Module 1: Introduction

1.0 Introduction

The widespread use of small, high speed electronic devices which are often operated near other electrical systems, as well as the explosion in the number and variety of wireless communication devices available, has resulted in concern about interference effects. Faster and more complex circuits are being crowded into ever smaller spaces, increasing the likelihood that devices containing such systems will adversely affect one another. Modern electronic devices must therefore be able function properly in an increasingly cluttered electromagnetic environment. Thus, the minimization of electromagnetic interference and susceptibility has become a major design objective.

Often the effects of electromagnetic interference are not discovered until product testing occurs. The resolution of interference problems in the late phases of product development often involves the addition of extraneous components which add to system complexity and reduce reliability. Additionally, it is illegal to sell products which do not meet government regulations regarding electromagnetic emissions. It is therefore desirable that electromagnetic interference issues, and compliance with federal regulations regarding emissions and susceptibility, be addressed in the initial stages of product design. As a result, much interest has recently centered on the area of electrical engineering that has come to be known as Electromagnetic Compatibility (EMC).

Often the roots of EMC-related problems lie in common misconceptions held by many engineers. Much of the material presented to electrical engineering students represents specializations of broader principles. The most fundamental understanding of the behavior of electronic devices and systems requires application of Maxwell's equations and signal analysis techniques. However, such application to simple devices and circuits is often cumbersome. To avoid this complexity, an approximate analysis technique, usually referred to as electric circuit theory, is used to describe the behavior of devices operated at low frequency. For example, Kirchoff's Voltage Law and Kirchoff's Current Law arise from Faraday's Law and Ampere's Law, respectively. Unfortunately, the basic concepts of circuit theory and electromagnetics, (as well as other areas of electrical engineering such as signal processing and control theory) are often presented as being completely detached from one another. For this reason, most engineers (mistakenly) expect that the familiar basic circuit elements, such as resistors, inductors and capacitors, always behave in the ideal, low frequency manner described by the circuit theory presented in undergraduate coursework.

EMC involves the operation of these and other familiar devices in a regime where the special cases and simplifications that are associated with "normal behavior" break down, and requires a return to a more fundamental set of rules to describe the behavior of these devices. It should be remembered that effects described by fundamental electromagnetic principles are *always* present, and are simply more pronounced under certain conditions. "Non-ideal behavior" is, in fact, a misnomer, because it implies that devices are functioning in an abnormal way, when they are really behaving in a perfectly natural way. It is only through the application of fundamental principles that the behavior of devices under all operating conditions is predictable.

What makes the task of producing electromagnetically compatible systems particularly difficult is that, in addition to understanding the broader principles which govern device behavior, the designer often cannot anticipate what types of interference devices will encounter, and must prepare for all contingencies. For instance, it is impossible to know where certain ubiquitous electronic devices such as laptop computers will be operated. Laptops are used in the home, in automobiles, at construction sites, onboard airplanes, and even aboard manned spacecraft in Earth orbit. Each of these environments presents unique hazards and also requires a variety of emission limits. The same laptop computer which must be designed to function in the presence of a hair dryer also cannot interfere with the instrument landing system of a commercial airliner. In addition, particularly in vehicles such as automobiles and airplanes, devices whose design has changed little in decades may be placed close to state-of-the-art solid state devices. For these reasons, systems must be designed not only to minimize emissions, but also to be immune from external interference. Unfortunately, as the electromagnetic environment becomes more complex, this goal becomes more difficult to achieve.

1.1 A brief history of EMC/EMI

Until the early part of the twentieth century, few man-made sources of electromagnetic radiation existed. While the first crude radio receivers tended to be susceptible to interference from natural noise sources, the correction of this problem was usually a relatively simple task. Conflicts between early radio transmitters were easily resolved by changing frequencies or by simply moving the transmitter or receiver. As a result, prior to the 1930's, the designers of electrical circuits and systems typically needed only to insure that their devices would function in the presence of natural noise sources such as lightning or sunspots. Understandably, little if any thought was given to designing systems which were immune from external interference, and virtually no effort was made to reduce electromagnetic emissions from electrical systems during this period.

