view to establishing basic lightning protection, grounding and bonding guidelines. Sufficient information is provided to assess the probability of lightning strike for a particular region in South Africa, thus providing a basis for cost-effective optimisation of a lightning protection and ground network system. Recommended practice for both signal and safety grounding is established, leading to practical measures for the protection of electronic components.

Chapter 7 - A Need for a Systematic Integrated Systems Approach

Because the various ground networks, which include lightning, power, signal and/or logic, are integral parts of a system and are expected to perform in a common EM environment, it is important to consider the various grounding requirements collectively. Hence, in this chapter the concept of a systematic integrated systems approach is presented, which emphasises the need to co-ordinate and integrate the requirements of the various earthing and grounding systems and to adopt a systematic engineering approach. Also in this chapter, the various earthing and grounding requirements are placed into perspective and the dilemma facing systems designers is highlighted. A planned program is suggested which includes the provision and scheduling of a earth/ground scheme with a strong emphasis on integration, co-ordination and a systems engineering approach.

Chapter 8 - The Earth Electrode System

This chapter discusses the fundamentals of electrical earthing, the dielectric nature of the soil, and the practical measurement of soil resistivity. The most common earth electrode arrangements are reviewed and a table of formulas relating the impedance of typical earthing arrangements as functions of their dimensions are presented as design aids. Different techniques for the measurement of the electrode impedance of installed arrangements is surveyed The transient surge impedance characteristics of electrodes is also examined. Additional topics include design objectives, layout considerations and specific recommendations regarding materials and dimensions.

Chapter 9 - Grounding of Control Systems

The various principles, concepts and practical guidelines set forth in previous chapters are applied to the grounding of large industrial control systems. Two basic types of systems are identified; isolated and clustered systems. The grounding requirements of typical control system configurations - i.e. centralised, decentralised, and distributed - are analysed in terms of these two systems. In addition, guidelines for providing the signal and equipment (facility) ground system are presented. This chapter also examines two types of bonding; direct and indirect, and discusses the frequency dependent properties of indirect bonds. In addition, a generalised set of bonding practices appropriate for electronic equipment are provided.

Chapter 10 - Measurement and Testing of Ground Systems

Measurement is a basic requirement in any engineering discipline. Unfortunately, in the design and installation of ground systems there is a shortage of comprehensive measurement techniques and devices. In this chapter two types of test procedures for measuring the parameters of electric bonds are presented; these are dc resistance measurement and swept frequency/shunt-T insertion loss measurement. In addition, the equipment normally used for measuring interference in ground systems is surveyed, and ground noise measurement techniques both in the time and frequency domain are presented.

Chapter 11 - Conclusion

CHAPTER 2

2.0 THE INDUSTRIAL INTERFERENCE ENVIRONMENT

2.1 INTRODUCTION

The modern industrial environment is becoming increasingly dependent upon the applications of highly complex microprocessor-based automatic control and instrumentation systems. A key issue in such systems is the proper earthing and grounding to reduce noise and interference so that a "quiet" environment for electronic systems can be ensured. The proper approach is thus to identify and recognise the interference environment so that proper earthing and grounding design and installation techniques can be applied which would either make the system resistant to interference or reduce the interference sources themselves. Hence, a major part of interference control in grounded systems is in understanding what the interference sources are and how they couple into the sensitive signal circuits.

In this chapter the industrial electromagnetic environment is described. It becomes apparent that practically all of the electrical equipment installed on site could generate interference of one form or the other which can affect the operation of process and production control computer systems. To ease identification, the interference sources are divided into four different categories;

- incidental internal sources
- external intentional sources
- power line phenomena, and
- natural phenomena.

The industrial environment is teeming with these sources for which quantitative information on the radiated output is either of little validity or virtually nonexistent. However, wherever possible graphical data have been included for purposes of an initial appraisal of the power and frequency levels available on site. Also in this chapter, the means by which these sources propagate and couple into the victim receptor elements is examined. In addition, the victim receptor elements are identified and classified. For a better understanding of the disturbing signal the characteristics of the EMI signal is examined in terms of narrow-band, broad-band, and transient EMI.

2.2 THE PROCESS CONTROL ENVIRONMENT

This study, as mentioned in Chapter 1, is primarily concerned with the industrial process control environment. Typical process industries include oil and chemical plants, factory assembly lines, electric power, ore refineries, rolling mills and pulp and paper. Besides the field cabling, sensors, and transducers, the electronic control systems used for input and output would include:

- Analog input devices, with and without special signal conditioning;
- Digital input devices, with and without change-of-state notification;
- Analog outputs;
- Digital outputs;
- Scanning and analytical instruments;
- Devices and/or systems that include process monitoring, alarm, and/or control algorithms;
- Remote terminal units;
- Intrinsic safety barrier devices;

Typically, such devices take the form of:

- Operators' process consoles;
- Alarm displays and anunciators;
- Video terminals;
- Teleprinters and label, tick and special-form printers;
- Keyboards and keypads;
- Controllers that perform process monitoring, alarm and/or control algorithms.

Formally these devices were connected to supervisory computers which controlled and interrogated them. In addition, they exchanged large blocks of data and/or programs; and the interconnected systems supported centralised intelligence systems.

With the advent of micro-processors and the economic viability of distributed control function, the new generation of plant control systems comprise of control and data acquisition equipment which features distributed intelligence and functions, hierarchically and laterally throughout the plant. Such a system is more commonly referred to as Distributed Computer Control System (DCCS). Figure 2.1 represents one such configuration of a DCCS system.

Typically such a system can be thought of as a large number of task-orientated control units where each unit communicates both with process monitoring devices, such as thermocouples and strain gauges, and with other control units. Furthermore the control units can be connected to a high speed serial data highway enabling communication with a central operator station or a host computer (the latter for supervisory control). Thus direct lateral communication among peer devices is possible.

