# Electromagnetic Compatibility

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# Chapter 1

# Electromagnetic Compatibility



Anechoic RF chamber used for EMC testing (radiated emissions and immunity). The furniture has to be made of wood or plastic, and not metal

**Electromagnetic compatibility** (EMC) is the branch of electrical sciences which studies the unintentional generation, propagation and reception of electromagnetic energy with reference to the unwanted effects (Electromagnetic interference, or EMI) that such energy may induce. The goal of EMC is the correct operation, in the same electromagnetic

environment, of different equipment which use electromagnetic phenomena, and the avoidance of any interference effects.

In order to achieve this, EMC pursues two different kinds of issues. **Emission** issues are related to the unwanted generation of electromagnetic energy by some *source*, and to the countermeasures which should be taken in order to reduce such generation and to avoid the escape of any remaining energies into the external environment. **Susceptibility** or **immunity** issues, in contrast, refer to the correct operation of electrical equipment, referred to as the *victim*, in the presence of unplanned electromagnetic disturbances.

Interference, or noise, mitigation and hence electromagnetic compatibility is achieved primarily by addressing both emission and susceptibility issues, i.e., quieting the sources of interference and hardening the potential victims. The coupling path between source and victim may also be separately addressed to increase its attenuation.

## *Types of interference*

Electromagnetic interference divides into several categories according to the source and signal characteristics.

The origin of noise can be man made or natural.

### Continuous interference

Continuous, or Continuous Wave (CW), interference arises where the source regularly emits a given range of frequencies. This type is naturally divided into sub-categories according to frequency range, and as a whole is sometimes referred to as "DC to daylight".

- Audio Frequency, from very low frequencies up to around 20 kHz. Frequencies up to 100 kHz may sometimes be classified as Audio. Sources include:
    o Mains hum from power supply units, nearby power supply wiring, transmission lines and substations.
    o Audio processing equipment, such as audio power amplifiers and loudspeakers.
    o Demodulation of a high-frequency carrier wave such as an FM radio transmission.
- Radio Frequency Interference, RFI, from 20 kHz to a limit which constantly increases as technology pushes it higher. Sources include:
    o Wireless and Radio Frequency Transmissions
    o Television and Radio Receivers
    o Industrial, scientific and medical equipment
    o Digital processing circuitry (For example microcontrollers)
- Broadband noise may be spread across parts of either or both frequency ranges, with no particular frequency accentuated. Sources include:
    o Solar Activity

        o   Continuously operating spark gaps such as arc welders
        o   CDMA mobile telephony

## Pulse or transient interference

Electromagnetic Pulse, EMP, also sometimes called Transient disturbance, arises where the source emits a short-duration pulse of energy. The energy is usually broadband by nature, although it often excites a relatively narrow-band *damped sine wave* response in the victim.

Sources divide broadly into isolated and repetitive events.

- Sources of isolated EMP events include:
    - Switching action of electrical circuitry, including inductive loads such as relays, solenoids, or electric motors.
    - Electrostatic Discharge (ESD), as a result of two charged objects coming into close proximity or even contact.
    - Lightning Electromagnetic Pulse (LEMP), although typically a short series of pulses.
    - Nuclear Electromagnetic Pulse (NEMP), as a result of a nuclear explosion.
    - Non-Nuclear Electromagnetic Pulse (NNEMP) weapons.
    - Power Line Surges/Pulses

- Sources of repetitive EMP events, sometimes as regular *pulse trains*, include:
    - Electric Motors
    - Gasoline engine ignition systems
    - Continual switching actions of digital electronic circuitry.

## *Coupling Mechanisms*

Some of the technical words employed can be used with differing meanings.

The basic arrangement of noise source, coupling path and victim, receptor or sink is shown in the figure below. Source and victim are usually electronic hardware devices, though the source may be a natural phenomenon such as a lightning strike, electrostatic discharge (ESD) or, in one famous case, the Big Bang at the origin of the Universe.
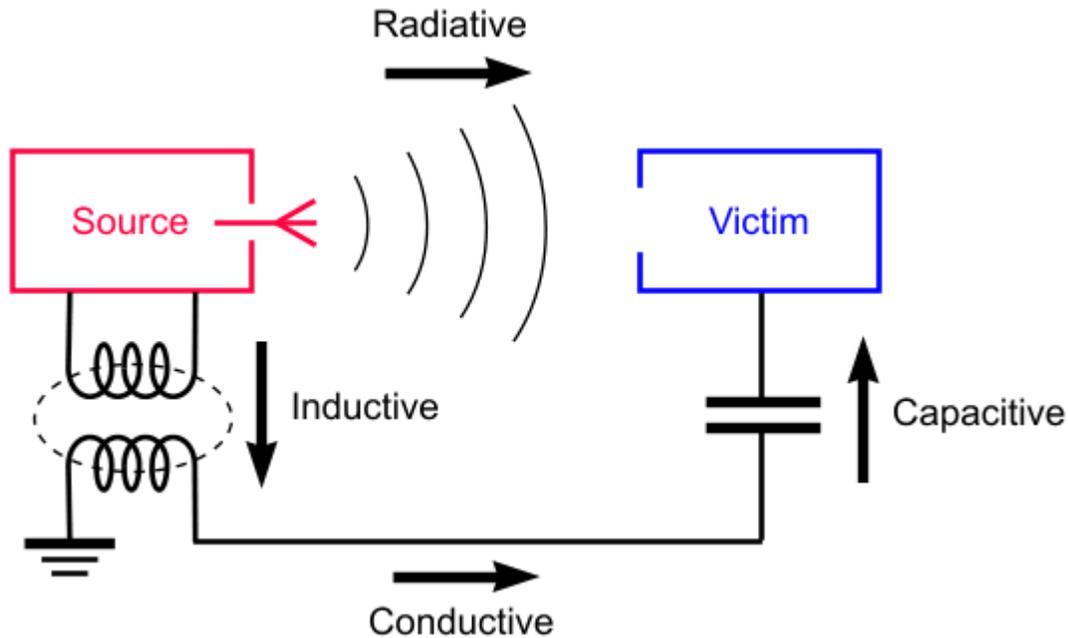
The four electromagnetic interference (EMI) coupling modes.

There are four basic coupling mechanisms: conductive, capacitive, magnetic or inductive, and radiative. Any coupling path can be broken down into one or more of these coupling mechanisms working together. For example the lower path in the diagram involves inductive, conductive and capacitive modes.

## Conductive coupling

**Conductive coupling** occurs when the coupling path between the source and the receptor is formed by direct contact with a conducting body, for example a transmission line, wire, cable, PCB trace or metal enclosure.

## Conduction modes

Conducted noise is also characterised by the way it appears on different conductors:

- **Common-mode** or **common-impedance**) coupling: noise appears in phase (in the same direction) on two conductors .
- **Differential-mode** coupling: noise appears out of phase (in opposite directions) on two conductors.

## Inductive coupling

**Inductive coupling** occurs where the source and receiver are separated by a short distance (typically less than a wavelength). Strictly, "Inductive coupling" can be of two

kinds, electrical induction and magnetic induction. It is common to refer to electrical induction as *capacitive coupling*, and to magnetic induction as *inductive coupling*.

## Capacitive coupling

**Capacitive coupling** occurs when a varying electrical field exists between two adjacent conductors typically less than a wavelength apart, inducing a change in voltage across the gap.

## Magnetic coupling

**Inductive coupling** or **magnetic coupling (MC)** occurs when a varying magnetic field exists between two parallel conductors typically less than a wavelength apart, inducing a change in voltage along the receiving conductor.

## Radiative coupling

**Radiative coupling** or **electromagnetic coupling** occurs when source and victim are separated by a large distance, typically more than a wavelength. Source and victim act as radio antennas: the source emits or radiates an electromagnetic wave which propagates across the open space in between and is picked up or received by the victim.

## *EMC control*

The damaging effects of electromagnetic interference pose unacceptable risks in many areas of technology, and it is necessary to control such interference and reduce the risks to acceptable levels.

The control of electromagnetic interference (EMI) and assurance of EMC comprises a series of related disciplines:

- Characterising the threat.
- Setting standards for emission and susceptibility levels.
- Design for standards compliance.
- Testing for standards compliance.

For a complex piece of equipment, this may require the production of a dedicated *EMC control plan* summarizing the application of the above and specifying additional documents required.

## Characterising the threat

Characterisation of the problem requires understanding of:

- The interference source and signal.
- The coupling path to the victim.

- The nature of the victim both electrically and in terms of the significance of malfunction.

The risk posed by the threat is usually statistical in nature, so much of the work in threat characterisation and standards setting is based on reducing the probability of disruptive EMI to an acceptable level, rather than its assured elimination.

## Laws and regulators

## Regulatory and standards bodies

Several international organizations work to promote international co-operation on standardization (harmonization), including publishing various EMC standards. Where possible, a standard developed by one organization may be adopted with little or no change by others. This helps for example to harmonize national standards across Europe. Standards organizations include:

- International Electrotechnical Commission (**IEC**), which has several committees working full time on EMC issues. These are:
  - Technical Committee 77 (**TC77**), working on electromagnetic compatibility between equipment including networks.
  - Comité International Spécial des Perturbations Radioélectriques (**CISPR**), or International Special Committee on Radio Interference.
  - The Advisory Committee on Electromagnetic Compatibility (**ACEC**) co-ordinates the IEC's work on EMC between these committees.
- International Organization for Standardization (**ISO**), which publishes standards for the automotive industry.

Among the more well known national organizations are:

- Europe:
  - Comité Européen de Normalisation (**CEN**) or European Committee for Standardization).
  - Comité Européen de Normalisation Electrotechniques (**CENELEC**) or European Committee for Electrotechnical Standardisation.
  - European Telecommunications Standards Institute (**ETSI**).
- United States:
  - The Federal Communications Commission (**FCC**).
  - The Society of Automotive Engineers (**SAE**).
- Britain: The British Standards Institution (**BSI**).
- Germany: The Verband der Elektrotechnik, Elektronik und Informationstechnik (**VDE**) or Association for Electrical, Electronic and Information Technologies.

### Laws

Compliance with national or international standards is usually required by laws passed by individual nations. Different nations can require compliance with different standards.

By European law, manufacturers of electronic devices are advised to run EMC tests in order to comply with compulsory CE-labeling. Undisturbed usage of electric devices for all customers should be ensured and the electromagnetic field strength should be kept on a minimum level. EU directive 2004/108/CE (previously 89/336/EEC) on EMC announces the rules for the distribution of electric devices within the European Union. A good overview of EME limits and EMI demands is given in List of EMC directives.

## EMC design

Electromagnetic noise is produced in the source due to rapid current and voltage changes, and spread via the coupling mechanisms described earlier.

Since breaking a coupling path is equally effective at either the start or the end of the path, many aspects of good EMC design practice apply equally to potential emitters and to potential victims. Further, a circuit which easily couples energy to the outside world will equally easily couple energy in and will be susceptible. A single design improvement often reduces both emissions and susceptibility.