In the years that followed, more and more man-made sources of electromagnetic radiation began to appear. At nearly the same time that it became possible to transmit and receive complex, information-carrying signals via radio, television, and telephones, the increased generation and use of electricity caused a proliferation of noise sources such as dc motors, ac power lines, relays, and fluorescent light bulbs. The design of electromagnetically compatible systems was still not a priority during this period, however conflicts between electrical devices became much more common. In 1933, the International Special Committee on Radio Interference (CISPR) was formed and produced a document regarding equipment for measuring EMI emissions.

World War II saw the introduction of radar and other remote sensing systems, along with the use of radio communication in combat. Instrumental in the development of radar was the introduction of small microwave sources, such as the cavity magnitron. This and other relatively small electronic devices, were incorporated into vehicles such as ships, airplanes, and automobiles. During the war, it became evident that vehicles which emitted electronic signals, even unintentionally, could be detected at a great distance. Moreover, an enemy could disrupt electrical systems such as radios and navigational devices by intentionally broadcasting electronic noise and false signals. The advent of electronic warfare ushered in the need for electromagnetic immunity and compatibility. After the war, the testing of nuclear weapons reveled that the electromagnetic pulse generated by a nuclear blast could damage or destroy certain types of electronic equipment. As a result the U.S. military became interested in creating systems which were immune from the effects of external interference. In the early 1960's, MIL-STD-461 was imposed, regulating not only electromagnetic emissions, but susceptibility as well. Also in the years following World War II, CISPR produced various publications dealing with recommended emissions limits, which were adopted by some European countries.

The U.S. government became involved as the manufacturers of digital computers and related devices began selling large numbers of products. With the proliferation of small, integrated circuit devices came a dramatic increase in the number of compatibility problems. In 1979, the Federal Communications Commission (FCC) began regulating the amount of electromagnetic energy that digital devices could emit. Today, the increasing speed, and decreasing size of micro-electronic circuits has made electromagnetic compatibility a critical aspect of product design.

1.2 Analysis of EMI

In general, electromagnetic interference scenarios may be decomposed into three major elements:

- a **source** (sometimes referred to as an emitter or a threat) which may be a noisy component, or a transmitter

- a **receptor** (sometimes referred to as a victim) which is a component or device that receives noise or interference from the source

- a **coupling path** which transmits the interference signal from the source to the receptor

The so called *source-path-receptor* model is illustrated in Figure 1. This model suggests that electromagnetic interference can be prevented in one of three ways:

- suppress emissions at the source

- interrupt or reduce the efficiency of the coupling path

- make the receptor immune to emissions

In designing and troubleshooting electronic systems for EMC, removing one of these elements will eliminate interference. The suppression of emissions at the source is usually the most desirable method of eliminating EMI. However, this is not always possible, such as in cases involving devices which intentionally transmit signals.

Of the three elements of the source-path-receptor model, clearly the receptor is the easiest element to identify, due to the fact that it does not function properly. The source is usually identified by examining the type of interference which is plaguing the receptor. The most often overlooked component of this model is the coupling path. One of the greatest difficulties in diagnosing interference is determining exactly which path interference is following to the receptor. Often coupling mechanisms are extremely subtle, and may be amazingly complex.

Coupling paths are typically classified as belonging to one of four general classes:

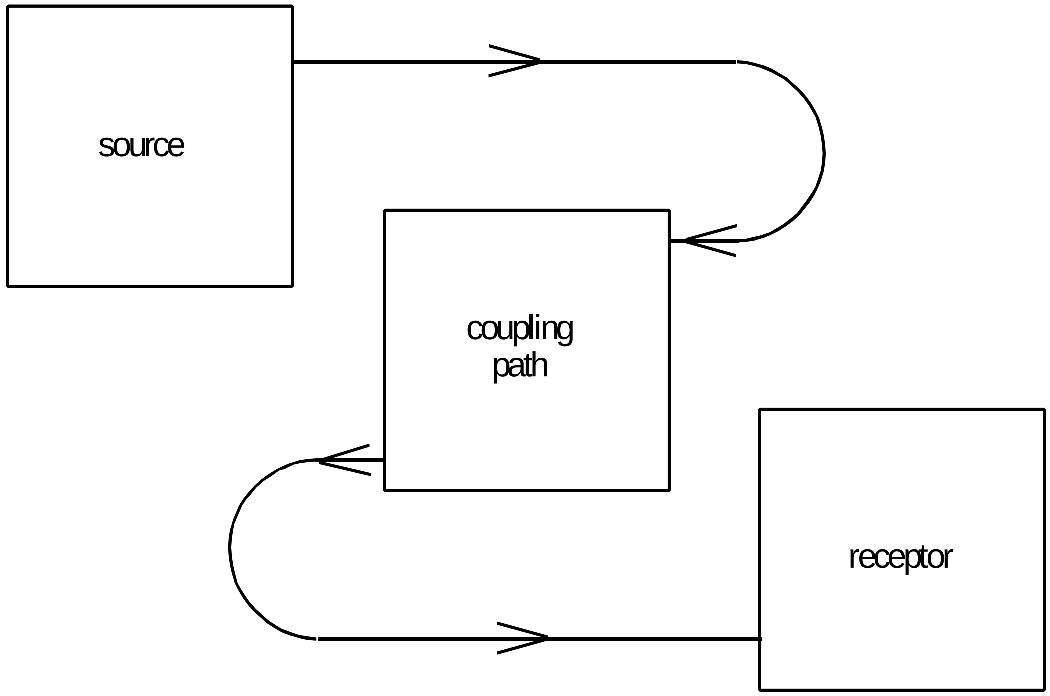

Figure 1. Source-Path-Receptor Model

- **conductive**

Conductive coupling occurs when the path of interference between the source and the receptor is formed by a conducting body. Conductive coupling can be by means of a power cord, interface cables, antenna input terminals, ground returns, or unintentional external conductors such as metallic cases or housings.

- **radiative**

Radiative, or electromagnetic coupling occurs when the path of interference lies through free space, or some other non-conductive medium. Radiative coupling usually occurs when distances between the source and receptor are on the order of several wavelengths. Because of this wide separation, the source is usually not affected by the presence of the receptor. Radiative fields decay as 1/R for points far away from the source.

- **inductive**

Inductive, or magnetic, coupling is similar to radiative coupling but is associated with near-fields, in a region where the magnetic field is dominant. Thus, inductive coupling usually occurs when distances between the source and receptor are much less than a wavelength. In this region field structures are more complex than in the far field. Due to the relatively small separation, the presence of the receptor can affect the behavior of the source. This two-way phenomenon is referred to as *mutual coupling*.

- **capacitive**

Like inductive coupling, capacitive, or electric, coupling occurs when the source and receptor are less than a wavelength apart. In the case of capacitive coupling, however, it is the electric field which is dominant.

1.3 Types of noise and interference

A nearly infinite number of interference and noise sources exist, some man-made, others natural. Some of the more common types of noise experienced by electronic systems are discussed below.

- **external noise**

External noise is considered to be that which originates somewhere outside of a receiver, and is generally categorized as being one of three types:

- **atmospheric noise**

Atmospheric noise is most commonly referred to as static, and is the result of lightning and other electrical discharges which occur in thunderstorms, or other parts of the Earth's atmosphere. These discharges are typically rapid, transient events, which give rise to electromagnetic pulses rich in spectral content. Such pulses excite spurious currents on receiving antennas, which are interpreted as noise by a receiver. The signals generated by atmospheric phenomena propagate over the Earth in the same manner as other radio transmissions, and thus may travel over great distances. Thus static tends to be more pronounced near thunderstorms, but is still experienced even when storms are quite distant. Typically atmospheric noise is limited to frequencies below 30 MHz (which is partially why AM radio is generally more prone to interference than FM radio). Very little atmospheric noise is detected at frequencies above the lower limit of the VHF band.