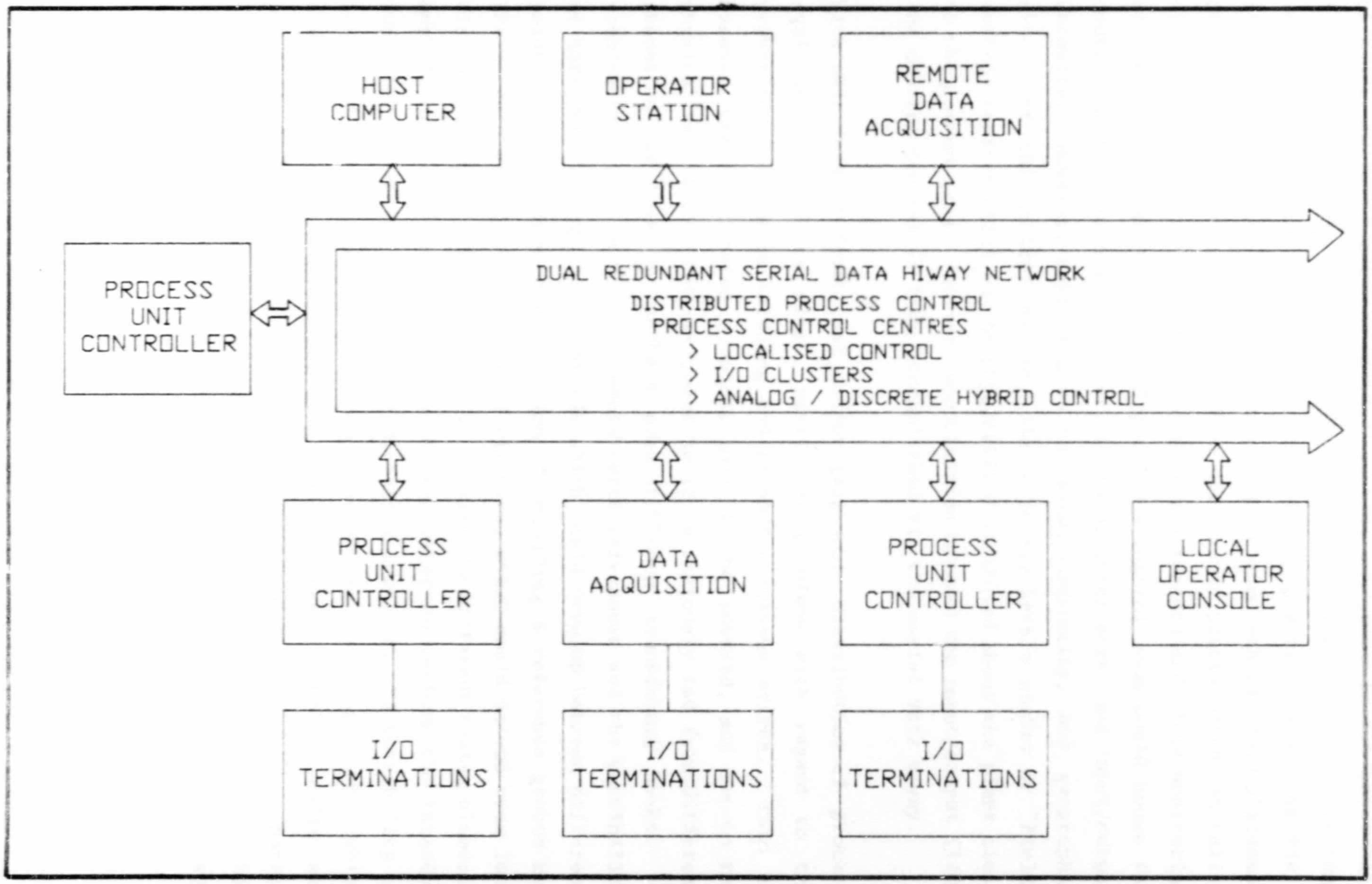


FIGURE 2.1 TYPICAL DISTRIBUTED PROCESS CONTROL SYSTEM CONFIGURATION

In many cases "distributed control" just means logical distribution of control; that is, various plant areas are under the control of separate hardware devices, but the actual control equipment is not physically distributed out into the plant. This often results when computer systems replace conventional control gear in existing plants. Here, the field signals have already been run to the control room, making field placement of the controllers unnecessary. Even new control plants often centralise distributed control equipment for easy maintenance and close monitoring of the equipment environment. Typically a control room would house the control units, the host computer, operator interfaces, and input/output hardware. However, depending on the size, complexity, and geographic extent of the control system, the site may have a number of "field" control centres which may be physically distributed about the plant close to the process area. Process communication between the input/output (I/O) and control centres is then accomplished via the serial data hiway.

With this form of functional and/or geographic distribution of process equipment around the plant, particular problems with regard to the provision of reliable earthing and grounding systems arises. This is because the distributed elements need to be powered, and due to the physical separation, the equipment could be variously fed from different phases of the line, or perhaps even different transformer banks. A problem with this is that of remote earth references and the possibility of hazardous voltage differentials which could develop between different points. In addition, the question of providing a reference ground for the network of signal and control circuits, which could extend over long distances, presents itself. This is because the different system elements must interconnect and interface with each other to perform the intended function. Also, due to the large distances involved, the possibility of increased susceptability to stray interference coupling arises, which could result in ground loops, to which low-level signal circuits are particularly susceptable. Furthermore, the need to provide a separate "clean" earth electrode system for the control system may be undesirable because the system could be centrally located and a earth system may already exists.

From the foregoing discussion, it is apparent that the design of earthing and grounding systems for distributed process control systems must give careful consideration to a number of problem areas - one of which is the threat of EMI. The first step in ensuring a EMI free system is, thus, to recognise that it exists.

2.3 THE INDUSTRIAL EMI ENVIRONMENT.

In simplest terms, before an electrical interference problem can exist, there must be three basic elements for an EMI situation to exist:

- an interference source
- a means of coupling
- and a susceptible receptor

Figure 2.2 illustrates diagrammatically the three elements; and identifies the different sources, the coupling mechanism and receptors. The simplification of the EMI problem into this three element problem lies in the fact that the problem can be eliminated by removing any one of the three elements. That is, by either suppressing the interference source, by eliminating the coupling path or by desensitising the equipment and making it insensitive to the interference. It is evident that the middle element in this problem is of prime concern in this study, although a knowledge of the other two elements is essential in EMI control.

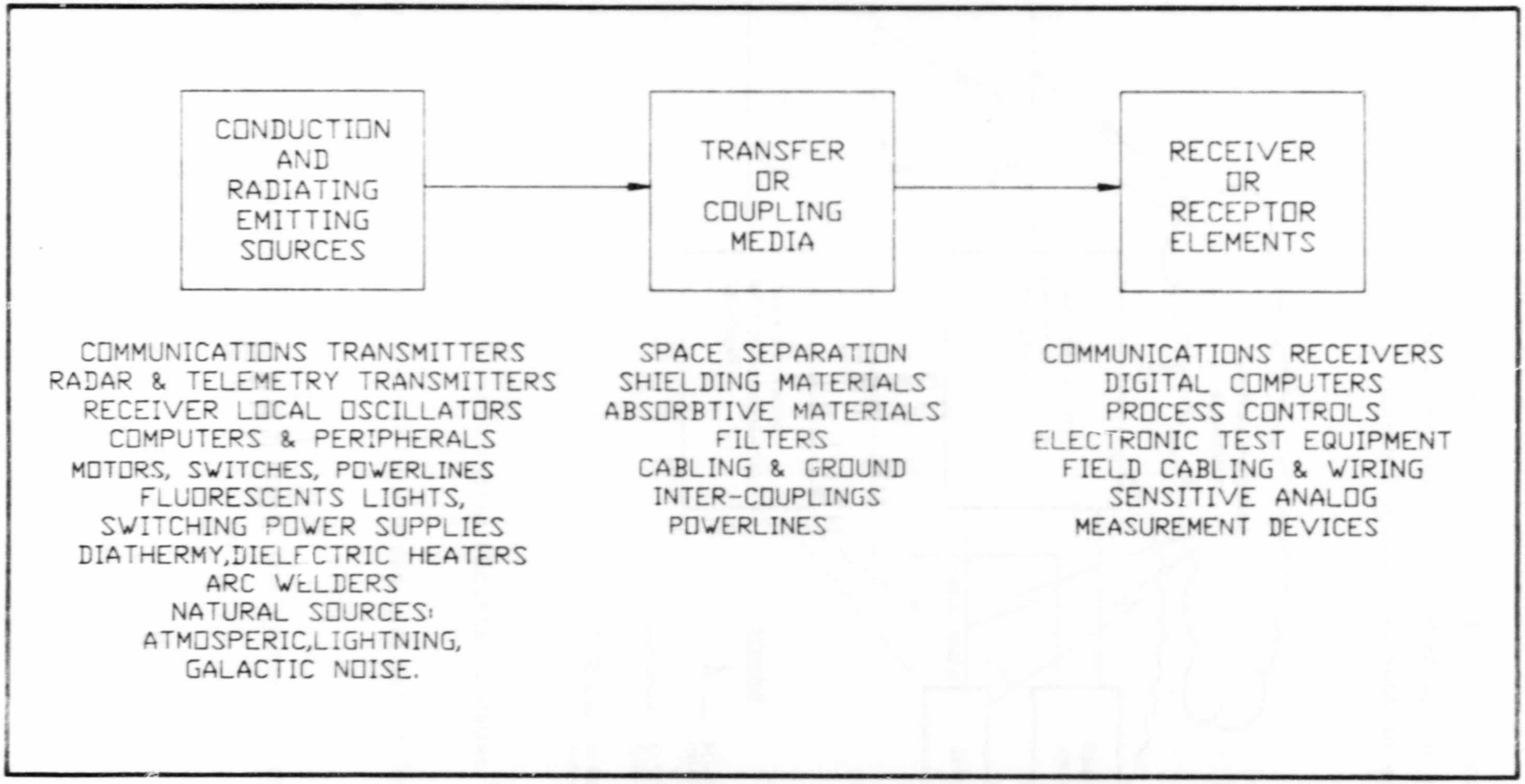


FIGURE 2.2 THREE BASIC ELEMENTS OF A EMITTING – SUSCEPTIBITY SITUATION (SOURCE: WHITE[2])

2.3.1 INTERFERENCE SOURCES

The operational electromagnetic environment in which electronic process control systems must operate is essentially created by the multitude of man-made and natural sources. Figure 2.3 typifies such an environment.