### Grounding and shielding

Grounding and shielding aim to divert EMI away from the victim by providing an alternative, low-impedance path. Techniques include:

- **Shielded Housings**.
- **Shielded Lines**.
- Grounding or earthing schemes such as **Star Earthing** for audio equipment, or **Ground planes** for RF.

### Other general measures

- **Decoupled Cable Entries** (Line filter, Signal filter) using RF chokes, or RC elements.
- **Transmission line** techniques for cables and wiring, such as balanced differential signal and return paths, and impedance matching.
- **Avoidance of Antenna Structures**, such as loops of circulating current, resonant mechanical structures, unbalanced cable impedances or poorly grounded shielding.

**Emissions suppression**



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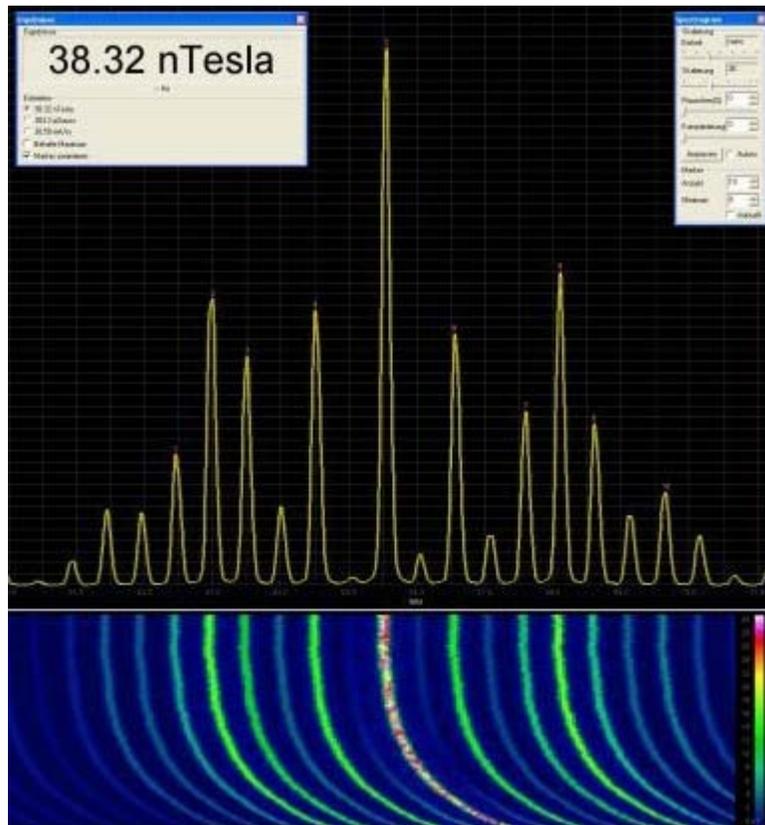
Spread spectrum method reduces EMC peaks. Frequency spectrum of the heating up period of a switching power supply which uses the spread spectrum method incl. waterfall diagram over a few minutes

Additional measures to reduce emissions include:

- Avoid unnecessary switching operations. Necessary switching should be done as slowly as technically possible.
- Noisy circuits (with a lot of switching activity) should be physically separated from the rest of the design.
- High peaks can be avoided by using the spread spectrum method.
- **Harmonic Wave Filters**.
- Design for operation at lower signal levels, reducing the energy available for emission.

**Susceptibility hardening**

Additional measures to reduce susceptibility include:

- Fuses, trip switches and circuit breakers.
- Transient absorbers.

- Design for operation at higher signal levels, reducing the relative noise level in comparison.

## EMC testing

Testing is required to confirm that a particular device meets the required standards. It divides broadly into emissions testing and susceptibility testing.

RF testing of a physical prototype is most often carried out in a radio-frequency anechoic chamber.

Open-air test sites, or OATS, are the reference sites in most standards. They are especially useful for emissions testing of large equipment systems.

Sometimes computational electromagnetics simulations are used to test virtual models.

Like all compliance testing, it is important that the test equipment, including the test chamber or site and any software used, be properly calibrated and maintained.

Typically, a given run of tests for a particular piece of equipment will require an *EMC test plan* and follow-up *Test report*. The full test program may require the production of several such documents.

## Susceptibility testing

Radiated field susceptibility testing typically involves a high-powered source of RF or EM pulse energy and a radiating antenna to direct the energy at the potential victim or device under test (DUT).

Conducted voltage and current susceptibility testing typically involves a high-powered signal or pulse generator, and a current clamp or other type of transformer to inject the test signal.

Transient immunity is used to test the immunity of the DUT against powerline disturbances including surges, lightning strikes and switching noise. In motor vehicles, similar tests are performed on battery and signal lines.

Electrostatic discharge testing is typically performed with a piezo spark generator called an "ESD pistol". Higher energy pulses, such as lightning or nuclear EMP simulations, can require a large current clamp or a large antenna which completely surrounds the DUT. Some antennas are so large that they are located outdoors, and care must be taken not to cause an EMP hazard to the surrounding environment.

## Emissions testing

Emissions are typically measured for radiated field strength and where appropriate for conducted emissions along cables and wiring. Inductive (magnetic) and capacitive (electric) field strengths are near-field effects, and are only important if the device under test (DUT) is designed for location close to other electrical equipment.

Typically a spectrum analyzer is used to measure the emission levels of the DUT across a wide band of frequencies (frequency domain). Specialized spectrum analyzers for EMC testing are available, called EMI Test Receivers or EMI Analyzers. These incorporate bandwidths and detectors as specified by international EMC standards. EMI Receivers along with specified transducers can often be used for both conducted and radiated emissions. Pre-selector filters may also be used to reduce the effect of strong out-of-band signals on the front-end of the receiver.

For conducted emissions, typical transducers are the LISN (Line Impedance Stabilisation Network) also sometimes called as the AMN (Artificial Mains Network) and the RF current clamp.

For radiated emission measurement, antennas are used as transducers. Typical antennas specified include dipole, biconical, log-periodic, double ridged guide and conical log-spiral designs. Radiated emissions must be measured in all directions around the DUT.

Some pulse emissions are more usefully characterized using an oscilloscope to capture the pulse waveform in the time domain.

## *History*

The earliest EMC issue was lightning strike (Lightning Electromagnetic Pulse, or LEMP) on buildings. Lightning rods or lightning conductors began to appear in the mid-18th century. With the advent of widespread electricity generation and power supply lines from the late 19th century on, problems also arose with equipment short-circuit failure affecting the power supply, and with local fire and shock hazard when the power line was struck. Power stations were provided with output circuit breakers. Buildings and appliances would soon be provided with input fuses, and later in the 20th century miniature circuit breakers (MCB) would come into use.

As radio communications developed in the first half of the 20th century, interference between broadcast radio signals began to occur and an international regulatory framework was set up to ensure interference-free communications.

As switching devices became commonplace, typically in petrol powered cars and motorcycles but also in domestic appliances such as thermostats and refrigerators, transient interference with domestic radio and (after World War II) TV reception became problematic, and in due course laws were passed requiring the suppression of such interference sources.

After World War II the military became increasingly concerned with the effects of nuclear electromagnetic pulse (NEMP), lightning strike, and even high-powered radar beams, on mobile vehicles of all kinds, and especially aircraft electrical systems.

ESD problems first arose with accidental electric spark discharges in hazardous environments such as coal mines and when refuelling aircraft or motor cars. Safe working practices had to be developed.

When high RF emission levels from other sources became a potential problem (such as with the advent of microwave ovens), certain frequency bands were designated for Industrial, Scientific and Medical (ISM) use, allowing unlimited emissions. A variety of issues such as sideband and harmonic emissions, broadband sources, and the increasing popularity of electrical switching devices and their victims, resulted in a steady development of standards and laws.

From the 1970s, the popularity of modern digital circuitry rapidly grew. As the technology developed, with faster switching speeds (increasing emissions) and lower circuit voltages (increasing susceptibility), EMC increasingly became a source of concern. Many more nations became aware of EMC as a growing problem and issued directives to the manufacturers of digital electronic equipment, which set out the essential manufacturer requirements before their equipment could be marketed or sold. Organizations in individual nations, across Europe and worldwide, were set up to maintain these directives and associated standards. This regulatory environment led to a growing EMC industry supplying specialist devices and equipment, analysis and design software, and testing and certification services.

Low-voltage digital circuits, especially CMOS transistors, became more susceptible to ESD damage as they were miniaturised, and a new ESD regulatory regime had to be developed.

From the 1980s, the ever-increasing use of mobile communications and broadcast media channels has put huge pressure on the available airspace. Regulatory authorities are squeezing band allocations closer and closer together, relying on increasingly sophisticated EMC design methods, especially in the digital communications arena, to keep cross-channel interference to acceptable levels. Digital systems are inherently less susceptible than the old analogue systems, and also offer far easier ways (such as software) to implement highly sophisticated protection measures.

Most recently, even the ISM bands are being used for low-power mobile digital communications. This approach relies on the intermittent nature of ISM interference and use of sophisticated error-correction methods to ensure lossless reception during the quiet gaps between bursts of interference.

## *EMC test equipment manufacturers (alphabetic)*

- Aaronia
- Aeroflex
- Agilent (formerly the test and measurement division of Hewlett-Packard)
- Anritsu
- AR
- CRFS Limited
- Dare/RadiMation
- EMC Partner AG
- EM TEST
- Haefely emc
- Instruments for Industry
- Kikusui America
- MILMEGA
- mk-messtechnik.de (opto transmitters)
- narda (formerly PMM)
- National Instruments
- Rainford EMC Systems (test chambers)
- Rohde & Schwarz
- Tektronix
- Teseq (formerly Schaffner).

# Chapter 2

# Electromagnetic Interference



Electromagnetic interference in analog TV signal

**Electromagnetic interference** (or **EMI**, also called **radio frequency interference** or **RFI**) is a disturbance that affects an electrical circuit due to either electromagnetic induction or electromagnetic radiation emitted from an external source. The disturbance

may interrupt, obstruct, or otherwise degrade or limit the effective performance of the circuit. The source may be any object, artificial or natural, that carries rapidly changing electrical currents, such as an electrical circuit, the Sun or the Northern Lights.

EMI can be intentionally used for radio jamming, as in some forms of electronic warfare, or can occur unintentionally, as a result of spurious emissions for example through intermodulation products, and the like. It frequently affects the reception of AM radio in urban areas. It can also affect cell phone, FM radio and television reception, although to a lesser extent.

## Types

Radiated EMI or RFI may be broadly categorized into two types; narrowband and broadband.

Narrowband interference usually arises from intentional transmissions such as radio and TV stations, pager transmitters, cell phones, etc. Broadband interference usually comes from incidental radio frequency emitters. These include electric power transmission lines, electric motors, thermostats, bug zappers, etc. Anywhere electrical power is being turned off and on rapidly is a potential source. The spectra of these sources generally resemble that of synchrotron sources, stronger at low frequencies and diminishing at higher frequencies, though this noise is often modulated, or varied, by the creating device in some way. Included in this category are computers and other digital equipment as well as televisions. The rich harmonic content of these devices means that they can interfere over a very broad spectrum. Characteristic of broadband RFI is an inability to filter it effectively once it has entered the receiver chain.