- **extraterrestrial noise**

Many types of extraterrestrial noise exist. Most sources fall into one of two groups:

i. solar noise

The sun is a tremendous source of emissions across much of the electromagnetic spectrum, including radio frequencies commonly used for communication. Solar output fluctuates in cycles, with maxima that occur approximately every 11 years, and supermaxima occurring approximately every 100 years. During periods of solar maximum, violent, localized electrical disturbances such as sunspots and flares may unpredictably erupt on the surface of the sun. Interference produced by such outbursts may be many orders of magnitude greater than the noise generated when the sun is at solar minimum.

ii. cosmic noise

Distant stars radiate energy toward Earth in the same way as the sun. While other stars are many light-years away, their vast numbers create a ubiquitous source of radio interference. Other sources of cosmic noise include the core of the Milky Way and the cores of other nearby galaxies, quasars, and pulsars. The noise produced by these objects may be quite intense, but is highly localized. Space noise typically occurs at frequencies from about 8 MHz to just above 1.43 GHz (the wavelength associated with this frequency is sometimes referred to as the 21 cm hydrogen line), and is strongest in the region from 20 MHz to 120 MHz. Cosmic noise at frequencies below 20 Mhz is usually absorbed by the ionosphere, while noise at frequencies above 1.5 GHz is absorbed by hydrogen in interstellar space.

- man-made noise

Interference produced by man-made sources typically is most pronounced at frequencies between 1 MHz and 600 MHz. The various types of man-made EMI fall into two general categories:

i. intentional radiators

Intentional radiators are devices which emit electromagnetic energy as part of their desired function. These include such devices as radio and radar transmitters, cellular phones, remote controls for car alarms, etc. Because intentional radiators emit signals by design, their operation may interfere with other electronic devices. For example, digital computers may interpret radio or television signals as data, resulting in spurious commands being executed.

ii. unintentional radiators

Unintentional radiators are devices which are not designed to radiate but still emit electromagnetic energy. These include digital devices, motors, relays and switches, etc. An intentional radiator such as a cellular phone may also be an unintentional radiator at frequencies other than those at which it normally transmits.

- **internal noise**

Internal or intrinsic noise is a source of interference that arises from the components that make up receivers and other electrical devices. This noise is generally random, and tends to be evenly distributed across the radio spectrum. While many types of internal noise exist, three primary types are thermal, shot, and contact noise.

- **thermal noise**

Thermal noise arises from the agitation of the electrons in a resistive component. This is sometimes also referred to as Johnson, or white noise, and is due to random collisions between electrons and the atoms and molecules that make up the resistor. Thermal noise power generated by a resistor is given by

$$P_T = kT\delta f$$

where $k = 1.38\text{x}10^{-23}$ J/K is Boltzmann's constant, T is temperature (Kelvin), and δf is the measurement bandwidth.