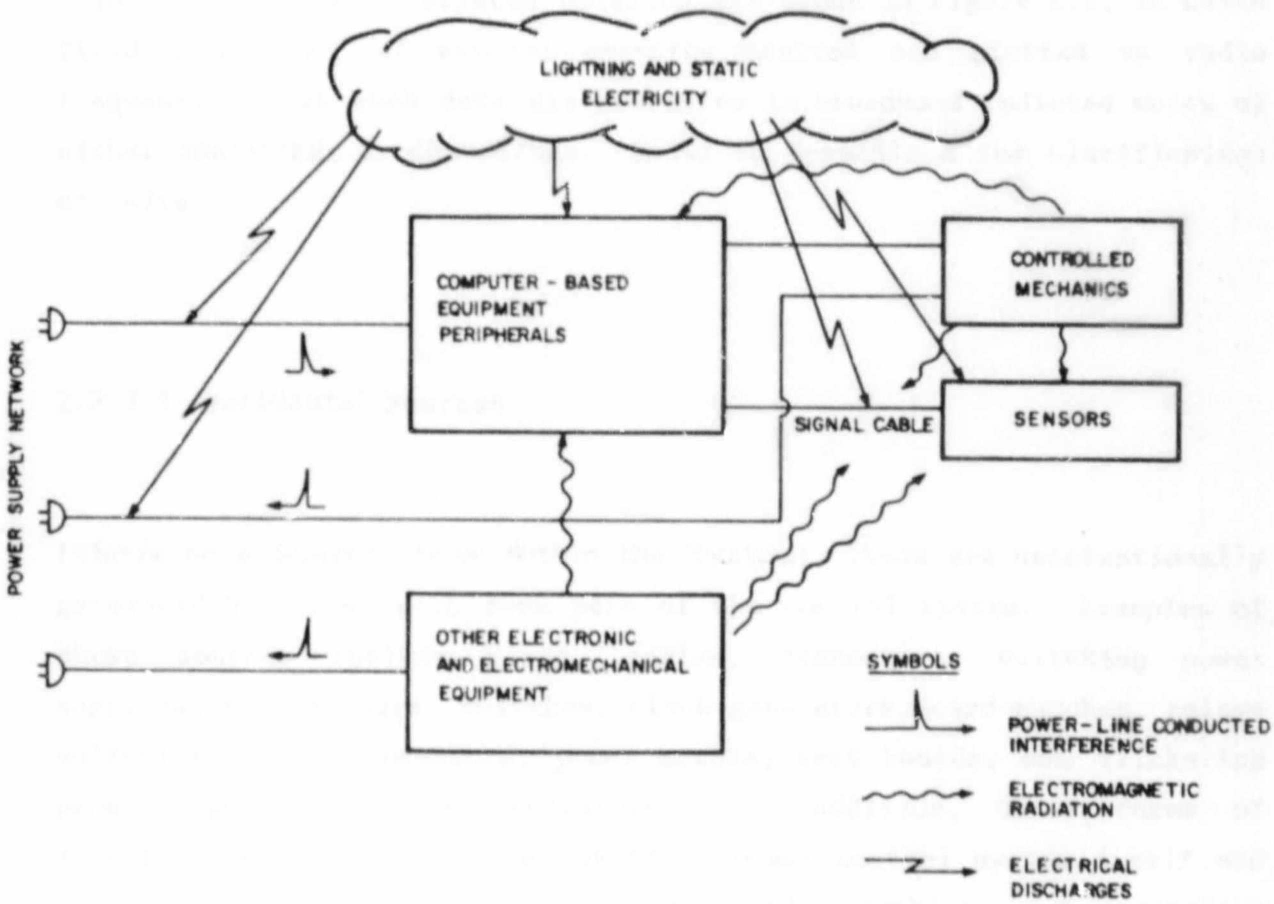


Figure 2.3 Interference Sce.ario (Source: Strauss[8])

In general, interference sources can be divided into the following general categories[4,31]

- Incidental sources which form part of the system and those in the vicinity of the system but are not intentional

- External intentional sources which are emissions of potentially interfering energy produced for other purposes

- power line phenomena

- Natural phenomena

These sources of electromagnetic interference are summarised in Figure 2.4. Depending on the kind of environment, these sources could cause interference over the frequency spectrum of a few hertz to tens of Gigahertz. Typical radiated emission are shown in Figure 2.5, in which field intensity of several emission sources are plotted vs radio frequency. Most such data are presented in broadband radiated units of either $dBm/m^2/kHz$ or $dB\mu V/m/kHz$. Refer to Appendix A for clarification of units.

2.3.1.1 Incidental Sources

Interference Sources from Within the System: These are unintentionally generated by units which form part of the control system. Examples of these sources include wires, cables, connectors, switching power supplies, card readers, switches, clock generators, card punches, relays solenoids, line suppressors, power motors, test boards, and flickering panel lights or alarm indicators. In addition, other forms of interference can be generated by the process control system itself and are commonly due to poorly designed earthing and grounding configurations, conducted and radiated coupling, cross-talk, inadequate suppression of contacts and differing voltage levels between the computers and the equipment that they control.

Wires and cables, while not generating EMI by themselves, provide an induction or radiating physics media to couple undesired energy into or out of other wires, circuits, or equipment. Generally, these sources are experienced from power cables, ground conductors, poor contacts and equipment wiring. At power frequencies the coupling is relatively poor but at higher frequencies the coupling could be more of a serious problem especially when equipment is operating directly with high frequencies.

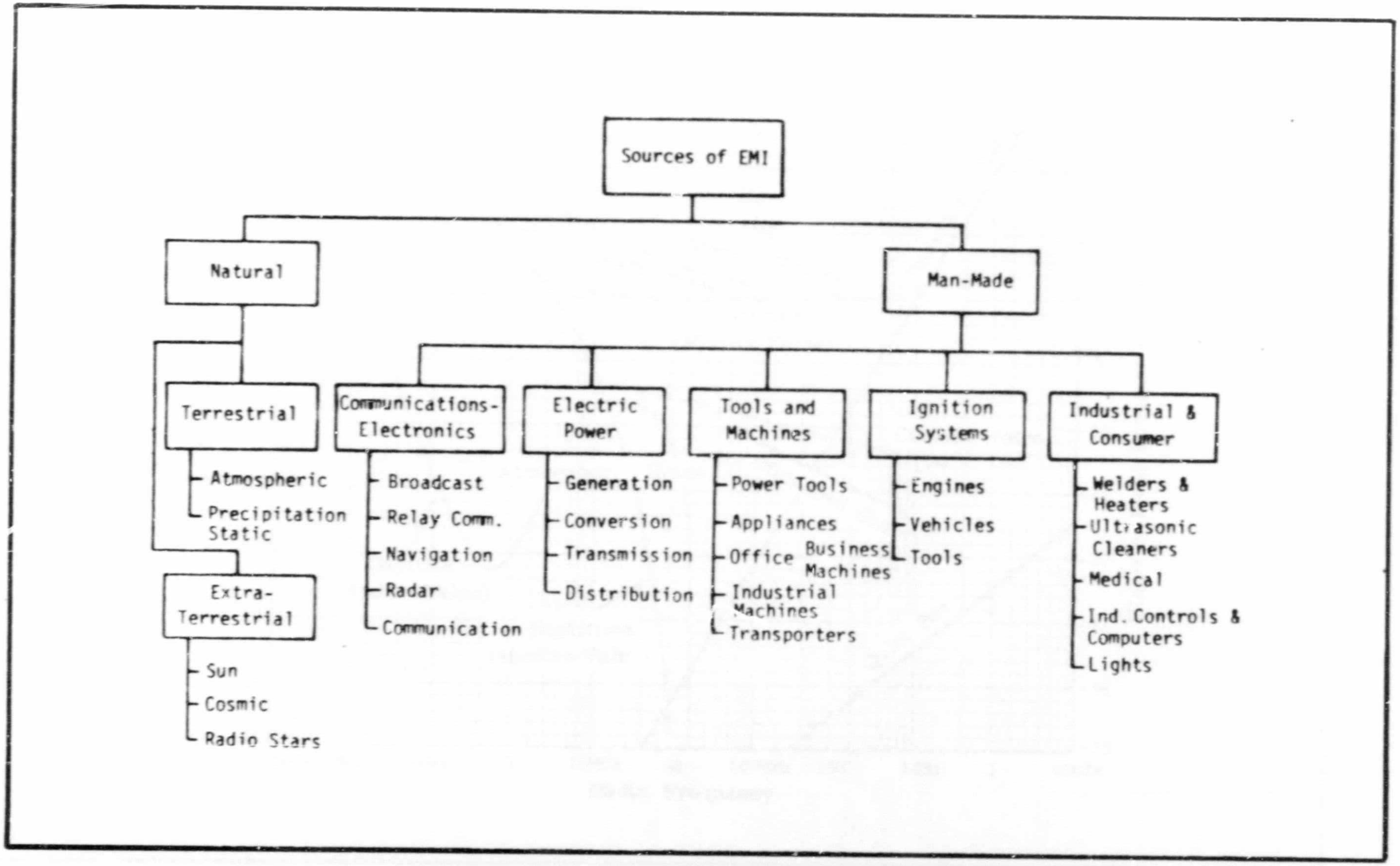


FIGURE 2.4 SOURCES OF ELECTROMAGNETIC INTERFERENCE (SOURCE: WHITE[2])