Conducted electromagnetic interference is caused by the physical contact of the conductors as opposed to radiated EMI which is caused by induction (without physical contact of the conductors). Electromagnetic disturbances in the EM field of a conductor will no longer be confined to the surface of the conductor and will radiate away from it. This persists in all conductors and mutual inductance between two radiated electromagnetic fields will result in EMI.

## Susceptibilities of different radio technologies

Interference tends to be more troublesome with older radio technologies such as analogue amplitude modulation, which have no way of distinguishing unwanted in-band signals from the intended signal, and the omnidirectional dipole antennas used with broadcast systems. Newer radio systems incorporate several improvements that enhance the selectivity. In digital radio systems, such as Wi-Fi, error-correction techniques can be used. Spread-spectrum and frequency-hopping techniques can be used with both analogue and digital signalling to improve resistance to interference. A highly directional receiver, such as a parabolic antenna or a diversity receiver, can be used to select one signal in space to the exclusion of others.

The most extreme example of digital spread-spectrum signalling to date is ultra-wideband (UWB), which proposes the use of large sections of the radio spectrum at low amplitudes to transmit high-bandwidth digital data. UWB, if used exclusively, would enable very efficient use of the spectrum, but users of non-UWB technology are not yet prepared to share the spectrum with the new system because of the interference it would cause to their receivers. The regulatory implications of UWB are discussed in the ultra-wideband article.

## *Interference to consumer devices*

Complex electronic circuitry is found in all sorts of devices used in the home. This results in a vast interference potential that didn't exist in earlier, simpler decades. In the United States, Public Law 97-259, enacted in 1982, gave the Federal Communications Commission (FCC) the authority to regulate the susceptibility of consumer electronic equipment sold in the country. The FCC, working with equipment manufacturers, decided to allow them to develop standards for EMI immunity and implement their own voluntary compliance programs.

Broadcast transmitters, two-way radio transmitters, paging transmitters, and cable TV are potential sources of RFI and EMI. Other possible sources of interference include a wide variety of devices, such as doorbell transformers, toaster ovens, electric blankets, ultrasonic pest control devices, electric bug zappers, heating pads, and touch controlled lamps. Multiple CRT computer monitors or televisions sitting too close to one another can sometimes cause a "shimmy" effect in each other, due to the electromagnetic nature of their picture tubes, especially when one of their de-gaussing coils is activated.

Electromagnetic interference at 2.4 GHz can be caused by 802.11b and 802.11g wireless devices, Bluetooth devices, baby monitors and cordless telephones, video senders, and microwave ovens.

Switching inductive loads, such as electric motors, often cause interference, but it is easily suppressed by connecting a snubber network, a resistor in series with a capacitor, across the switch. Exact values can be optimised for each case, but 100 ohms in series with 100 nanofarads is usually satisfactory.

Switched-mode power supplies can be a source of EMI, but have become less of a problem as design techniques have improved, such as integrated power factor correction.

Most countries have legal requirements that mandate electromagnetic compatibility: electronic and electrical hardware must still work correctly when subjected to certain amounts of EMI, and should not emit EMI which could interfere with other equipment (such as radios).

## History

Since the earliest days of radio communications, the negative effects of interference from both intentional and unintentional transmissions have been felt and the need to manage the radio frequency spectrum became apparent.

In 1933, a meeting of the International Electrotechnical Commission (IEC) in Paris recommended the International Special Committee on Radio Interference (CISPR) be set up to deal with the emerging problem of EMI. CISPR subsequently produced technical publications covering measurement and test techniques and recommended emission and immunity limits. These have evolved over the decades and form the basis of much of the world's EMC regulations today.

In 1979, legal limits were imposed on electromagnetic emissions from all digital equipment by the FCC in the USA in response to the increased number of digital systems that were interfering with wired and radio communications. Test methods and limits were based on CISPR publications, although similar limits were already enforced in parts of Europe.

In the mid 1980s, the European Union member states adopted a number of "new approach" directives with the intention of standardizing technical requirements for products so that they do not become a barrier to trade within the EC. One of these was the EMC Directive (89/336/EC) and it applies to all equipment placed on the market or taken into service. Its scope covers all apparatus "liable to cause electromagnetic disturbance or the performance of which is liable to be affected by such disturbance".

This was the first time there was a legal requirement on immunity as well as emissions on apparatus intended for the general population. And although there may be additional costs involved for some products to give them a known level of immunity, it increases their perceived quality as they are able to co-exist with apparatus in the active EM environment of modern times and with fewer problems.

Many countries now have similar requirements for products to meet some level of EMC regulation.

## Standards

The International Special Committee for Radio Interference sets standards for radiated and conducted electromagnetic interference.

## EMI in integrated circuits

Integrated circuits are often a source of EMI, but they must usually couple their energy to larger objects such as heatsinks, circuit board planes and cables to radiate significantly.

On integrated circuits, important means of reducing EMI are: the use of bypass or decoupling capacitors on each active device (connected across the power supply, as close to the device as possible), rise time control of high-speed signals using series resistors, and $V_{CC}$ filtering. Shielding is usually a last resort after other techniques have failed, because of the added expense of shielding components such as conductive gaskets.

The efficiency of the radiation depends on the height above the ground plane or power plane (at RF one is as good as the other) and the length of the conductor in relation to the wavelength of the signal component (fundamental frequency, harmonic or transient (overshoot, undershoot or ringing)). At lower frequencies, such as 133 MHz, radiation is almost exclusively via I/O cables; RF noise gets onto the power planes and is coupled to the line drivers via the $V_{CC}$ and ground pins. The RF is then coupled to the cable through the line driver as common-mode noise. Since the noise is common-mode, shielding has very little effect, even with differential pairs. The RF energy is capacitively coupled from the signal pair to the shield and the shield itself does the radiating. One cure for this is to use a braid-breaker or choke to reduce the common-mode signal.

At higher frequencies, usually above 500 MHz, traces get electrically longer and higher above the plane. Two techniques are used at these frequencies: wave shaping with series resistors and embedding the traces between the two planes. If all these measures still leave too much EMI, shielding such as RF gaskets and copper tape can be used. Most digital equipment is designed with metal, or conductive-coated plastic, cases.

## RF immunity and testing

Integrated circuits tend to demodulate high-frequency carrier signals commonly found in regular environment due presence of cell phones. These ICs demodulate the high frequency cell phone carrier (e.g., GSM850 and GSM1900, GSM900 and GSM1800) and produce low-frequency (e.g., 217 Hz) demodulated signals. This demodulation manifests itself into unwanted audible buzz in audio appliances such as microphone amplifier, speaker amplifier, car radio, telephones etc. Adding on-board EMI filters or special layout techniques help in bypassing EMI or improving RF immunity. Some ICs are designed (e.g., LMV831-LMV834, MAX9724) to have integrated RF filters and/or special design which prevent demodulation of high frequency carrier. These ICs are also subjected to tests for measuring their capability to reject RF.

Designers often need to carry out special tests for testing the RF immunity of the parts to be used in the system. These tests are usually carried inside a special anechoic chamber with a controlled RF environment where the test vectors produce RF field similar to that produced in an actual environment.

### *Electromagnetic interference manufacturers*

- MILMEGA
- ON Semiconductor

# Chapter 3

# EMC Problem (Excessive Field Strength)

In electromagnetic compatibility, **EMC problems** can occur when the system which is being adversely affected is subject to a high field strength due to a radio transmitter. These effects are not due to defects in the transmitter (other than poor RF shielding), transmitter defects such as harmonics are considered in Radio transmitter design. Here we intended to give an overview of the nature of these effects and the methods used to mitigate or eliminate them.

## *Singing sparks and allied effects*

The singing spark can be thought of as the ultimate form of the rusty bolt effect. This is a situation where the output of a transmitter is clean, the receiver is able to reject the transmitter's frequency but some object energised by the RF field is then able to generate harmonics or act as a non-linear mixer which generates intermodulation products.

To solve this the best thing to do is to locate the *rusty bolt* and either remove it or render it harmless. Possible examples of rusty bolts include the pole holding an aerial, cast iron drainpipes, loose manhole covers and guy wires on radio masts.

## *TV and radio equipment*

### Common problems

### Motorboating

Motorboating can be seen in radio equipment, it can be regarded as a self inflicted EMC problem. While this idea of self imposed EMC effects could include all manner of unwanted feed back and crosstalk effects within an item of equipment, for reasons of brevity no discussion of internal feed back (which does not involve a signal leaving an item of equipment) will be included here.

The best method of curing this defect is to improve the RF shielding and the RF filtering of all power, audio and control leads entering the affected unit.

### Harmonics generated *in situ*

In situ harmonics occur when an RF current flows through a device, and harmonics are generated due to the non-linear nature of the device. This can be regarded as a rusty bolt effect which exists within the malfunctioning device. A good example of this is the pair of diodes which protect the receivers in many VHF rigs lacking an electromechanical relay to switch between transmit and receive (*such as the 144 MHz DJ-F1E*) from the transmitter's RF output. In the case of the DJ-F1E, these dioides can create intermodulation products when the radio set is overloaded.

### Reproduction of the signal in an IF stage

It is possible for the unwanted signal to enter an Intermediate frequency stage, and if it falls within the passband of the stage, it can cause an unwanted effect. In an AM system, it is possible that the unwanted signal will be amplified by the linear stage and appear finally to the detector as if it were a sideband of the carrier, it is possible sometimes for harmonics of an HF transmitter generated within a TV set to enter the video IF (which is at about 30 MHz). These harmonics which enter the TV IF could give similar herring bone pattern effects to those seen when harmonics of the HF transmitter are generated in the front end.

In FM systems where the IF stage gain is very high and the stage is designed to be linear, it is likely that if the unwanted signal is at least 10dB weaker than the wanted signal that the capture effect will result in the receiver ignoring the unwanted signal. If however the unwanted signal is stronger than the wanted signal then it is likely that the receiver will be unable to demodulate the wanted signal. This is related to the normal method of jamming FM systems, to jam an FM signal it is normal to transmit a signal which is 10 dB stronger (at the front end of the target receiver) and is within the plateau of most narrow IF stage.

### Cures

### Braid-breakers

If an electronic device with a long coaxial aerial lead is disturbed by a signal from a HF transmitter then the braid of the coaxial should be considered as a path of entry of RF into the affected device. One additional feature which can assist a braid breaker is the use of an RF ground, a quarter wave length of wire will act as an RF ground even when it goes nowhere. This is because the quarterwave transforms the infinite impedance into a zero impedance. The quarterwave length of wire can be regarded as an artificial earth for RF purposes.

By adding a braid-breaker filter to the system common mode signals will be attenuated while unbalanced signals will be allowed to pass unhindered. This is also something which is added to long leads in military electronic equipment which is intended to continue to function even after being subjected to a nuclear electromagnetic pulse (EMP)

and also would increase the likelihood of an electronic device surviving a near-by lightning strike (direct lightning hits are very hard to protect against).

