directive. Chapter 3 covers the test methods for RF emissions and mains input current harmonics that are laid down in the standards and which will need to be followed both in-house and by external test houses. Chapter 4 does the same for the immunity tests: RF immunity, ESD and transient immunity, as well as the low frequency techniques of magnetic field and voltage dips and interruptions.

The second part of the book discusses techniques for achieving an acceptable EMC performance at minimum extra cost, at the design stage. It is usually possible to add screening and suppression components to an existing design to enable it to meet EMC standards. This brute force method is expensive, time consuming and inefficient. Far better is to design to the appropriate principles from the start, so that the product has a good chance of achieving compliance first time, or if it doesn't then modifications are made easy to implement.

Chapter 5 covers the basic principles involved in coupling electromagnetic interference from a source to a victim. Chapter 6 looks at the techniques which can be applied before resorting to the more traditional methods of screening and suppression: attention to equipment and PCB layout and grounding, and Chapter 7 discusses choice of circuit configuration, components and software features. Chapter 8 carries on to detail the accepted "special" EMC techniques which include cable configuration and termination, filtering methods and components, and shielding. Chapter 9 discusses EMC management and control principles and finally, a series of appendices gather together some of the more detailed reference information.

Much of the book has grown out of course notes that were prepared for seminars on Design and Test for EMC, and I am grateful to those designers who attended these seminars and stimulated me to continually improve and hone the presentation. Many people have helped with its progress. I would particularly like to acknowledge the work of Prof. Andy Marvin and Dr John Dawson and their colleagues at York University, as well as that of Dr Jasper Goedbloed and Prof. Piet van der Laan. I have had a long and fruitful relationship with Schaffner-Chase EMC, and am continually grateful especially to David Riley, John Dearing, Ray Hughes and Nick Smith. I must also mention Adrian McLeod, editor of *Approval* magazine, and particularly my consultant colleagues, Dave Imeson, Keith Armstrong and Phil Carter. As always the responsibility for this book remains the author's alone. I hope you find it useful.

Tim Williams
December 2000

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 will increase.

Some reported examples of electromagnetic incompatibility are:

- in Germany, a particular make of car would stall on a stretch of Autobahn opposite a high power broadcast transmitter. Eventually that section of the motorway had to be screened with wire mesh;
- on another 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;
- in America, police departments complained that coin-operated electronic games were causing harmful interference to their highway communications system;
- 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;

- perhaps the most tragic example was the fate of HMS Sheffield in the Falklands war, when the missile warning radar that could have detected the Exocet missile which sank the ship was turned off because it interfered with the ship's satellite communications system.

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 has 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.
>
> 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.
>
> 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.
>
> 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)

† Especially if they regard their need for personal communication as more important than a mere request from the crew. [57] reports that an aircraft carrying a German foreign minister was forced 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".

- 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 [57]. 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.

Another critical area with potentially life-threatening consequences is the EMC of electronic medical devices. A 1995 review article [116] 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.

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. Because there had been 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 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.

These are all examples of the lack of a product's "fitness for purpose": that is, to operate

† CDRH: Center for Devices and Radiological Health, US FDA

correctly and safely in its intended environment, which includes the electromagnetic environment. There are clear safety implications in the reports. Not only the US is affected, as can be deduced from the following items:

> The UK Department of Health has issued guidelines banning the use of cordless, cellular and mobile phones within certain areas in hospitals, because their electromagnetic field can interfere with medical equipment, including life-support machines... The DoH has been forced to issue the guidelines following a number of reported cases where medical equipment has been reset, or stopped working, due to the interference from cellular phones.
>
> *Electronics Weekly 8th February 1995*

> 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.
>
> *BSI News December 1993*

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-5's 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, it quacked apparently at random and with no-one 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!

1.1.1 Compatibility between systems

The threat of EMI is controlled by adopting the practices of electromagnetic *compatibility* (EMC). This is defined [146] as "the ability of a device, unit of equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment". The term 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.

1.1.1.1 Subsystems within an installation

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 in to 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.

Since this book is concerned with product design to meet the EMC Directive, we shall not be considering this “intra-system” aspect to any great extent. The subject has a long history and there are many textbooks dealing with it.

1.1.1.2 Equipment in isolation

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. 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.

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.

1.1.2 The scope of EMC

The principal issues which are addressed by EMC are discussed below. The use of microprocessors in particular has stimulated the upsurge of interest in EMC. These devices are widely responsible for generating radio frequency interference and are themselves susceptible to many interfering phenomena. At the same time, the widespread replacement of metal chassis and cabinets by moulded plastic enclosures has drastically reduced the degree of protection offered to circuits by their housings.

1.1.2.1 Malfunction of 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.

Phenomena

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

- supply voltage interruptions, dips, surges and fluctuations;
- transient overvoltages 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.

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.

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.

1.1.2.2 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. Digital communications are designed to be even more immune, but this just means that when the interference reaches a higher level, failure of the link is sudden and catastrophic rather than graceful.

Field strength level

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 5.1.4.2 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 EN 55 011 [136] 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. 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.

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 2). CISPR publication 23 [153] gives an account of how such limits are derived, including the statistical basis for the probability of interference occurring.

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.

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 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 intentional radio receivers. The two principal EMC aspects of emissions and immunity therefore address two different issues.

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, use subject to special authorization

Frequency, MHz	Maximum radiation limit	Notes
0.009 – 0.010	unlimited	Germany
3.370 – 3.410	unlimited	Netherlands
13.533 – 13.553	110dBμV/m at 100m	UK
13.567 – 13.587	110dBμV/m at 100m	UK
83.996 – 84.004	130dBμV/m at 30m	UK
167.992 – 168.008	130dBμV/m at 30m	UK
886.000 – 906.000	120dBμV/m at 30m	UK

Frequencies designated on a national basis in CENELEC countries

Table 1.1 ITU designated industrial, scientific and medical free radiation frequencies
Source: EN55011:1991

Co-channel interference

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.

1.1.2.3 Disturbances on 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 are:

- *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 the UK. The effect of the shift in nominal voltage from 240V to 230V, as required by CENELEC Harmonization Document HD 472 S1 : 1988 and implemented in the UK by BS 7697 : 1993 [161], is that from 1st January 1995 the UK nominal voltage is 230V with a tolerance of +10%, –6%. After 1st January 2003 the nominal voltage will be 230V with a tolerance of ±10% in line with all other Member States.
- *voltage fluctuations*: short-term (sub-second) fluctuations with quite small amplitudes are annoyingly perceptible 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 interruptions*: faults on power distribution systems cause almost 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 almost no pan-European standards which regulate conducted emissions on the mains below 150kHz, although EN 50065-1 [138] 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.

1.1.2.4 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.

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 [158] 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 [159] discusses the hazard to EEDs.

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.

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.

1.1.3 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 [31] 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, a phenomenon which has been aptly described as a form of electromagnetic “smog”.

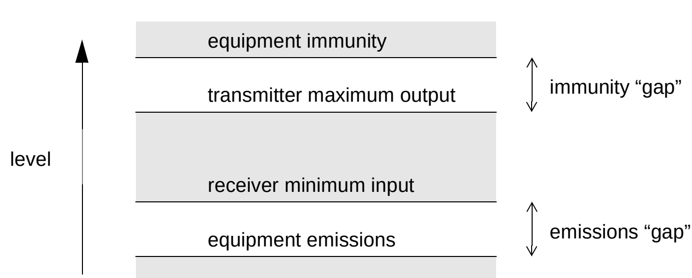

Figure 1.1 The EMC gap