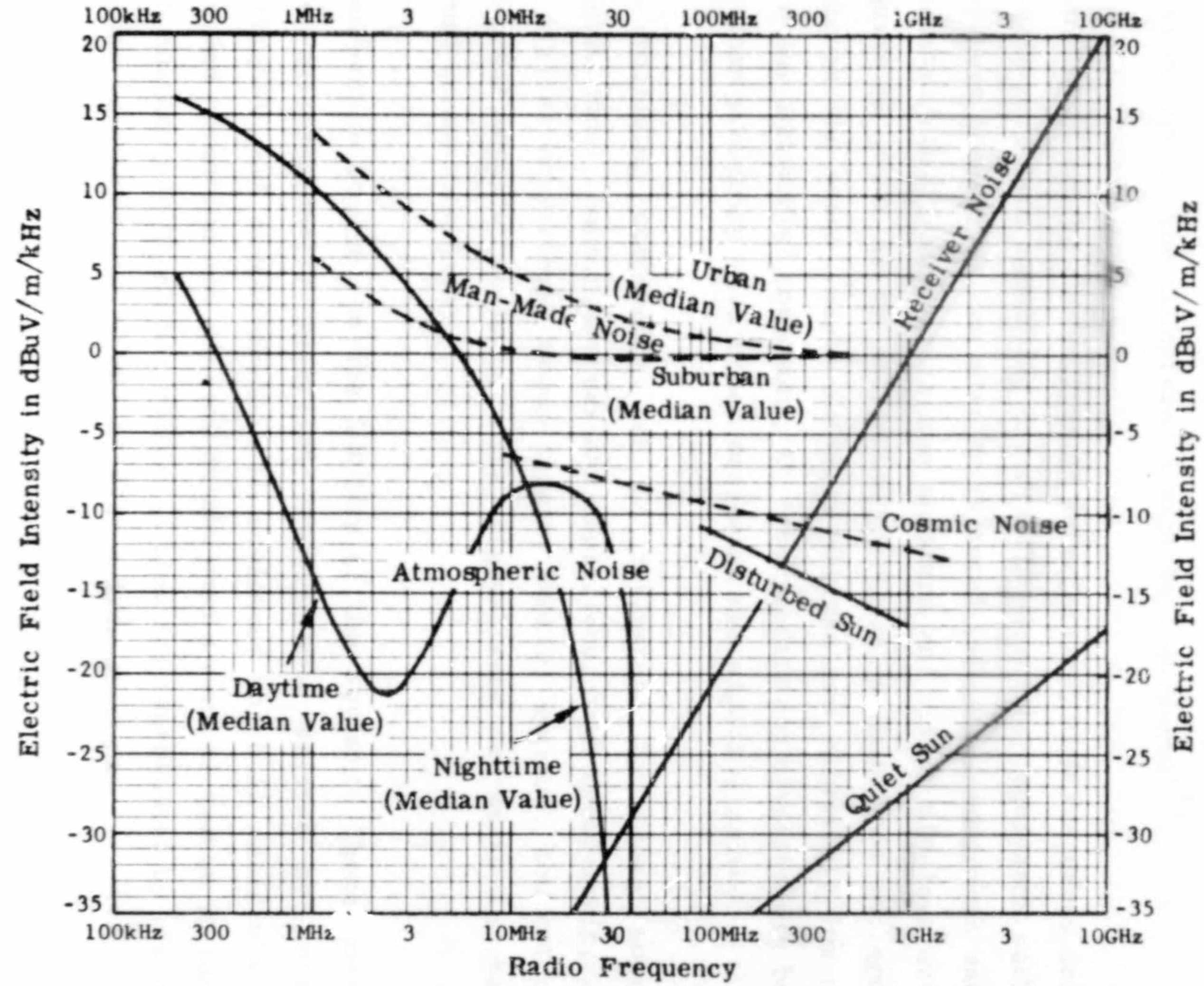


FIGURE 2.5 SUMMARY OF ELECTROMAGNETIC NOISE SOURCES AND LEVELS (SOURCE: WHITE[2])

Relays, clock generators, motors, and few other sources could cause interference over the frequency spectrum of 19 kHz to 1 GHz, depending on clock frequencies and rise time of impulses. However, above 300 kHz the amplitudes of the fields are usually too low to cause problems. Maximum amplitudes of other devices usually occur in the low frequencies, but can have high levels at frequencies as high as 20 to 40 MHz. Although the energy is radiated over a broad frequency band, digital equipment can often be sensitive to broad band interference and the influence of the total energy in the interference must be considered(8).

In addition, to the above types of interference, high frequency continuous interference from switching circuits in electronic equipment such as the computers themselves can also be injected into other equipment and signal circuits. Oscilloscopes, video monitors and visual displays units also require RF power as an incidental to their normal mode of operation. Although the power levels in these devices are relatively low compared to other industrial equipment, RF interference can nevertheless be caused by close proximity with other equipment and signal circuits.

The following components can be influenced by these sources of interference: sensor systems and amplifiers, high-speed logic, analogue to digital converters, modem inputs, control systems, control circuits for power supplies, display units, digital read out units and cable and signal connection lines.

Interference Sources in the Vicinity of the System: These sources are also unintentionally generated interferences emitted by surrounding electrical and electromechanical equipment which is incidental to its intended operation and already exists when a control system is installed. Such sources may be either random in time and represented by a stochastic process or deterministic and display a line spectrum.

Typical examples of the sources include noise from motors, generators, dielectric heaters, mining equipment, power cables which carry exceptionally high currents, equipment associated with arc discharges, switching power supplies, static converters, and fluorescent lights (especially with on/off switching or where the light is defective). In addition, mechanical vibration and shock can produce false signals which can result in improper operation. Shock and vibration also effect printed circuit boards plugged into back plane connectors.

Motors and generators, which uses brushes and commutators in order to perform, are inherent sources of broadband-transient EMI interference. These transients are due to the arc discharge upon separation of the rotating brush-commutator interface. Repetitive spikes with frequencies upto 100 MHz (wavelengths less than about 3 metres) are characteristic of these sources. In addition, most of these items also cause harmonics to be generated in the mains supply. Figure 2.6 shows the radiated noise spectra from an alternating current continuous mining machine.

Random spikes on the other hand, can be expected from circuit breakers, equipment switches, relays and thermostats of which there are an abundance in industry. Due to contact bounce and voltage breakdown of the contact gap, each operation of a mechanical switch consists of a sequence of makes and breaks lasting for several microseconds. The rate at which current and voltage change during this operation period is considerable, giving rise to the generation of transient interference over a very broad frequency spectrum ranging upto 1000 MHz (down to a wavelength of 30 cm).

Figure 2.7 shows maximum values of radiated noise for two cold and one hot cathode, unmodified fluorescent assemblies. The legend indicated the length and number of fluorescent bulbs used in each unit. The distinctive high frequency radiation is clearly evident and this can be especially problematic where many such lights are used.

An example of radiated radio noise from power lines, automotive traffic, and radio-frequency-stabilised arc welders is shown in Figure 2.8. Skomal[29] has concluded that below 25 MHz lower voltage transmission lines and radio-frequency-stabilised arc welders are the major incidental interference sources when the observer is within 30 metres of the source and that above 40 MHz automotive traffic and lower voltage transmission lines are the major radio noise sources, with neither appearing to be consistently the greater when an observer is within 15 meters or less of the source.

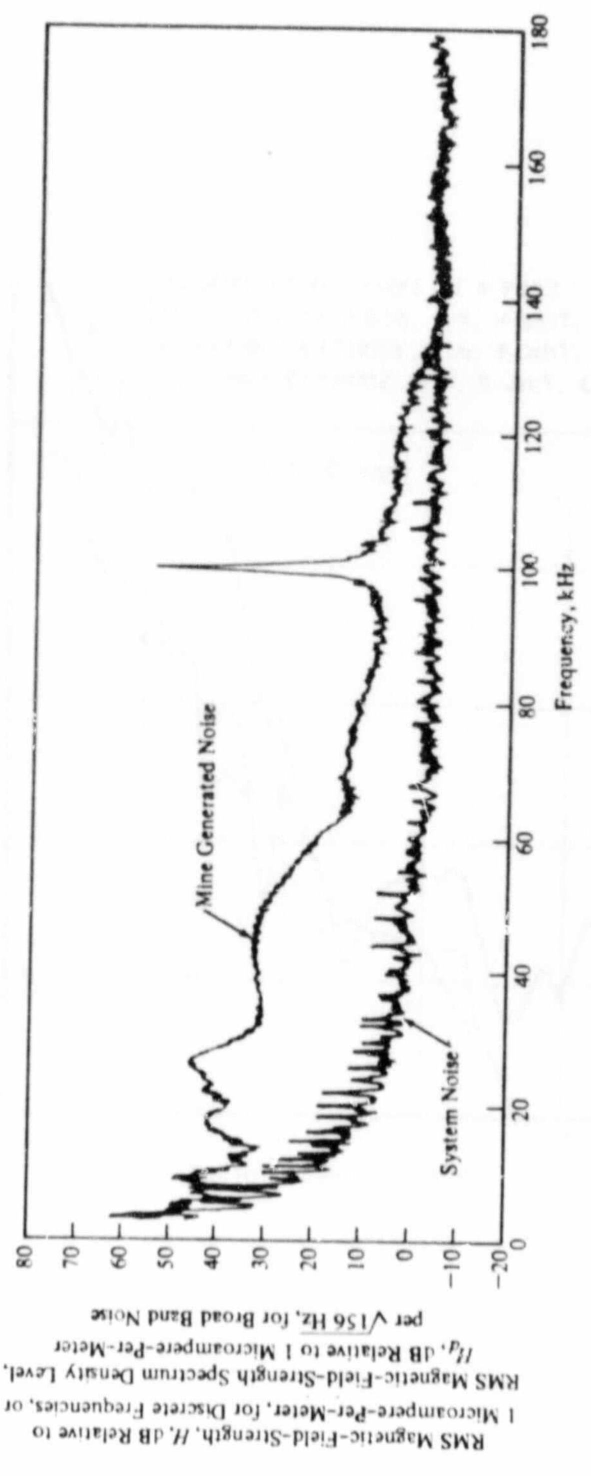


FIGURE 2.6 RADIATED NOISE FROM MINING MACHINERY OBSERVED AT A DISTANCE OF 3m (SOURCE: SKOMAL[29])