For UHF TV a wide range of good designs exist, these include a ferrite RF choke on the downlead and some networks of passive components.
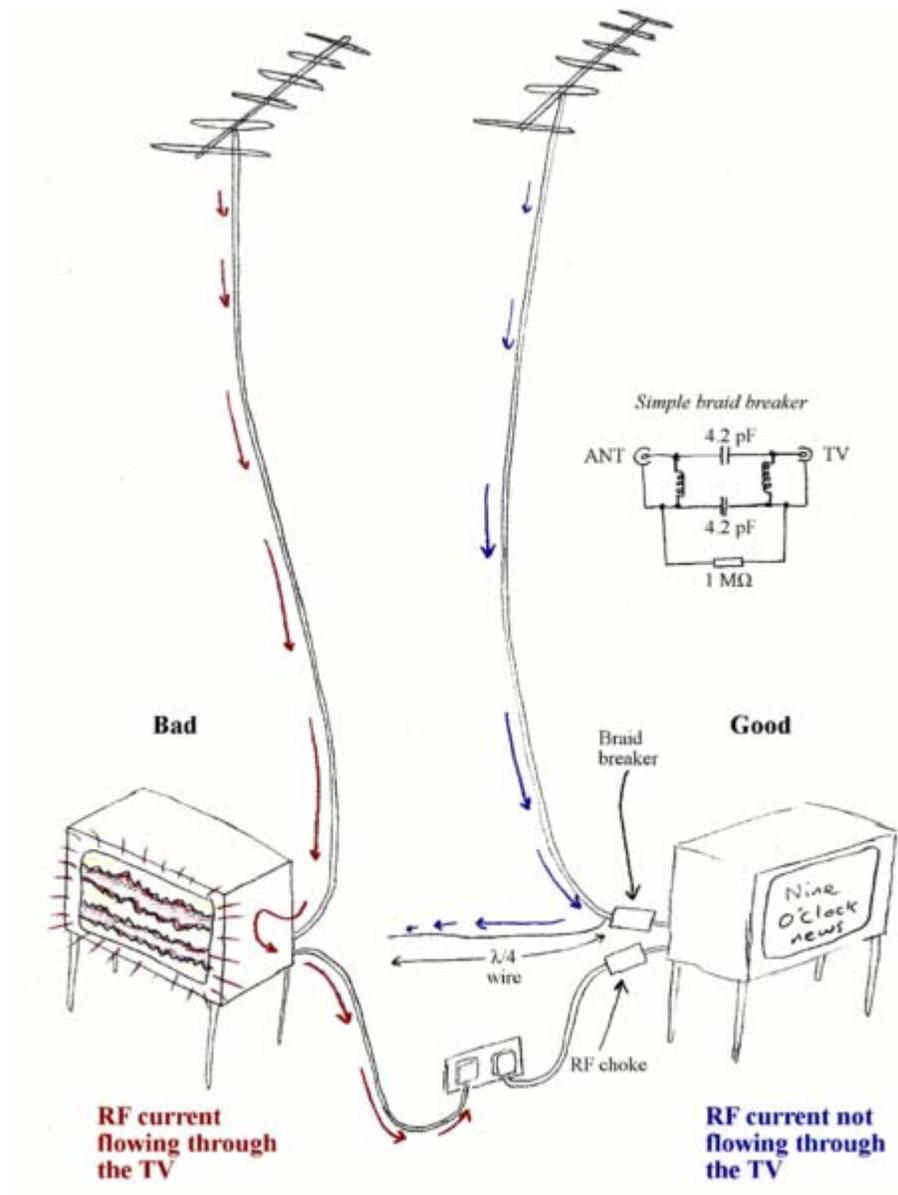


## RF chokes on leads

RF chokes are a well used method for filtering many leads on communication equipment. In common with the braid breaker the intention is to suppress common mode signals. One popular method of making an RF choke is to use a large ferrite bead where the cable passes through the hole. Such chokes can often be seen on the power connection leads of laptops and on the video signal leads of computer monitors.

The addition of RF chokes can often reduce greatly the RF current flowing through a TV set and hence improve the immunity of the installation.

## Filters in the aerial lead

If the receiver's input is routed via a device which rejects the unwanted signals then this additional filtering can improve the immunity of the installation. It is the case that the additional filter will improve the situation. When a transmitter needs to be colocated with a receiver where the frequency difference is very small (*for example 145.000 and 145.600 MHz*) the cavity filters can be used on both the transmitter and the receiver to improve the purity of the transmitter and the immunity of the receiver.

One design for VHF/UHF TV which also has the ability to filter out 144 MHz, 432 MHz and 1296 MHz signals has been created by a Russian (UA9FAD).. A design for UHF TV which is designed for the six meter band (50 MHz) has been published by the UK six meter group.  One design for FM radios (band II) has been created by a German (DF9CY)

## *Audio equipment*

### Different transmitter modes

It is possible for the non-linear circuits within audio equipment to act as an inadvertent radio receiver. In the case of FM transmitters a click may be heard as the RF field appears and also when it disappears.

In the case of amplitude modulation it is possible for the original audio to be recovered by the affected device. AM is still used for longwave and mediumwave broadcasting, and sometimes in communications equipment used by services such as the fire brigade, military or police.

A weird animal quacking or an unintelligible human voice is a likely sign that the transmitter is using single-sideband modulation. SSB (single-sideband) tends to be used in applications where long range communication is needed. Here, the non-linear device is mixing frequencies, but because the carrier has been suppressed, it is not possible to restore the original audio with such a simple demodulator.

### Stereo leads as a dipole

It is the case that a *stereo system* with external speaker attached by long leads to the main unit (holding the audio electronics) can be troubled by EMC problems which are caused by the speaker leads acting as a dipole aerial.

One method of curing this is to add a ferrite choke to the speaker leads close to where they enter the main unit.

## Rectification in the audio equipment

According to the RSGB handbook one common way in which stereo systems are affected is when the RF current picked up by the speaker cable, and then flows through the feedback circuit into an early stage in the audio amplifier. The RF is then rectified when it flows through the base/emitter junction of a bipolar transistor.

# Chapter 4

# Electromagnetic Pulse

An **electromagnetic pulse** (sometimes abbreviated **EMP**) is a burst of electromagnetic radiation that results from an explosion (usually from the detonation of a nuclear weapon) and/or a suddenly fluctuating magnetic field. The resulting rapidly changing electric fields or magnetic fields may couple with electrical/electronic systems to produce damaging current and voltage surges.

In military terminology, a nuclear bomb detonated hundreds of kilometers above the Earth's surface is known as a high-altitude electromagnetic pulse (**HEMP**) device. Effects of a HEMP device depend on a very large number of factors, including the altitude of the detonation, energy yield, gamma ray output, interactions with the Earth's magnetic field, and electromagnetic shielding of targets.

## *History*

The fact that an electromagnetic pulse is produced by a nuclear explosion was known since the earliest days of nuclear weapons testing. The magnitude of the EMP and the significance of its effects, however, were not realized for some time.

During the first United States nuclear test on 16 July 1945, electronic equipment was shielded due to Enrico Fermi's expectation of an electromagnetic pulse from the detonation. The official technical history for that first nuclear test states, "All signal lines were completely shielded, in many cases doubly shielded. In spite of this many records were lost because of spurious pickup at the time of the explosion that paralyzed the recording equipment." During British nuclear testing in 1952–1953 there were instrumentation failures that were attributed to "radioflash," which was then the British term for EMP.

The high altitude nuclear tests of 1962, as described below, increased awareness of EMP beyond the original small population of nuclear weapons scientists and engineers. The larger scientific community became aware of the significance of the EMP problem after a series of three articles were published about nuclear electromagnetic pulse in 1981 by William J. Broad in the weekly publication *Science*.

**Starfish Prime**

In July 1962, a 1.44 megaton (6.0 PJ) United States nuclear test in space, 400 kilometres (250 mi) above the mid-Pacific Ocean, called the Starfish Prime test, demonstrated to nuclear scientists that the magnitude and effects of a high altitude nuclear explosion were much larger than had been previously calculated. Starfish Prime also made those effects known to the public by causing electrical damage in Hawaii, about 1,445 kilometres (898 mi) away from the detonation point, knocking out about 300 streetlights, setting off numerous burglar alarms and damaging a telephone company microwave link.

Starfish Prime was the first successful test in the series of United States high-altitude nuclear tests in 1962 known as Operation Fishbowl. The subsequent Operation Fishbowl tests gathered more data on the high-altitude EMP phenomenon.

The *Bluegill Triple Prime* and *Kingfish* high-altitude nuclear tests of October and November 1962 in Operation Fishbowl finally provided electromagnetic pulse data that was clear enough to enable physicists to accurately identify the physical mechanisms that were producing the electromagnetic pulses.

The EMP damage of the Starfish Prime test was quickly repaired because of the ruggedness (compared to today) of the electrical and electronic infrastructure of Hawaii in 1962. Realization of the potential impacts of EMP became more apparent to some scientists and engineers during the 1970s as more sensitive solid-state electronics began to come into widespread use.

The relatively small magnitude of the Starfish Prime EMP in Hawaii (about 5600 volts/metre) and the relatively small amount of damage done (for example, only 1 to 3 percent of streetlights extinguished) led some scientists to believe, in the early days of EMP research, that the problem might not be as significant as was later realized. Newer calculations showed that if the Starfish Prime warhead had been detonated over the northern continental United States, the magnitude of the EMP would have been much larger (22 to 30 kilovolts/metre) because of the greater strength of the Earth's magnetic field over the United States, as well as the different orientation of the Earth's magnetic field at high latitudes. These new calculations, combined with the accelerating reliance on EMP-sensitive microelectronics, heightened awareness that the EMP threat could be a very significant problem.

**Soviet Test 184**

In 1962, the Soviet Union also performed a series of three EMP-producing nuclear tests in space over Kazakhstan, which were the last in the series called "The K Project". Although these weapons were much smaller (300 kilotons or 1.3 PJ) than the Starfish Prime test, since those tests were done over a populated large land mass (and also at a location where the Earth's magnetic field was greater), the damage caused by the resulting EMP was reportedly much greater than in the Starfish Prime nuclear test. The geomagnetic storm-like E3 pulse (from the test designated as "Test 184") even induced

an electric current surge in a long underground power line that caused a fire in the power plant in the city of Karaganda. After the collapse of the Soviet Union, the level of this damage was communicated informally to scientists in the United States. Formal documentation of some of the EMP damage in Kazakhstan exists but is still sparse in the open scientific literature.

## Non-nuclear history

The concept of the explosively pumped flux compression generator for generating a non-nuclear electromagnetic pulse was conceived as early as 1951 by Andrei Sakharov in the Soviet Union, but nations have usually kept their most recent work on non-nuclear EMP highly classified until the technology was old enough for similar ideas to be conceived by physicists in other nations.

## *Characteristics of nuclear EMP*

The case of a **nuclear electromagnetic pulse** differs from other kinds of electromagnetic pulse (EMP) in being a complex electromagnetic multi-pulse. The complex multi-pulse is usually described in terms of three components, and these three components have been defined as such by the international standards commission called the International Electrotechnical Commission (IEC).