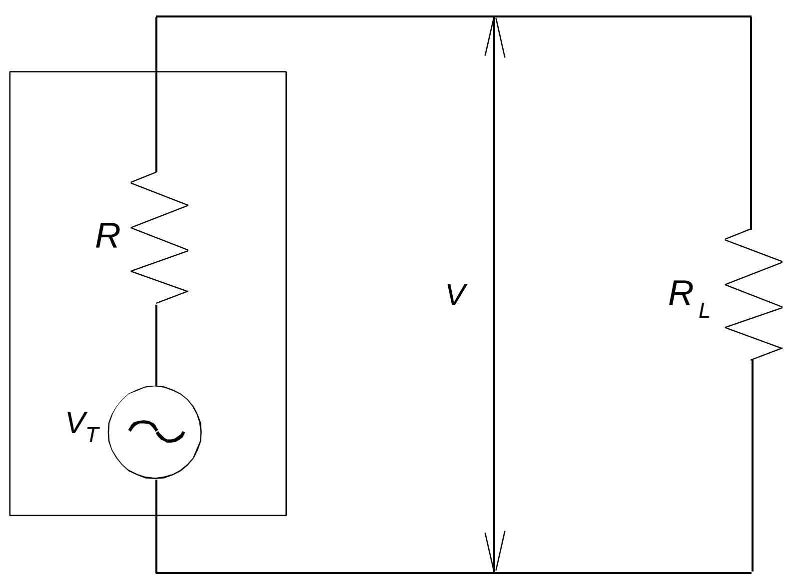

Figure 2. Equivalent circuit for determining resistor thermal noise voltage.

The thermal noise voltage present in a resistor may be calculated by considering the equivalent circuit shown in Figure 2. A noiseless resistance R_L is connected in series with the equivalent resistor model having thermal noise voltage V_T. In order to receive the maximum noise power, R_L must equal R. In this case

$$P_T = \frac{V^2}{R_L} = \frac{V^2}{R} = \frac{(V_T/2)^2}{R} = \frac{V_T^2}{4R}$$

therefore

$$V_T^2 = 4RP_T = 4RkT\delta f$$

$$V_T = \sqrt{4kT\delta fR}\,.$$

All electronic components with a non-zero resistance have an associated thermal noise, which therefore marks the lower bound on possible noise levels in an electronic system.

- **shot noise**

Shot noise, which is present in semiconductors as well as vacuum tubes, is the result of the random emission of electrons associated with charge flowing across a potential barrier. The current flowing at a point within a device varies slightly about an average value due to random variations in the arrival time of individual electrons. This random noise current modifies the signal carrying current, and manifests itself as noise when passed through an amplifier. Schottky found that the RMS current I_{sh} due to shot noise in a vacuum-tube diode is

$$I_{sh} = \sqrt{2qI_{dc}\delta f}$$

where q is the magnitude of an electronic charge, I_{dc} is the dc current through the barrier, and, δf is the system bandwidth. For other types of devices, empirical shot noise formulas have been developed.

- **contact noise**

Contact noise results when conducting materials are imperfectly joined, such that fluctuations in conductivity between the materials occur. Contact noise is sometimes referred to as "excess noise" in resistors, or "flicker noise" in vacuum tubes. The noise current, I_f, can be approximated as

$$I_f \approx \frac{K I_{dc} \sqrt{\delta f}}{\sqrt{f}}$$

where K is a material dependant constant, f is operational frequency, I_{dc} is average dc current, and δf is system bandwidth. Note that this type of noise is dependent on device operational frequency, and can become quite large for low frequency operation.

1.4 Electromagnetic compatibility

Electromagnetic compatibility (EMC) refers to the ability of an electronic system to function properly in its intended electromagnetic environment, and also not be a source of electromagnetic interference itself. An electromagnetically compatible system satisfies three criteria:

- It does not interfere with the operations of other systems.

- It is immune from the emissions of other systems.

- It does not interfere with its own operation.

The most easily overlooked aspect of EMC is that an electronic system must be designed so as not to interfere with itself. Four interference transfer methods will be examined: radiated emissions, radiated susceptibility, conducted emissions, and conducted susceptibility.

- **radiated emissions and susceptibility**

Most modern electronic devices are composed of many individual components, including a power supply, a power cord, some sort of processing system or device, and internal cabling or busses. Each of these types of components may radiate or receive electromagnetic signals as depicted in Fig. 3:

- A long power cord may act as an antenna, by either broadcasting noise or receiving signals from other sources. Ac power cords or designed to carry 60 Hz signals, however much higher frequency signals may exist on the cord.

- Unshielded components such as transformers, computer processors, or vacuum tubes may radiate or receive signals. **Note**: a recent trend has been to replace metal components with plastic to save weight and reduce cost. Often a metal enclosure or casing inadvertently provides shielding for electronic systems contained within. If this enclosure is replaced with plastic, the components inside are susceptible to external interference, or may themselves become a source of interference.