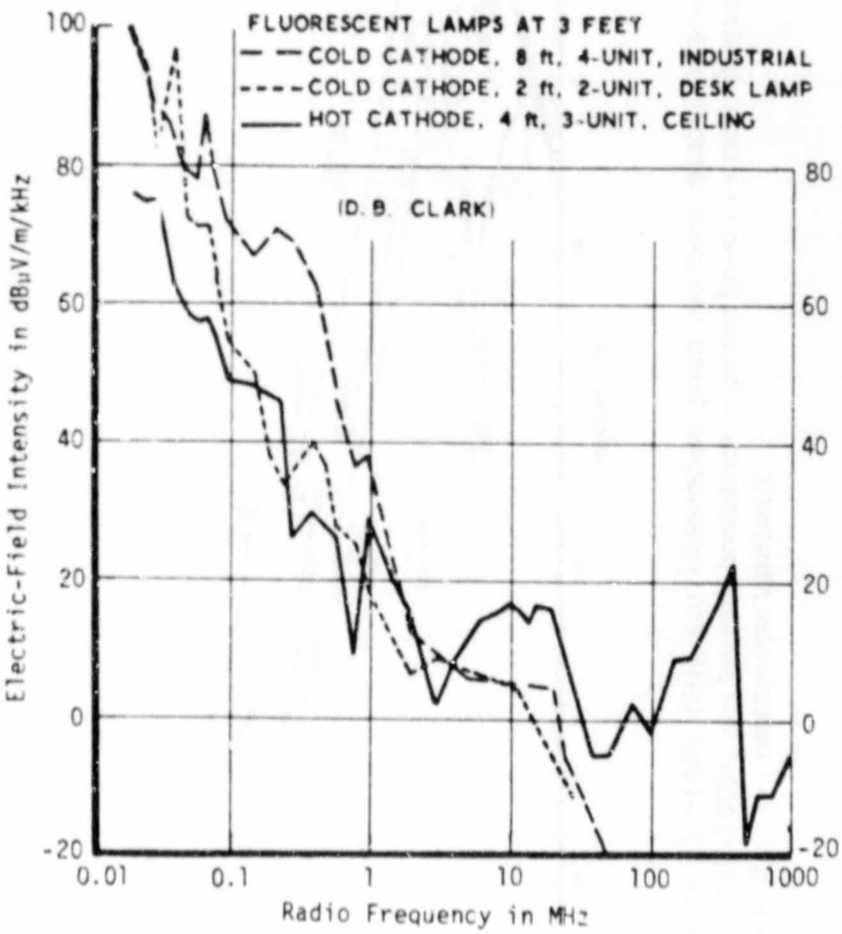
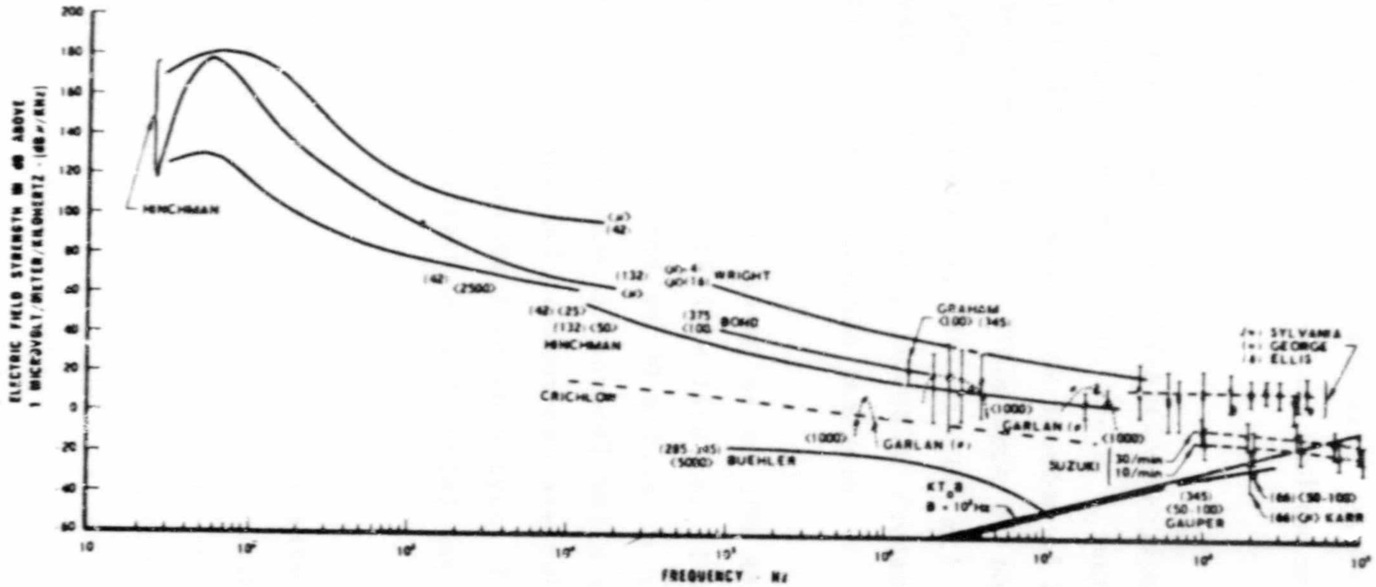


FIGURE 2.2 RADIATED FLUORESCENT LAMP NOISE (SOURCE: WHITE[2])



(Line voltages in kV—(40), (60), etc; observation point locations relative to sources in ft <μ> — <25>, <50>, <50-100>, etc; beneath conductor — power lines; • • • radio-frequency-stabilized arc welders at 1000 ft; - - - - - automotive ignition.)

FIGURE 2.8 RADIATED NOISE FROM POWER LINES, AUTOMOTIVE TRAFFIC, AND RADIO–FREQUENCY–STABILIZED WELDERS (SOURCE: IEEE Std 518–1982(30))

2.3.1.2 External Intentional Sources

This class of interference sources fall into the intentional radiator category and is usually beyond the control of the affected party. These include licensed transmitters such as AM/FM/TV stations, citizens band radios, military, radar transmitters, air-traffic control, mobile electrically powered transport systems and other communication services, and navigation systems.

Also, quite a large number of industrial equipment types rely on the generation of high frequency for their effective operation and are, therefore, particularly prominent as sources of RF interference, i.e. 10 kHz - 1 GHz (3×10^4 m - 30 cm). This type of equipment comes under the category of ISM (Industrial, Scientific and Medical) equipment and includes RF heaters and melters, induction furnaces, RF drying equipment, microwave ovens and spectrographic analysis.

Tests carried out on typical examples of ISM equipment have shown them to be very potent sources of interference. Field strengths of upto 1 volt/metre have been measured at 30 metres from equipment under test, whilst interference waveforms of several volts can be injected into the mains supply where no special precautions are taken to reduce the amount of RF radiation and conduction from this type of equipment. The extent to which these sources affect an industrial environment is dependent on localised conditions.

Figures 2.9 and 2.10 present the field intensity and frequency spectrum of selected radiated interference sources. Within this group only arc welders emit a spark spectrum, while for the others radiation occurs as a line spectrum at harmonics of the radio-excitation frequency. However, identifying potential interference sources can be a difficult and time consuming process. In general, this is hardly a simple task especially when incidental sources are the cause of EMI or when several sources are active at the same time. However, it is usually necessary to obtain assistances from persons or organisations with the required knowledge and measuring equipment (e.g. CSIR, SABS).