The three components of nuclear EMP, as defined by the IEC, are called **E1**, **E2** and **E3**.

### E1

The **E1** pulse is the very fast component of nuclear EMP. The **E1** component is a very brief but intense electromagnetic field that can quickly induce very high voltages in electrical conductors. The **E1** component causes most of its damage by causing electrical breakdown voltages to be exceeded. **E1** is the component that can destroy computers and communications equipment and it changes too fast for ordinary lightning protectors to provide effective protection against it.
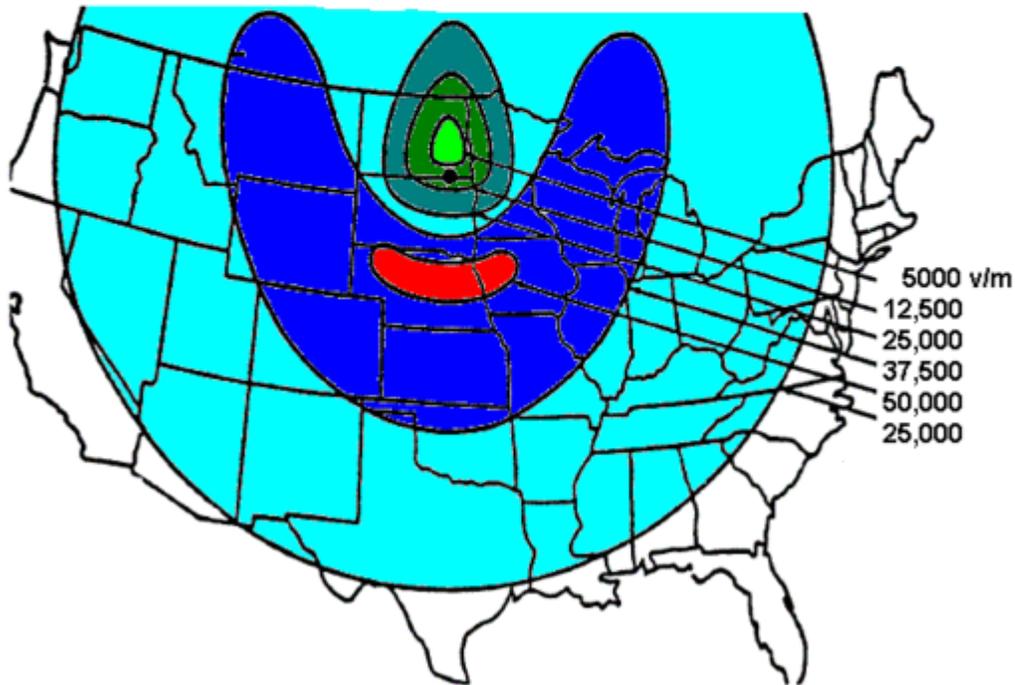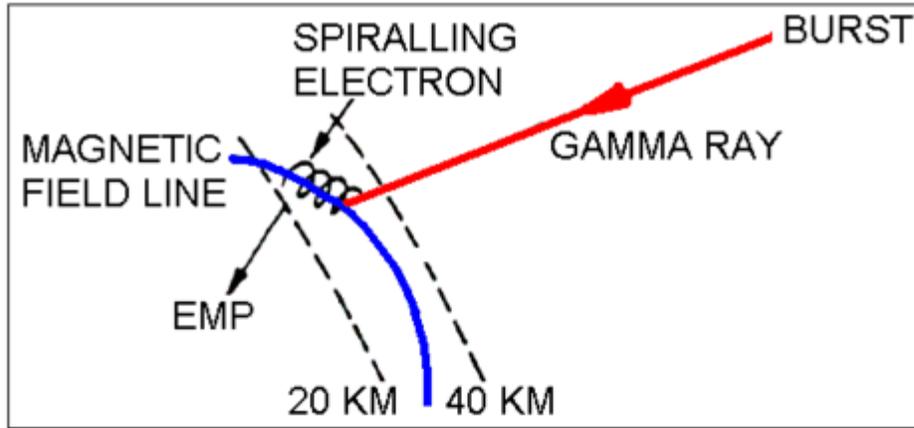
Source: Nuclear Environment Survivability,
U. S. Army, report AD-A278230 (1994)

The mechanism for a 400 km high altitude burst EMP: gamma rays hit the atmosphere between 20–40 km altitude, ejecting electrons which are then deflected sideways by the Earth's magnetic field. This makes the electrons radiate EMP over a massive area. Because of the curvature and downward tilt of Earth's magnetic field over the USA, the maximum EMP occurs south of the detonation and the minimum occurs to the north.

The E1 component is produced when gamma radiation from the nuclear detonation knocks electrons out of the atoms in the upper atmosphere. The electrons begin to travel in a generally downward direction at relativistic speeds (more than 90 percent of the speed of light). In the absence of a magnetic field, this would produce a large pulse of electric current vertically in the upper atmosphere over the entire affected area. The Earth's magnetic field acts on these electrons to change the direction of electron flow to a right angle to the geomagnetic field. This interaction of the Earth's magnetic field and the

downward electron flow produces a very large, but very brief, electromagnetic pulse over the affected area.

Physicist Conrad Longmire has given numerical values for a typical case of the E1 pulse produced by a second generation nuclear weapon such as those used in high altitude tests of Operation Fishbowl in 1962. According to him, the typical gamma rays given off by the weapon have an energy of about 2 MEV (million electron volts). When these gamma rays collide with atoms in the mid-stratosphere, the gamma rays knock out electrons. This is known as the Compton effect, and the resulting electrons produce an electric current that is known as the *Compton current*. The gamma rays transfer about half of their energy to the electrons, so these initial electrons have an energy of about 1 MEV. This causes the electrons to begin to travel in a generally downward direction at about 94 percent of the speed of light. Relativistic effects cause the mass of these high energy electrons to increase to about 3 times their normal rest mass.

If there were no geomagnetic field and no additional atoms in the lower atmosphere for additional collisions, the electrons would continue to travel downward with an average current density in the stratosphere of about 48 amperes per square metre.

Because of the downward tilt of the Earth's magnetic field at high latitudes, the area of peak field strength is a U-shaped region to the equatorial side of the nuclear detonation. As shown in the diagram at the right, for nuclear detonations over the continental United States, this U-shaped region is south of the detonation point. Near the equator, where the Earth's magnetic field is more nearly horizontal, the E1 field strength is more nearly symmetrical around the burst location.

The Earth's magnetic field quickly deflects the electrons at right angles to the geomagnetic field, and the extent of the deflection depends upon the strength of the magnetic field. At geomagnetic field strengths typical of the central United States, central Europe or Australia, these initial electrons spiral around the magnetic field lines in a circle with a typical radius of about 85 metres (about 280 feet). These initial electrons are stopped by collisions with other air molecules at a average distance of about 170 metres (a little less than 580 feet). This means that most of the electrons are stopped by collisions with air molecules before they can complete one full circle of its spiral around the Earth's magnetic field lines.

This interaction of the very rapidly moving negatively charged electrons with the magnetic field radiates a pulse of electromagnetic energy. The pulse typically rises to its peak value in about 5 nanoseconds. The magnitude of this pulse typically decays to half of its peak value within 200 nanoseconds. (By the IEC definition, this E1 pulse is ended at one microsecond (1000 nanoseconds) after it begins.) This process occurs simultaneously with about $10^{25}$ other electrons.

There are a number of secondary collisions which cause the subsequent electrons to lose energy before they reach ground level. The electrons generated by these subsequent

collisions have such reduced energy that they do not contribute significantly to the E1 pulse.

These 2 MEV gamma rays will normally produce an E1 pulse near ground level at moderately high latitudes that peaks at about 50,000 volts per metre. This is a peak power density of 6.6 megawatts per square metre.

The process of the gamma rays knocking electrons out of the atoms in the mid-stratosphere causes this region of the atmosphere to become an electrical conductor due to ionization, a process which blocks the production of further electromagnetic signals and causes the field strength to saturate at about 50,000 volts per metre. The strength of the E1 pulse depends upon the number and intensity of the gamma rays produced by the weapon and upon the rapidity of the gamma ray burst from the weapon. The strength of the E1 pulse is also somewhat dependent upon the altitude of the detonation.

There are reports of "super-EMP" nuclear weapons that are able to overcome the 50,000 volt per metre limit by the very nearly instantaneous release of a burst of gamma radiation of much higher energy levels than are known to be produced by second generation nuclear weapons. The reality and possible construction details of these weapons are classified, and therefore cannot be confirmed by scientists in the open scientific literature.

## E2

The **E2** component is generated by scattered gamma rays and inelastic gammas produced by weapon neutrons. This E2 component is an "intermediate time" pulse that, by the IEC definition, lasts from about 1 microsecond to 1 second after the beginning of the electromagnetic pulse. The E2 component of the pulse has many similarities to the electromagnetic pulses produced by lightning, although the electromagnetic pulse induced by a nearby lightning strike may be considerably larger than the E2 component of a nuclear EMP. Because of the similarities to lightning-caused pulses and the widespread use of lightning protection technology, the E2 pulse is generally considered to be the easiest to protect against.

According to the United States EMP Commission, the main potential problem with the E2 component is the fact that it immediately follows the E1 component, which may have damaged the devices that would normally protect against E2.

According to the EMP Commission Executive Report of 2004, "In general, it would not be an issue for critical infrastructure systems since they have existing protective measures for defense against occasional lightning strikes. The most significant risk is synergistic, because the E2 component follows a small fraction of a second after the first component's insult, which has the ability to impair or destroy many protective and control features. The energy associated with the second component thus may be allowed to pass into and damage systems."

**E3**

The **E3** component is very different from the other two major components of nuclear EMP. The E3 component of the pulse is a very slow pulse, lasting tens to hundreds of seconds, that is caused by the nuclear detonation heaving the Earth's magnetic field out of the way, followed by the restoration of the magnetic field to its natural place. The E3 component has similarities to a geomagnetic storm caused by a very severe solar flare. Like a geomagnetic storm, E3 can produce geomagnetically induced currents in long electrical conductors, which can then damage components such as power line transformers.

Because of the similarity between solar-induced geomagnetic storms and nuclear E3, it has become common to refer to solar-induced geomagnetic storms as "solar EMP." At ground level, however, "solar EMP" is not known to produce an E1 or E2 component.

For a more thorough description of E3 damage mechanisms,

## *Practical considerations for nuclear EMP*

Older, vacuum tube (valve) based equipment is generally much less vulnerable to EMP than newer solid state equipment. Soviet Cold War–era military aircraft often had avionics based on vacuum tubes due both to limitations in Soviet solid-state capabilities and a belief that the vacuum-tube gear would survive better.

Although vacuum tubes are far more resistant to EMP than solid state devices, other components in vacuum tube circuitry can be damaged by EMP. Vacuum tube equipment actually was damaged in 1962 nuclear EMP testing.  Also, the solid state PRC-77 VHF manpackable 2-way radio survived extensive EMP testing. The earlier PRC-25, nearly identical except for a vacuum tube final amplification stage, had been tested in EMP simulators but was not certified to remain fully functional.