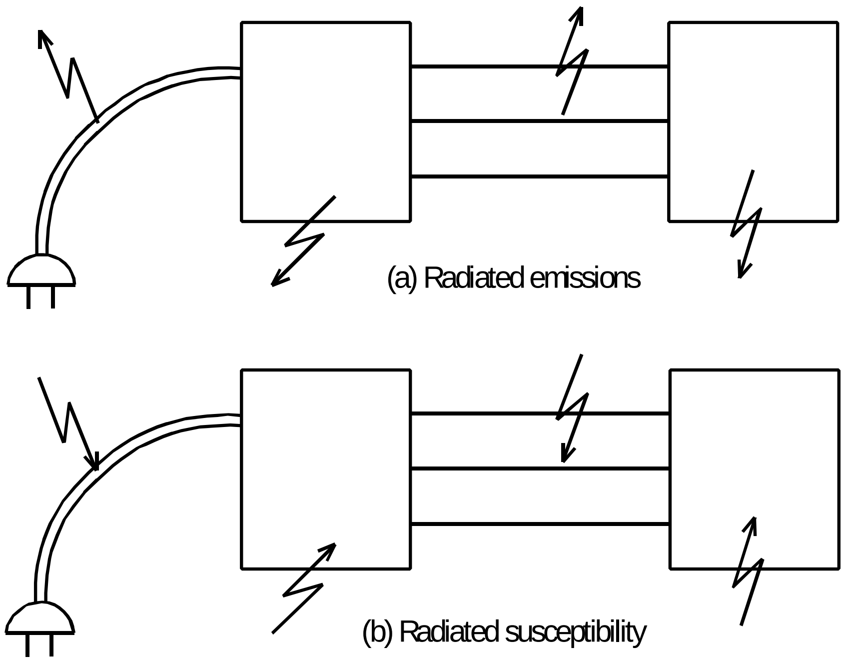

Figure 3. (a) Radiated emission model; (b) Radiated susceptibility model

- Internal cables or interconnections such as the data ribbons or busses in a computer may also act as antennas, if they are sufficiently long.

- Improperly designed metallic shielding enclosures may radiate or receive external signals.

- **conducted emissions and susceptibility**

Interference signals may be directly conducted to components over power cords, internal cables, or metallic enclosures as depicted in Fig. 4. To prevent this, barriers such as filters and chokes are designed. It should be noted that conducted coupling paths are often much more efficient than radiated coupling paths.

- External signals received by the ac power cord or internal cables may be conducted to other components or devices within a system.

- Noise or interference may be conducted over a power grid, and transferred to components via the ac power cord. Also a noisy component may cause interference with external devices if signals are conducted out through the power cord onto a power grid. Once on the grid, a noise signal may radiate, thus a conducted emission may become a radiated emission.