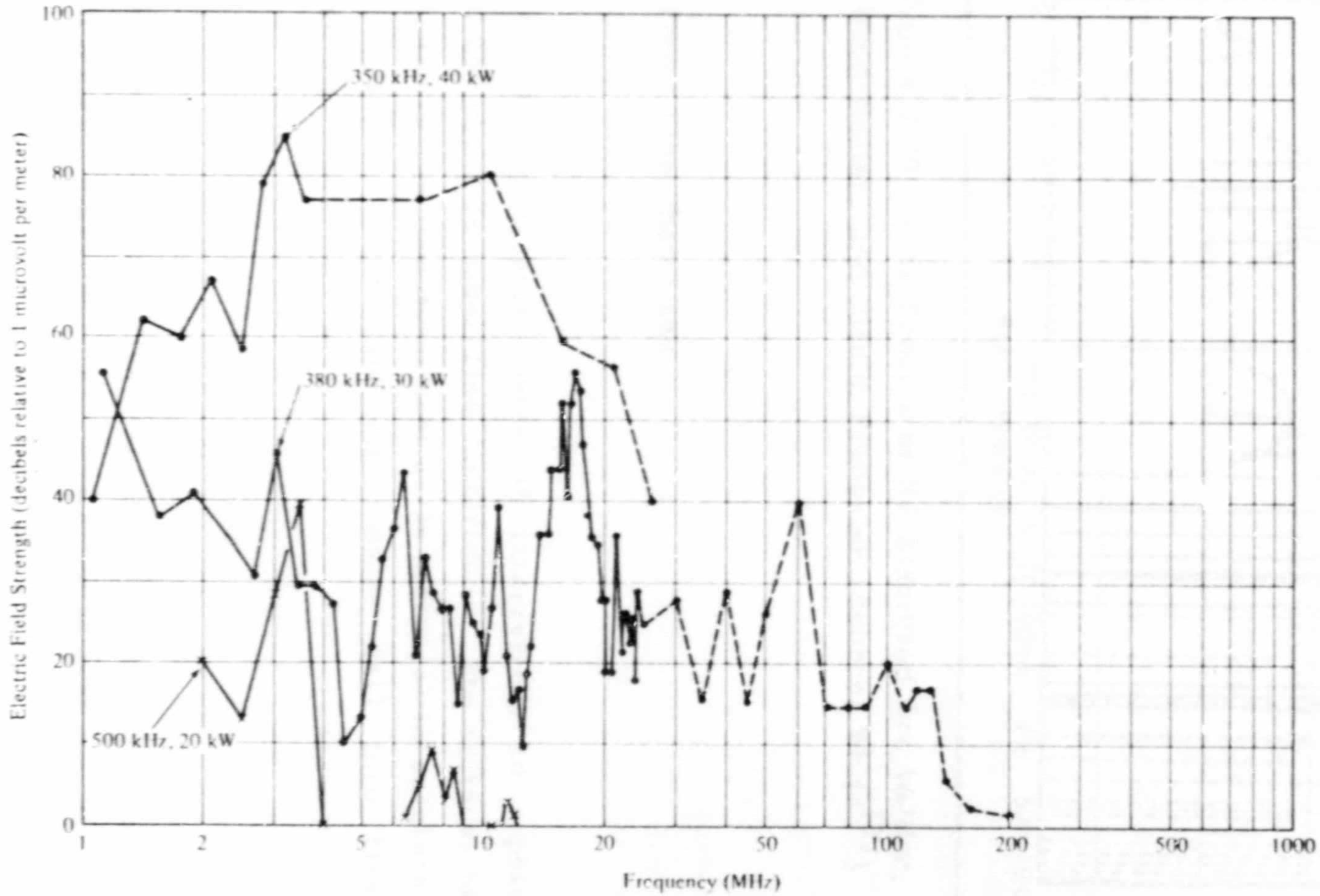


FIGURE 2.9 RADIATED NOISE LINE SPECTRA FOR THREE RADIO-FREQUENCY INDUCTION HEATERS (SOURCE: SKOMAL[29])

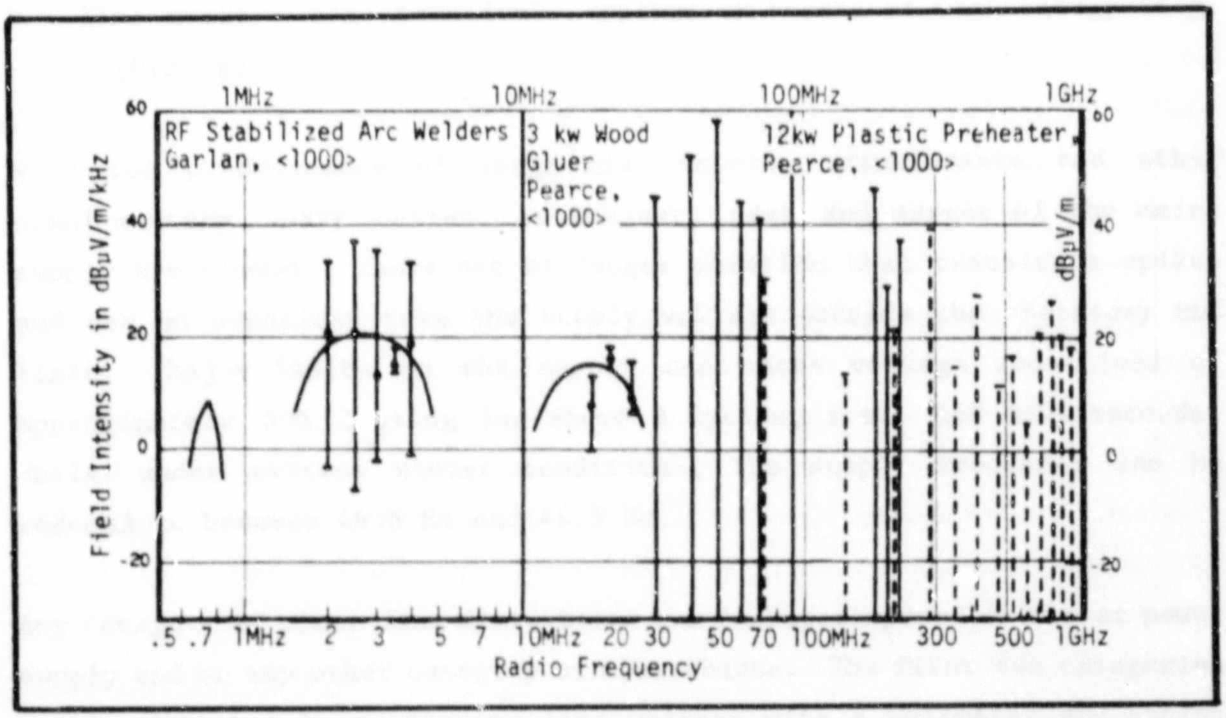


Figure 2.10 Noise Spectra of RF Stabilised Arc Welder, Wood-Heater, and Plastic Preheater (Source: White[2])

2.3.1.3 Power Line Phenomena

Probably the single largest source of interference to sophisticated electronic equipment is power-line disturbance. The critical nature of many computer applications means that it is essential to maintain "clean" ac mains supply. Power line disturbances fall into five basic categories[38]:

- total loss of power for extended periods
- high or low line voltage (insufficient or excessive) for a few cycles only or of long duration
- short-term voltage fluctuations at slow rates.
- short-term voltage fluctuations at high rates.

- line noise - e.g. transients, spikes or bursts of high energy (e.g. lightning)

With the predominance of large mill motors, transformers and other complimentary heavy current switchgear, sags and surges of the mains supply are common. These are of longer duration than transients spikes and can on occasions take the supply voltage outside the statutory ±6% limit. Major faults on the supply can cause voltage reductions of approximately 50% lasting for above 8 cycles, i.e. 160 milliseconds, whilst under extreme winter conditions, the supply frequency can be reduced to between 49.3 Hz and 49.5 Hz.

Any category of power-line disturbance can be superimposed on the ac power supply and on any other category of disturbance. The first two categories can be detected by monitoring line voltage with a voltmeter and noting whether system equipment (especially computers) malfunctions coincide with periods of low (or high) voltage. The last three can be detected only by particularly responsive power-line monitoring equipment. The detection and correlation of fast a.c. power fluctuations and transients is further complicated because these disturbances can be coupled into a circuit. Since entry could be at any one of many routes, detection is made more difficult.

2.3.1.4 Natural Phenomena

Natural sources can be divided into:

- terrestrial sources - sources emanating from the earths atmosphere.
- extra-terrestrial sources - sources emanating from regions beyond the earth.
- static discharge.

As explained below, terrestrial sources of interference (e.g. lightning) tend to be more transient-like in nature whereas, with certain exceptions, interference from stars, the galaxy, and other regions tend to behave more like bandwidth-limited white noise and thus will not be considered in this study.

Atmospheric Sources - Lightning The dominant, naturally-occurring interference source below 30 MHz is from the atmosphere and is produced by electrical discharges occurring during thunderstorms. Probably the most severe source to which any control system could ever be exposed is lightning. Most electronic control systems will probably fail under a direct lightning strike. But even remote strikes can cause trouble. As lightning travels along a power line in search of earth, much of its energy is dissipated by the power distribution networks earthing system. High voltage transients and large potentials generated direct into circuits through coupling can, however, still reach equipment even if it is well removed from the lightning strike. If the common earth connection network is large in relation to the wavelength of the above mentioned high frequency components, potential differences can develop between subsystems and units. This can also occur when equipment is not correctly earthed. However, this subject is further considered in Chapter 6.