Many nuclear detonations have taken place using bombs dropped by aircraft. The B-29 aircraft that delivered the nuclear weapons at Hiroshima and Nagasaki did not lose power due to damage to their electrical or electronic systems. This is simply because electrons (ejected from the air by gamma rays) are stopped quickly in normal air for bursts below roughly 10 km (about 6 miles), so they do not get a chance to be significantly deflected by the Earth's magnetic field (the deflection causes the powerful EMP seen in high altitude bursts), thus the limited use of smaller burst altitudes for widespread EMP.

If the aircraft carrying the Hiroshima and Nagasaki bombs had been within the intense nuclear radiation zone when the bombs exploded over those cities, then they would have suffered effects from the charge separation (radial) EMP. But this only occurs within the severe blast radius for detonations below about 10 km altitude.

During nuclear tests in 1962, EMP disruptions were suffered aboard KC-135 photographic aircraft flying 300 km (190 mi) from the 410 kt (1,700 TJ) *Bluegill Triple*

*Prime* and 410 kt (1,700 TJ) *Kingfish* detonations (48 and 95 km (30 and 59 mi) burst altitude, respectively) but the vital aircraft electronics were far less sophisticated than today and the aircraft were able to land safely.

## *Generation of nuclear EMP*

Several major factors control the effectiveness of a nuclear EMP weapon. These are

1. The altitude of the weapon when detonated;
2. The yield and construction details of the weapon;
3. The distance from the weapon when detonated;
4. Geographical depth or intervening geographical features;
5. The local strength of the magnetic field of the Earth.

Beyond a certain altitude a nuclear weapon will not produce any EMP, as the gamma rays will have had sufficient distance to disperse. In deep space or on worlds with no magnetic field (the moon or Mars for example) there will be little or no EMP. This has implications for certain kinds of nuclear rocket engines, such as Project Orion.

### Weapon altitude
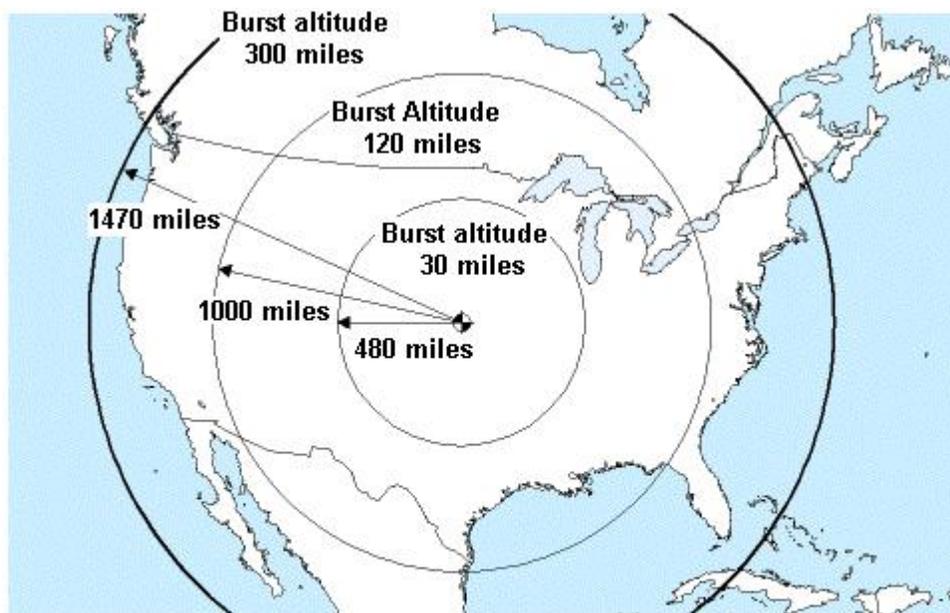


**EMP AREA BY BURSTS AT 30, 120 and 300 MILES**
Gary Smith, "Electromagnetic Pulse Threats", testimony to House
National Security Committee on July 16, 1997

How the area affected depends on the burst altitude.

Peak electric field at ground zero

Louis W. Seiler, Jr., A Calculational Model for High Altitude EMP, AD-A009208 March 1975, pp. 33, 36

No pre-ionisation

100 km assuming pre-ionisation with 0.03 kilotons of prompt gamma rays

Prompt gamma output in 1962 Starfish test was 1.4 kt (total yield 1.4 Mt)

Prompt gamma yield in 1962 Russian test No. 184 was 0.39 kt (total yield 300 kt)

How the peak EMP on the ground varies with the weapon yield and burst altitude. The yield here is the prompt gamma ray output measured in kilotons. This varies from 0.115–0.5% of the total weapon yield, depending on weapon design. The 1.4 Mt total yield 1962 Starfish Prime test had a gamma output of 0.1%, hence 1.4 kt of prompt gamma rays. (The **blue** 'pre-ionisation' curve applies to certain types of thermonuclear weapon, where gamma and x-rays from the primary fission stage ionise the atmosphere and make it electrically conductive before the main pulse from the thermonuclear stage. The pre-ionisation in some situations can literally short out part of the final EMP, by allowing a conduction current to immediately oppose the Compton current of electrons.)

According to an internet primer published by the Federation of American Scientists

*A high-altitude nuclear detonation produces an immediate flux of gamma rays from the nuclear reactions within the device. These photons in turn produce high energy free electrons by Compton scattering at altitudes between (roughly) 20 and 40 km. These electrons are then trapped in the Earth's magnetic field, giving rise to an oscillating electric current. This current is asymmetric in general and gives rise to a rapidly rising radiated electromagnetic field called an electromagnetic pulse (EMP). Because the electrons are trapped essentially simultaneously, a very large electromagnetic source radiates coherently.*

*The pulse can easily span continent-sized areas, and this radiation can affect systems on land, sea, and air. The first recorded EMP incident accompanied a high-altitude nuclear test over the South Pacific and resulted in power system failures as far away as Hawaii. A large device detonated at 400–500 km (250 to 312 miles) over Kansas would affect all of the continental U.S. The signal from such an event extends to the visual horizon as seen from the burst point.*

Thus, for equipment to be affected, the weapon needs to be above the visual horizon. Because of the nature of the pulse as a large, high powered, noisy spike, it is doubtful that there would be much protection if the explosion were seen in the sky just below the tops of hills or mountains.

The altitude indicated above is greater than that of the International Space Station and many low Earth orbit satellites. Large weapons could have a dramatic impact on satellite operations and communications such as occurred during the 1962 tests. The damaging effects on orbiting satellites are usually due to other factors besides EMP. In the Starfish Prime nuclear test, most satellite damage was due to damage to the solar panels from satellites passing through radiation belts created by the high altitude nuclear explosion.

## Weapon yield

Typical nuclear weapon yields used during Cold War planning for EMP attacks were in the range of 1 to 10 megatons (4.2 to 42 PJ) This is roughly 50 to 500 times the sizes of the weapons the United States used in Japan at Hiroshima and Nagasaki. Physicists have testified at United States Congressional hearings, however, that weapons with yields of 10 kilotons (42 TJ) or less can produce a very large EMP.

The EMP at a fixed distance from a nuclear weapon does not depend directly on the yield but at most only increases as the square root of the yield. This means that although a 10 kiloton weapon has only 0.7% of the total energy release of the 1.44-megaton Starfish Prime test, the EMP will be at least 8% as powerful. Since the E1 component of nuclear EMP depends on the prompt gamma ray output, which was only 0.1% of yield in Starfish Prime but can be 0.5% of yield in pure fission weapons of low yield, a 10 kiloton bomb can easily be 5 x 8% = 40% as powerful as the 1.44 megaton Starfish Prime at producing EMP.

The total prompt gamma ray energy in a fission explosion is 3.5% of the yield, but in a 10 kiloton detonation the high explosive around the bomb core absorbs about 85% of the

prompt gamma rays, so the output is only about 0.5% of the yield in kilotons. In the thermonuclear Starfish Prime the fission yield was less than 100% to begin with, and then the thicker outer casing absorbed about 95% of the prompt gamma rays from the pusher around the fusion stage. Thermonuclear weapons are also less efficient at producing EMP because the first stage can pre-ionize the air which becomes conductive and hence rapidly shorts out the electron Compton currents generated by the final, larger yield thermonuclear stage. Hence, small pure fission weapons with thin cases are far more efficient at causing EMP than most megaton bombs.

This analysis, however, only applies to the fast E1 and E2 components of nuclear EMP. The geomagnetic storm-like E3 component of nuclear EMP is more closely proportional to the total energy yield of the weapon.

## Weapon distance

A unique and important aspect of **nuclear** EMP is that all of the components of the electromagnetic pulse are generated **outside** of the weapon. The important E1 component is generated by interaction with the electrons in the upper atmosphere that are hit by gamma radiation from the weapon — and the subsequent effects upon those electrons by the Earth's magnetic field.

For high-altitude nuclear explosions, this means that much of the EMP is actually generated at a large distance from the detonation (where the gamma radiation from the explosion hits the upper atmosphere). This causes the electric field from the EMP to be remarkably uniform over the large area affected.

According to the standard reference text on nuclear weapons effects published by the U.S. Department of Defense, "The peak electric field (and its amplitude) at the Earth's surface from a high-altitude burst will depend upon the explosion yield, the height of the burst, the location of the observer, and the orientation with respect to the geomagnetic field.  As a general rule, however, the field strength may be expected to be tens of kilovolts per meter over most of the area receiving the EMP radiation."

The same reference book also states that, "... over most of the area affected by the EMP the electric field strength on the ground would exceed $0.5E_{max}$.   For yields of less than a few hundred kilotons, this would not necessarily be true because the field strength at the Earth's tangent could be substantially less than $0.5E_{max}$."

($E_{max}$ refers to the maximum electric field strength in the affected area.)

In other words, the electric field strength in the entire area that is affected by the EMP will be fairly uniform for weapons with a large gamma ray output; but for much smaller weapons, the electric field may fall off at a comparatively faster rate at large distances from the detonation point.

It is the **peak electric field** of the EMP that determines the **peak voltage** induced in equipment and other electrical conductors on the ground, and most of the damage is determined by induced voltages.

For nuclear detonations within the atmosphere, the situation is more complex. Within the range of gamma ray deposition, simple laws no longer hold as the air is ionised and there are other EMP effects, such as a radial electric field due to the separation of Compton electrons from air molecules, together with other complex phenomena. For a surface burst, absorption of gamma rays by air would limit the range of gamma ray deposition to approximately 10 miles, while for a burst in the lower-density air at high altitudes, the range of deposition would be far greater.

## *Non-nuclear electromagnetic pulse*

**Non-nuclear electromagnetic pulse** (**NNEMP**) is an electromagnetic pulse generated without use of nuclear weapons. There are a number of devices that can achieve this objective, ranging from a large low-inductance capacitor bank discharged into a single-loop antenna or a microwave generator to an explosively pumped flux compression generator. To achieve the frequency characteristics of the pulse needed for optimal coupling into the target, wave-shaping circuits and/or microwave generators are added between the pulse source and the antenna. A vacuum tube particularly suitable for microwave conversion of high energy pulses is the vircator.