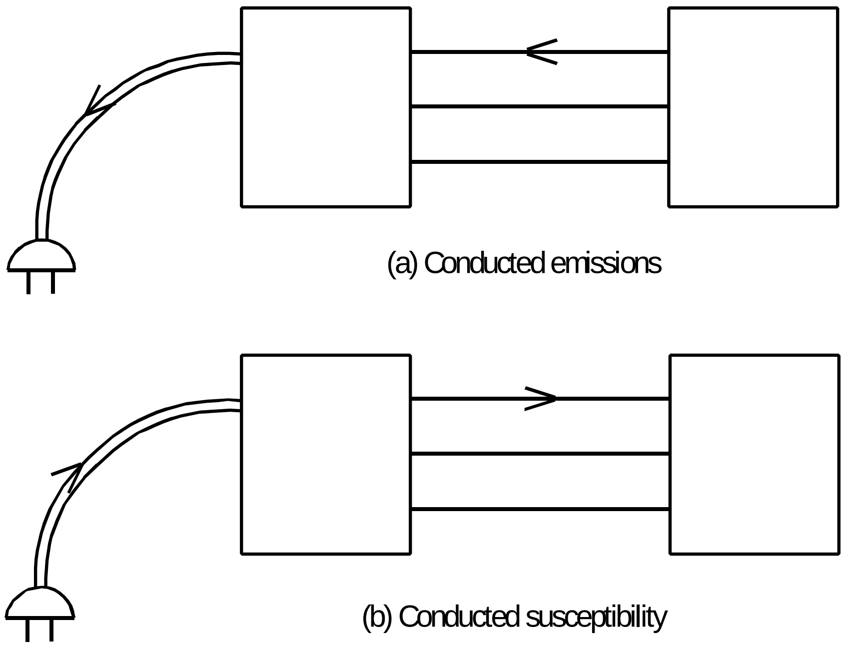

Figure 4. (a) Conducted emission model; (b) Conducted susceptibility model

- Noise signals may be conducted via improperly designed shields or metallic enclosures.

1.5 Benefits of good EMC design

Of the many benefits of good EMC design (such as product reputation), four in particular are worth note:

- **safety**

Recently, safety has become a great concern in the design of electronic devices. The number of cases involving injury caused by malfunctions due to electromagnetic interference has increased dramatically. As the number of small electronic devices such as cellular phones and laptop computers increases, the potential for possible safety hazards also increases. Also as more electronic components are incorporated in complex vehicle systems, as in automobiles and airplanes, the possibility of interference induced malfunctions increases. Several examples of EMC related problems that resulted in injury are included at the end of this chapter.

- **reduction of expense**

  It is generally far less expensive to identify and fix problems during the design phase of a product, rather than during the production phase. Often, once a problem is identified during the production phase, the product must re-enter the design phase to properly correct the problem.

- **increased reliability**

  Proper EMC techniques applied during the design phase can increase product reliability. Late development fixes often require the addition of extra components which not only increase cost, but compound system complexity. This added complexity tends to decrease the reliability of the product. The added components may also adversely affect the functionality and operation of the product. For example, the incorporation of shielding in an automobile may increase weight, thus reducing performance, and limiting fuel efficiency. In addition, product manufacturing may become more difficult and require more time, because assembly line personnel must perform additional tasks.

- **legality**

  Electronic devices must meet various legal requirements in nearly every country in the world. Devices which do not meet these requirements cannot legally be sold, or in most cases used. Also, improperly designed devices which are shown to have caused injury may lead to costly lawsuits.

1.6 Brief Description of EMC Regulations

In 1979, The Federal Communications Commission (FCC) began regulating the electromagnetic emissions of digital devices with clock speeds over 9 kHz. Several other agencies, including the US military and international agencies such as the International Special Committee on Radio Interference (CISPR) and Verband Deutsher Elektrotechniker (VDE), also regulate limits of EMI. Self imposed limits, such as those found in the automobile industry, are also other EMI regulatory limits. A more complete discussion of EMC regulations will be given in Module 8.

1.7 Examples of EMC Related Problems

This section will present several of the many examples of EMC/EMI problems and failures. Along with these examples, there are countless everyday EMC problems such as computers interfering with radio reception, automobile ignition noise interfering with radio reception, refrigerator condensers creating current spikes over computer speakers, MRI machines creating magnetic fields large enough to disturb computer monitors in nearby rooms, and overhead power lines interfering with automobile AM radio reception.

- A building that was used for government projects experienced difficulties with a grounding system. The single-point grounding system of the building and the safety ground were experiencing low frequency radiated and conducted interference problems. Diagnostics and troubleshooting did not initially identify the problem. Eventually, it was determined that a grounded conductor created an unintentional secondary winding in the building's power transformer, causing the interference.

- The launch of the Magellan spacecraft in 1991 was nearly canceled due to an improperly functioning synthetic aperture radar system. Troubleshooting indicated that the circuitry which controlled the radar was not functioning because wire loops that were inserted to connect ICs to a printed circuit board were radiating signals which were being coupled into other parts of the circuit. Once the problem was identified, the chips were shielded and the spacecraft was successfully launched, producing the first detailed surface images of Venus.