Static Discharges Static electricity is another natural source which can cause errors and, in extreme cases, physical damage to equipment and electronic components. Some types of components are damaged by voltage or current discharge. Others may be damaged by mere exposure to electrostatic fields. Static electricity with potentials as high as 10 kV can be generated between operator and equipment and can causes temporary failure or permanent damage. This is often the result of incorrect clothing, furniture and, especially, carpets. Static discharges are also aggravated by dry atmosphere and high personnel activity. Such discharges can be reduced or eliminated by proper grounding, controlling the relative humidity, use of antistatic spray, metallic casing or conductive paints, and shielding cables and using ferrite beads on susceptible wiring.

2.3.2 PROPAGATION AND COUPLING MEDIA

The second element in the EMI situation (see Figure 2.2) is the propagation and/or the coupling medium. In general, this includes free-space separation (for field radiation coupling); shielding absorptive materials; power and signal cabling; grounding systems; conductive coupling and electric and magnetic near-field coupling.

Radiated EMI is coupled into network loops bounded by equipment boxes, interconnecting cables, and the ground plane or safety wires, where it can induce both common-mode and differential-mode interference. Current flowing through common ground impedances between grounded points within a network or in signal transmission circuits also induce interference. Electric and magnetic near-field coupling is possible, especially when cables carrying relatively high-level signals are routed close to cables that carry low level signals into sensitive circuits. Network ac and dc power mains can pick up external radiated or conducted interference and provide an entry path into equipment.

The role of the propagated medium is incorporated and further analysed and discussed in Chapter 4 on EMI coupling paths and mechanisms.

2.3.3 RECEPTOR ELEMENTS

The previous sections surveyed sources of electromagnetic interference and the propagation and/or coupling medium. Since it takes both an emission source and a susceptible receptor to make EMI possible, it helps to have an appreciation of the susceptibility of victim elements.

The term receptor here refers to the generic class of devices, equipment, and/or systems which when exposed to conducted and/or radiated electromagnetic energy from interference sources will either degrade or malfunction in performance.

Figure 2.11 gives a summary of the general class of receptors. Since this study is concerned with the industrial environment, only industrial receptors will be considered.

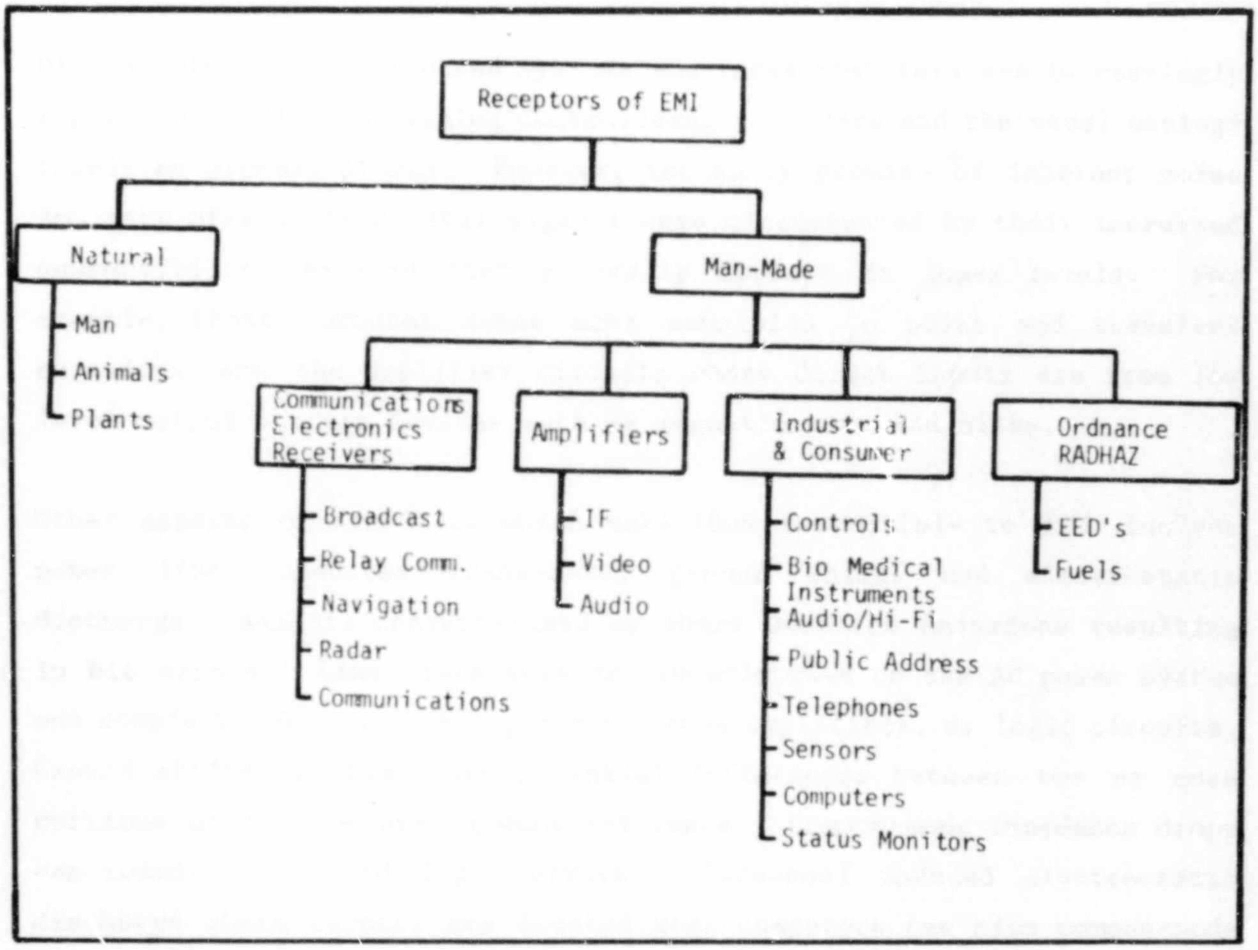


Figure 2.11 Receptors of Electromagnetic Interference (Source: White[2])

Industrial receptors are electrical, electromechanical, and electronic systems, equipment and/or products which may mal-perform or degrade in the presence of electromagnetic ambient environments indigenous to these items. Most of these items require amplifiers of one form or another in order to accomplish their intended performance. Amplifiers operating at low signal levels (e.g thermocouple transmitters) are relatively vulnerable to interference noise. Industrial process plants are generally characterised by closed-loop servo systems. These analog servo amplifiers and associated control processes will often malfunction when the electric-field intensity exceeds about 5 V/m. Not infrequently, this results from the pick-up of the sense amplifier harness or cable. In such cases cable shielding and grounding are critical EMI control requirements. Figure 2.12 shows typical receptor susceptibility of various receivers and amplifiers.

Digital microprocessor-based systems and large computers are increasingly replacing traditional analog controllers, recorders and the usual analogy panels on process plants. However, the early promise of inherent noise immunity offered by digital signals were circumvented by their increased susceptibility because they generally operate at lower levels. For example, those computer areas most sensitive to pulse and transient emissions are the amplifier circuits whose direct inputs are from low level output storage devices such as magnetic tape and disks.

Other aspects of computers which make them susceptible to EMI include power line conducted transients, ground shifts and electrostatic discharge. All are characterised by short duration emissions resulting in bit errors. Line transients are superimposed on the AC power system and couple to the computer logic bus, sense amplifiers, or logic circuits. Ground shifts are transient potential differences between two or more portions of the computer ground reference. Common-mode impedance drops can result in sensed logic errors. Personnel induced electrostatic discharge where carpets are located near computers can also common-mode impedance couple into logic circuits.

2.4 EMI CHARACTERISTICS

The correct operation of complex electronic equipment and facilities is inherently dependent upon the frequencies and amplitudes of both the signals utilised in the system and the potential interference emissions that are present. If the frequency and amplitude of an undesired signal is out of bound of the operating frequency and amplitude circuits, the circuits could malfunction which may either be temporary or permanent.