NNEMP generators can be carried as a payload of bombs and cruise missiles, allowing construction of electromagnetic bombs with diminished mechanical, thermal and ionizing radiation effects and without the political consequences of deploying nuclear weapons.

The range of NNEMP weapons (non-nuclear electromagnetic bombs) is severely limited compared to nuclear EMP. This is because nearly all NNEMP devices used as weapons require chemical explosives as their initial energy source, but nuclear explosives have an energy yield on the order of one million times that of chemical explosives of similar weight. In addition to the large difference in the energy density of the initial energy source, the electromagnetic pulse from NNEMP weapons must come from within the weapon itself, while nuclear weapons generate EMP as a secondary effect, often at great distances from the detonation. These facts severely limit the range of NNEMP weapons as compared to their nuclear counterparts, but allow for more surgical target discrimination. The effect of small e-bombs has proven to be sufficient for certain terrorist or military operations. Examples of such operations include the destruction of certain fragile electronic control systems of the type critical to the operation of many ground vehicles and aircraft.

A right front view of a Boeing E-4 National Airborne Operations Center aircraft on the electromagnetic pulse (EMP) simulator (HAGII-C) for testing.

USS *Estocin* (FFG-15) moored near the Electro Magnetic Pulse Radiation Environmental Simulator for Ships I (EMPRESS I) facility (antennae at top of image).

NNEMP generators also include large structures built to generate EMP for testing of electronics to determine how well it survives EMP. In addition, the use of ultra-wideband radars can generate EMP in areas immediately adjacent to the radar; this phenomenon is only partly understood.

Information about the EMP simulators used by the United States during the latter part of the Cold War, along with more general information about electromagnetic pulse, are now in papers under the care of the SUMMA Foundation, which is now hosted at the University of New Mexico.

The SUMMA Foundation web site includes documentation about the huge wooden Trestle simulator in New Mexico, which was the world's largest EMP simulator.  Nearly all of these large EMP simulators used a specialized version of a Marx generator.  The SUMMA Foundation now has a 44-minute documentary movie on its web site called "TRESTLE: Landmark of the Cold War".

Many large EMP simulators were also built in the Soviet Union, as well as in the United Kingdom, France, Germany, The Netherlands, Switzerland and Italy.

## Post–Cold War nuclear EMP attack scenarios

The United States military services have developed, and in some cases have published, a number of hypothetical EMP attack scenarios.

The United States EMP Commission was authorized by the United States Congress in Fiscal Year 2001, and re-authorized in Fiscal Year 2006. The commission is formally known as the **Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack**.

The United States EMP Commission has brought together a group of notable scientists and technologists to compile several reports. In 2008, the EMP Commission released the **Critical National Infrastructures Report**. This report describes, in as much detail as practical, the likely consequences of a nuclear EMP on civilian infrastructures. Although this report was directed specifically toward the United States, most of the information can obviously be generalized to the civilian infrastructure of other industrialized countries.

The 2008 report was a followup to a more generalized report issued by the commission in 2004.

In written testimony delivered to the United States Senate in 2005, an EMP Commission staff member reported:

*The EMP Commission sponsored a worldwide survey of foreign scientific and military literature to evaluate the knowledge, and possibly the intentions, of foreign states with respect to electromagnetic pulse (EMP) attack. The survey found that the physics of EMP phenomenon and the military potential of EMP attack are widely understood in the international community, as reflected in official and unofficial writings and statements. The survey of open sources over the past decade finds that knowledge about EMP and EMP attack is evidenced in at least Britain, France, Germany, Israel, Egypt, Taiwan, Sweden, Cuba, India, Pakistan, Iraq under Saddam Hussein, Iran, North Korea, China and Russia.*
            *. . .*
*Many foreign analysts–particularly in Iran, North Korea, China, and Russia–view the United States as a potential aggressor that would be willing to use its entire panoply of weapons, including nuclear weapons, in a first strike. They perceive the United States as having contingency plans to make a nuclear EMP attack, and as being willing to execute those plans under a broad range of circumstances.*
*Russian and Chinese military scientists in open source writings describe the basic principles of nuclear weapons designed specifically to generate an enhanced-EMP effect, that they term "Super-EMP" weapons. "Super-EMP" weapons, according to these foreign open source writings, can destroy even the best protected U.S. military and civilian electronic systems.*

## Clarification of common misconceptions

In non-technical writings about nuclear EMP, both in print and on the Internet, some common misconceptions about EMP are nearly always found. These widely-repeated misconceptions have led to a very considerable amount of confusion about the subject. In 2010, a technical report written for a United States government laboratory, Oak Ridge National Laboratory, even included a brief section addressing some of those EMP myths. Here are some further clarifications on common areas of confusion that have already been discussed (with references) in the above sections:

1. Most nuclear weapons effects vary greatly depending upon the altitude of the detonation. This is especially true of nuclear EMP. The standard reference text on nuclear weapon effects published by the U.S. Department of Defense discusses this relationship extensively in the first two chapters, and provides mutually-exclusive definitions for phrases such as "air burst" and "high-altitude burst."  As explained in above sections, nuclear detonations at all altitudes within the Earth's magnetic field will produce an electromagnetic pulse; but the magnitude of the EMP and area that is affected by the EMP are strongly affected by many factors, and is especially strongly dependent upon the altitude of the detonation. A nuclear explosion in deep space and not in a strong planetary magnetic field would be ineffective at generating EMP.

2. EMP is not a new kind of weapon effect. As stated in the "History" section above, nuclear EMP from a nuclear air burst has been known since 1945. The unique characteristics of high-altitude nuclear EMP have been known since at least 1962. Non-nuclear EMP has been known since at least 1951. Electromagnetic pulse is a prompt *secondary* effect of a nuclear explosion, and nearly all of the nuclear EMP is produced outside of the weapon.  *All* nuclear weapons can produce EMP as a secondary effect, but the effect can be enhanced by special weapon design.

3. The E3 component of nuclear EMP that produces geomagnetically induced currents in very long electrical conductors is roughly proportional to the total energy yield of the weapon. The other components of nuclear EMP are less likely to be dependent on total energy yield of the weapon. The E1 component, in particular, is proportional to prompt gamma ray output; but EMP levels can be strongly affected if more than one burst of gamma rays occurs in a short time period. Large thermonuclear weapons produce large energy yields through a multi-stage process. This multi-stage process is completed within a small fraction of a second, but it nevertheless requires a finite length of time. The first fission reaction is usually of relatively small yield, and the gamma rays produced by the first stage pre-ionize atmospheric molecules in the stratosphere. This pre-ionization causes the gamma ray emission from the high-energy final stage of the thermonuclear weapon (a fraction of a second later) to be relatively ineffective at producing a large *E1* pulse.

4. It has long been known that there are many ways to protect against nuclear EMP (or to quickly begin repairs where protection is not practical); but the United States EMP Commission determined that such protections are almost completely absent in the civilian infrastructure of the United States, and that even large

sectors of the United States military services were no longer protected against EMP to the level that they were during the Cold War. The public statements of the physicists and engineers working in the EMP field tend to emphasize the importance of making electronic equipment and electrical components resistant to EMP — and of keeping adequate spare parts on hand, and in the proper location, to enable prompt repairs to be made. The United States EMP Commission did not look at the civilian infrastructures of other nations.

**Chapter 5**

# Capacitive Coupling and Inductive Coupling

# Capacitive coupling

In electronics, **capacitive coupling** is the transfer of energy within an electrical network by means of the capacitance between circuit nodes. This coupling can have an intentional or accidental effect. Capacitive coupling is typically achieved by placing a capacitor in series with the signal to be coupled.

## Use in analog circuits

In analog circuits, a coupling capacitor is used to connect two circuits such that only the AC signal from the first circuit can pass through to the next while DC is blocked. This technique helps to isolate the DC bias settings of the two coupled circuits. Capacitive coupling is also known as *AC coupling* and the capacitor used for the purpose is known as a *coupling or DC blocking capacitor*. Capacitive coupling has the disadvantage of degrading the low frequency performance of a system containing capacitively coupled units. Each coupling capacitor along with the input electrical impedance of the next stage forms a high-pass filter and each successive filter results in a cumulative filter with a -3dB frequency that may be higher than each individual filter. So for adequate low frequency response the capacitors used must have high capacitance ratings. They should be high enough that the reactance of each is at most a tenth of the input impedance of each stage, at the lowest frequency of interest. This disadvantage of capacitively coupling DC biased, transistor amplifier circuits is largely minimized in directly coupled designs.

## Use in digital circuits

AC coupling is also widely used in digital circuits to transmit digital signal with a zero DC component, known as DC-balanced signals. DC-balanced waveforms are useful in communications systems, since they can be used over AC-coupled electrical connections

to avoid voltage imbalance problems and charge accumulation between connected systems or components.

For this reason, most modern line codes are designed to produce DC-balanced waveforms. The most common classes of DC-balanced line codes are constant-weight codes and paired-disparity codes.

### *Gimmick*

A "gimmick" is a very simple kind of capacitive coupling: a piece of wire that is placed in proximity to another one, providing a capacitive coupling between two nodes of a few picofarads in value. Sometimes the wires are twisted together for physical stability.

### *Parasitic capacitive coupling*

Capacitive coupling is often unintended, such as the capacitance between two wires or PCB traces that are next to each other. Often one signal can capacitively couple with another and cause what appears to be noise. To reduce coupling, wires or traces are often separated as much as possible, or ground lines or ground planes are run in between signals that might affect each other. Breadboards are particularly prone to these issues due to the long pieces of metal that line every row creating a several-picofarad capacitor between lines. To prototype high-frequency (10s of MHz) or high-gain analog circuits, often the circuits are built over a ground plane so that the signals couple to ground more than to each other. If a high-gain amplifier's output capacitively couples to its input it often becomes an electronic oscillator.

# Inductive coupling

In electrical engineering, two conductors are referred to as **mutual-inductively coupled** or **magnetically coupled** when they are configured such that change in current flow through one wire induces a voltage across the ends of the other wire through electromagnetic induction. The amount of inductive coupling between two conductors is measured by their mutual inductance.

The coupling between two wires can be increased by winding them into coils and placing them close together on a common axis, so the magnetic field of one coil passes through the other coil. The two coils may be physically contained in a single unit, as in the primary and secondary sides of a transformer, or may be separated. Coupling may be intentional or unintentional.

Unintentional coupling is called cross-talk, and is a form of electromagnetic interference. Inductive coupling favors low frequency energy sources. High frequency energy sources generally use capacitive coupling.

An inductively coupled transponder comprises an electronic data carrying device, usually a single microchip, and a large coil that functions as an antenna. Inductively coupled transponders are almost always operated passively.