- A certain model of automobile with a plastic fuel tank had problems with sparking at the fuel filler neck. Under cold, dry conditions, as owners would attempt to refuel, large sparks would sometimes jump between the filler neck and the fuel pump nozzle, causing fires. It was determined that the gasoline in the plastic fuel tank had become charged as it passed through a fuel filter which had an ungrounded plastic casing. This was creating an electrostatic force on the electrons in the ungrounded metal filler neck (which was not in direct contact with the gasoline). These electrons would arc to the grounded pump nozzle as it was brought close to the filler neck. Placing a grounding strap between the filler neck and the automobile chassis remedied the problem.

- Fires were reported from several owners of pick-up trucks with plastic bedliners who were attempting to fill portable metal gasoline containers with fuel. Sparks would jump between the gasoline container and the pump nozzle after fueling. It was found that the plastic bedliner formed an insulating layer between the grounded truck bed and the metal gasoline container, thus creating a capacitor. As the container was fueled, electrons were transferred from the gasoline to the metal container. The gasoline containers would thus become charged to more than 10 kV after fueling. The grounded fuel pump nozzle would then sometimes be brought close to the metal container so that a breakdown would occur and a spark would be created.

- In the development cycle of a certain automobile, it was found that the pump motor for the windshield washer was creating interference and causing an ABS warning light to activate. This vehicle's brake lines were coated with a new material which had a much higher conductivity than the brake lines on older models. It was later determined that the pump motor was generating a transient that was directly coupled to the ABS module by the new conductive coating on the brake lines. This transient was interfering with the

ABS module and activating the ABS warning light. A capacitor was placed inside the pump motor housing and the housing material was changed from plastic to aluminum to fix the problem.

- Electrostatic discharges can destroy sensitive electronics. Under dry conditions the human body can carry an electrostatic charge of up to 30 kV. Discharges of as little as 80 V can destroy MOS transistors, while humans typically cannot detect static discharges of less than 3 kV.

- Many common household appliances such as vacuum cleaners and blenders can be sources of EMI. Arcing occurs when the dc motor brushes inside the equipment make and break connection with the armature commutator. This arcing creates radiated and conducted emissions rich in spectral content which can interfere with other household appliances. The most common symptom of this is the interference that appears as lines on a television set.

- On July 29, 1967 during only its fifth day of combat operations, an accident occurred aboard the aircraft carrier USS *Forrestal*. While a group of aircraft were waiting to be launched, a missile on an F-4 Phantom was fired and struck a parked A-4 Skyhawk. The missile impact ruptured an external fuel tank aboard the A-4, spilling jet fuel onto the flight deck, and igniting a fire. A 1,000 pound bomb carried aboard the A-4 was released, and exploded after exposure to the fire on the flight deck. A chain reaction caused the detonation of other ordinance on the crowded deck and nearby aircraft. Burning fuel and bombs fell through holes blown in the flight deck, igniting fires, and triggering explosions deep within the ship. The resulting calamity lasted nearly 13 hours, and claimed the lives of 134 servicemen. The *Forrestal* required extensive repairs and did not return to service until April 8, 1968. This incident marks the single greatest loss of life on a U.S. navy vessel since World War II. The exact cause of the accident has never been determined, however it is suspected that the missile was activated when the ship's surveillance radar illuminated the F-4 aircraft while it was waiting for launch.

- In 1982 a British destroyer, the HMS *Sheffield*, was deployed off the Falkland Islands during the conflict with Argentina. Emissions from the ship's anti-missile system produced interference in the communications system. In order to communicate clearly with the UK, the anti-missile system would be shut down. During one such period, an Exocet missile fired by an enemy aircraft struck the ship. The resulting explosions and fires destroyed the ship, killing twenty servicemen.

- Several UH-60 Black Hawk helicopters crashed in the 1980's killing 22 Army servicemen. It is believed that the helicopter's electronic flight control systems were susceptible to various emission sources, including CB, radar, and radio transmitters.

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