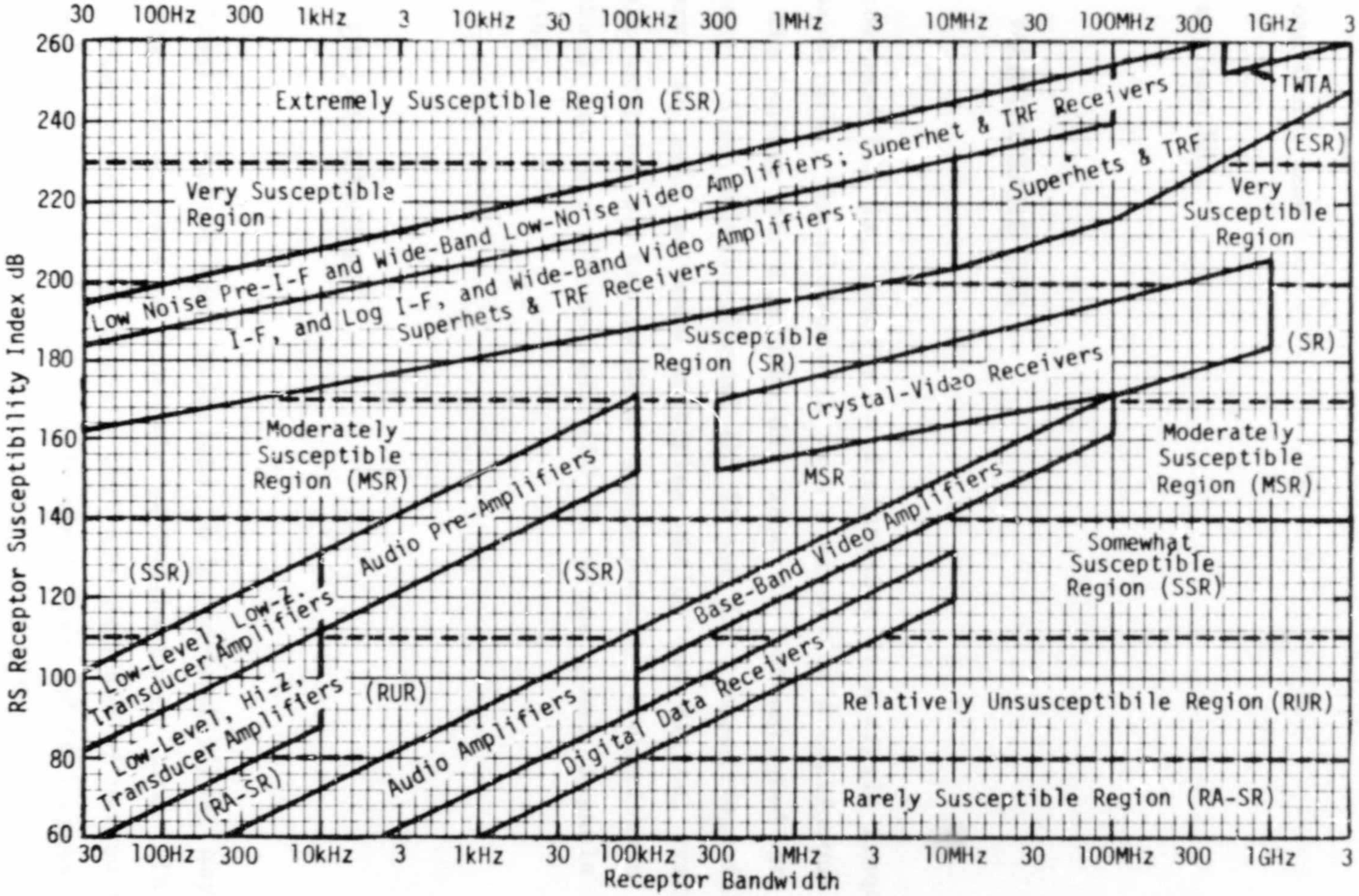


FIGURE 2.12 TYPICAL RECEPTOR SUSCEPTABILITY SCORES OF RECEIVERS AND AMPLIFIERS (SOURCE: WHITE [2])

In order to have a better approach to EMI control, it is necessary to have a clear understanding of the characteristics of the disturbing signal. EMI can, in general, be divided into three classes:

- narrow-band EMI
- broad-band, and
- transient EMI.

2.4.1 NARROWBAND EMI

A narrow-band EMI is, ideally, a disturbance at a single frequency with zero bandwidth. The ultimate in such a signal is a continuous sinewave, since the energy in a sinusoidal wave is concentrated at a single frequency. Also, single-channel AM, FM and SSB transmitters fall in this category, as well as some multiplex analog and digital systems. The harmonic outputs of narrow-band communication transmitters are also narrowband; so are 50 Hz and 400 Hz prime power signals and their harmonics.

2.4.2 BROAD-BAND EMI

In contrast to narrow-band emissions, a broad-band signal may disperse its energy across tens or hundreds of Megahertz or more. This type of distribution results from signals that are composed of narrow repetitive rectangular pulses having relatively short rise and fall times. Consider the square ware of Figure 2.13(a). Figure 2.13(b) is an expanded view of the fast rising portion of the square wave. This portion of the waveform approximates part of a sinewave (dotted line of Figure 2.13(b)), and by extrapolation the equivalent transient frequency f can be calculated from

$$f = \frac{1}{3.4t_r} \text{ MHz} \tag{2.1}$$

where t_r is the signal rise time in microseconds.
Thus, a system sees as its maximum frequency not the frequency of the recurring waveform but instead the rise time transient frequency, which is much higher.

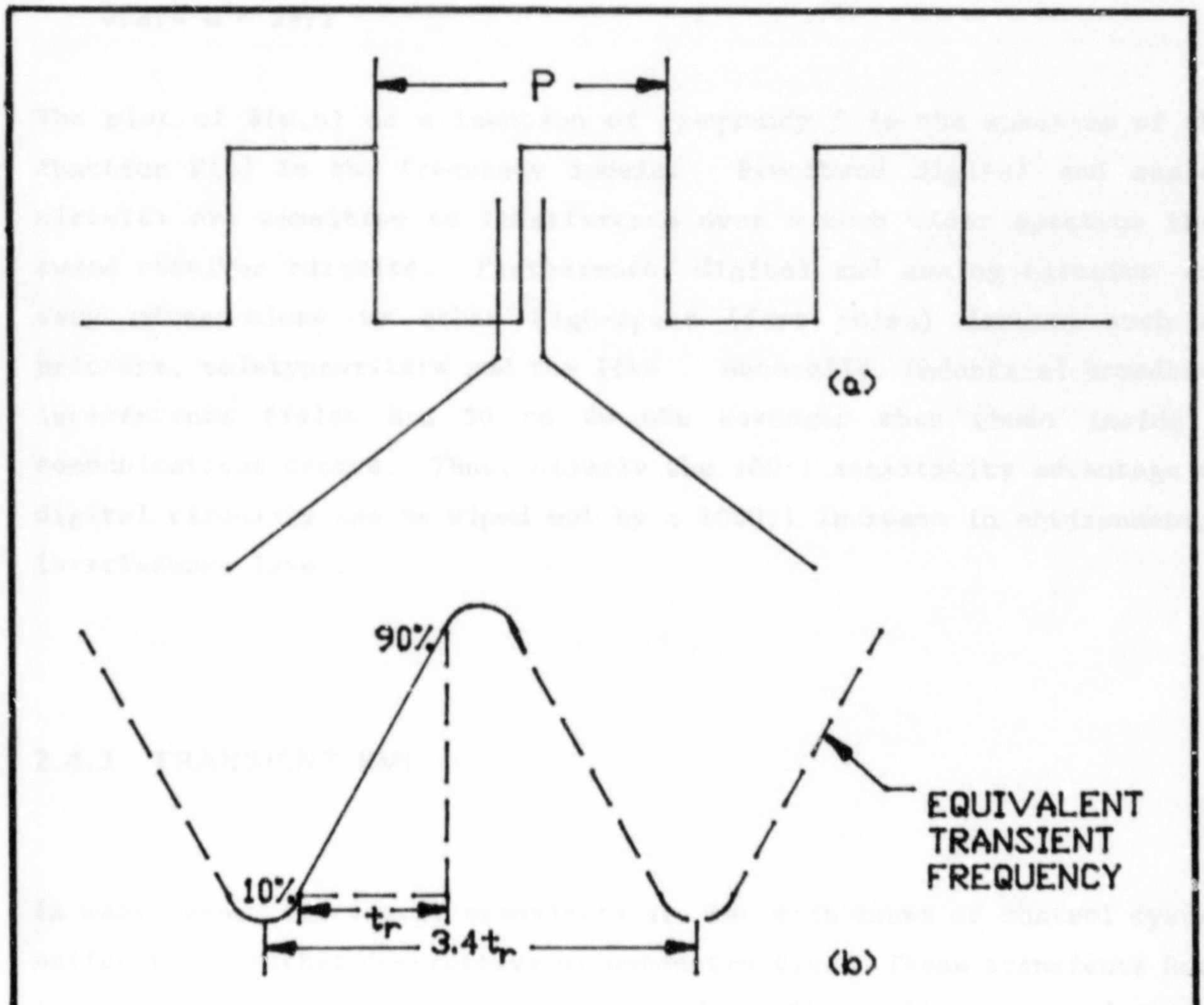


Figure 2.13 Expanded View of Rising Portion of Square Wave

In the frequency domain a periodic rectangular pulse train in the time domain can be expressed mathematically by Fourier Series (Figure 2.14) as