## *Uses*

Devices that use inductive coupling include:

- Transformers
- Electric motors and generators
- Induction loop communication systems
- Metal detectors
- Graphics tablet
- Radio Frequency Identification
- Electronic article surveillance tags to prevent theft (most types).
- Inductive Modems
- Resonant energy transfer
- Inductive charging products charge batteries using inductive coupling, such as eCoupled; Torches, Cochlear Implants and many electric toothbrushes.
- Induction cookers and induction heating systems

## *Low frequency induction*

Low frequency induction is an unwanted form of inductive coupling, which can occur when a metallic pipeline is installed parallel to a high-voltage power line. The pipeline, which is a conductor, and is insulated from the earth by its protective coating, can develop voltages which are hazardous to personnel operating valves or otherwise contacting the pipeline.

# Chapter 6

# Ground Loop (Electricity)

In an electrical system, a **ground loop** usually refers to a current, generally unwanted, in a conductor connecting two points that are supposed to be at the same potential, often ground, but are actually at different potentials. Ground loops created by improperly designed or improperly installed equipment are a major cause of noise and interference in audio and video systems. They can also create an electric shock hazard, since ostensibly "grounded" parts of the equipment, which are often accessible to users, are not at ground potential.

## *How it works*
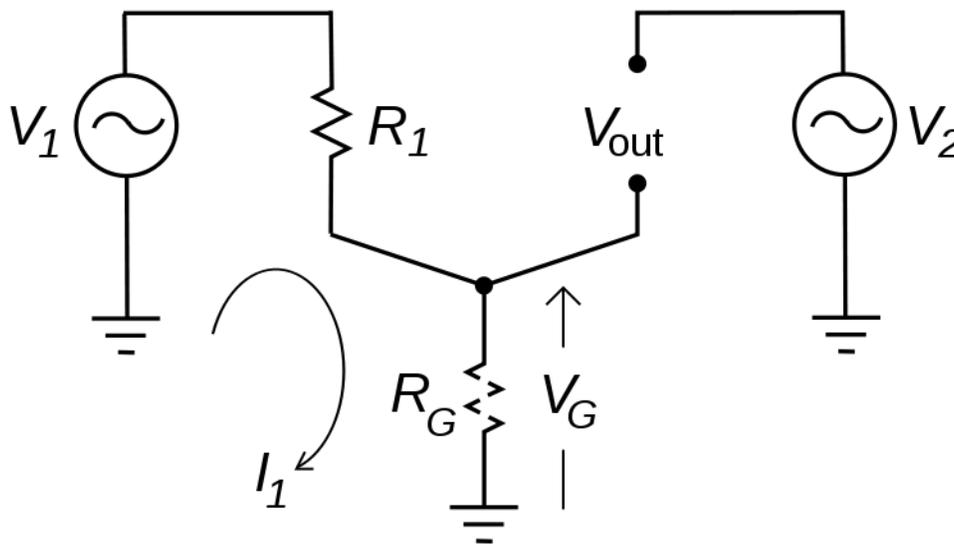


Simplified circuit illustrating a ground loop.

The simplified circuit diagram at right illustrates in principle how a ground loop works. Two circuits share a common wire connecting them to ground. Ideally the ground

conductor should have no resistance ($R_G = 0$), so the voltage drop across it, $V_G$, should be zero, keeping the point at which the circuits connect at a constant ground potential, isolating them from each other. In this case the output of circuit 2 is simply $V_{out} = V_2$. However, if the ground conductor has significant resistance, $R_G$, and current of magnitude $I_1$ is flowing through it from circuit 1, a voltage drop $V_G = I_1 R_G$, across $R_G$ will occur and the ground connection of both circuits will no longer be at the actual ground potential. This voltage across the ground conductor will be applied to circuit 2 and added to the output:

$$V_{out} = V_2 - V_G = V_2 - \frac{R_G}{R_G + R_1} V_1.$$

Thus the two circuits are no longer isolated from each other, and circuit 1 can introduce interference into the output of circuit 2. If circuit 2 is an audio system, and circuit 1 has large AC currents flowing in it, the interference may be heard as a 50 or 60 Hz hum in the speakers. Also, both circuits will have voltage $V_G$ on their grounded parts that may be exposed to contact, possibly presenting a shock hazard. This is true even if circuit 2 is turned off.

## Description

A ground loop in a system which connects circuits designed to be at the same potential but which are actually at different potentials can be hazardous, or cause problems with the electrical system, because the electrical potential and soil resistance at different points on the surface of the earth can vary.

In a floating ground system, that is, one not connected to earth, the voltages will probably be unstable, and if some of the conductors that constitute the return circuit to the source have a relatively high resistance, or have high currents through them that produce a significant voltage (I·R) drop, they can be hazardous.

Low current wiring is particularly susceptible to ground loops. If two pieces of audio equipment are plugged into different power outlets, there will often be a difference in their respective ground potentials. If a signal is passed from one to the other via an audio connection with the ground wire intact, this potential difference causes a spurious current through the cables, creating an audible buzz at the AC mains base frequency (50 or 60 Hz) and the harmonics thereof (120 Hz, 240 Hz, and so on), called mains hum. Sometimes, performers remove the grounding pin from the cord connecting an appliance to the power outlet; however, this creates an electrocution risk. The first solution is to ensure that all metal chassis are interconnected, then connected to the electrical distribution system at *one* point (often referred to as a "single-point ground"). The next solution is to have shielded cables for the low currents, with the shield connected *only* at one end (this, however, increases the possibility of radio frequency interference (RF) since the shield may act as an antenna). Another solution is to use isolation transformers, opto-isolators or baluns to avoid a direct electrical connection between the different

grounds. However, bandwidth of such is of consideration. The better isolation transformers have grounded shields between the two sets of windings. In circuits having high frequencies, such as computer monitors, chokes are placed at the end of the cables just before the termination to the next appliance (e.g., the computer). These chokes are most often called ferrite core devices.

In video, ground loops can be seen as hum bars (bands of slightly different brightness) scrolling vertically up the screen. These are frequently seen with video projectors where the display device has its case grounded via a 3-prong plug, and the other components have a floating ground connected to the CATV coax. In this situation the video cable is grounded at the projector end to the home electrical system, and at the other end to the cable TV's ground, inducing a current through the cable which distorts the picture. As with audio ground loops, this problem can be solved by placing an isolation transformer on the cable-TV coax. Alternatively, one can use a surge protector that includes coax protection. If the cable is routed through the same surge protector as the three-prong device, both will be regrounded to the surge protector.

Ground loop issues with television coaxial cable can also affect any connected audio devices such as a receiver. Even if all of the audio and video equipment in, for example, a home theater system is plugged into the same power outlet, and thus all share the same ground, the coaxial cable entering the TV is sometimes grounded to a different point than that of the house's electrical ground by the cable company. The potential of this ground is likely to differ slightly from the potential of the house's ground, so a ground loop occurs, causing undesirable mains hum in the system's speakers. A cheap way to resolve this problem is a *75-ohm coax combiner/splitter* and a *matching Transformer*. The 75-ohm coax combiner/splitter converts the impedance from 75 ohms to 300 ohms and the matching transformer converts the impedance from 300 ohms to 75 ohms. Both parts connected together will act as a "poor man's" isolation transformer.

Ground and ground loops are also important in designing circuits. In many circuits, large currents may exist through the ground plane, leading to voltage differences of the ground reference in different parts of the circuit, leading to hum and other problems. Several techniques should be used to avoid ground loops, and otherwise, guarantee good grounding:

- The external shield, and the shields of all connectors, should be connected together. If the power supply design is non-isolated, this external ground should be connected to the ground plane of the PCB at only one point; this avoids large current through the ground plane of the PCB. If the design is an isolated power supply, this external ground should be connected to the ground plane of the PCB via a high voltage capacitor, such as 2200pF@2KV. If the connectors are mounted on the PCB, the outer perimeter of the PCB should contain a strip of copper connecting to the shields of the connectors. There should be a break in copper between this strip, and the main ground plane of the circuit. The two should be connected at only one point. This way, if there is a large current between connector shields, it will not pass through the ground plane of the circuit.

- A star topology should be used for ground distribution, avoiding loops.
- High-power devices should be placed closest to the power supply, while low-power devices can be placed farther from it.
- Signals, wherever possible, should be differential.
- Isolated power supplies require careful checking for parasitic, component, or internal PCB power plane capacitance that can allow AC present on input power or connectors to pass into the ground plane, or to any other internal signal. The AC might find a path back to its source via an I/O signal. While it can never be eliminated, it should be minimized as much as possible. The acceptable amount is implied by the design.

# Chapter 7

# Twisted Pair



25-pair color code Chart

**Twisted pair** cabling is a type of wiring in which two conductors (the forward and return conductors of a single circuit) are twisted together for the purposes of canceling out electromagnetic interference (EMI) from external sources; for instance, electromagnetic radiation from unshielded twisted pair (UTP) cables, and crosstalk between neighboring pairs. It was invented by Alexander Graham Bell.

## *Explanation*

In balanced pair operation, the two wires carry equal and opposite signals and the destination detects the difference between the two. This is known as differential mode transmission. Noise sources introduce signals into the wires by coupling of electric or magnetic fields and tend to couple to both wires equally. The noise thus produces a common-mode signal which is cancelled at the receiver when the difference signal is taken. This method starts to fail when the noise source is close to the signal wires; the closer wire will couple with the noise more strongly and the common-mode rejection of the receiver will fail to eliminate it. This problem is especially apparent in telecommunication cables where pairs in the same cable lie next to each other for many miles. One pair can induce crosstalk in another and it is additive along the length of the cable. Twisting the pairs counters this effect as on each half twist the wire nearest to the noise-source is exchanged. Providing the interfering source remains uniform, or nearly so, over the distance of a single twist, the induced noise will remain common-mode. Differential signaling also reduces electromagnetic radiation from the cable, along with the associated attenuation allowing for greater distance between exchanges.

The twist rate (also called *pitch* of the twist, usually defined in twists per meter) makes up part of the specification for a given type of cable. Where nearby pairs have equal twist rates, the same conductors of the different pairs may repeatedly lie next to each other, partially undoing the benefits of differential mode. For this reason it is commonly specified that, at least for cables containing small numbers of pairs, the twist rates must differ.

In contrast to **FTP** (foiled twisted pair) and **STP** (shielded twisted pair) cabling, **UTP** (unshielded twisted pair) cable is not surrounded by any shielding. It is the primary wire type for telephone usage and is very common for computer networking, especially as patch cables or temporary network connections due to the high flexibility of the cables.

## *History*
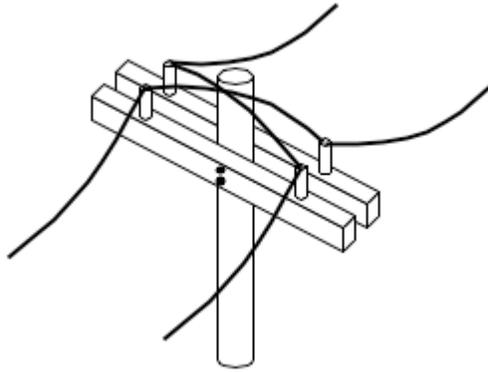


Wire transposition on top of pole

The earliest telephones used telegraph lines, or open-wire single-wire earth return circuits. In the 1880s electric trams were installed in many cities, which induced noise into these circuits. Lawsuits being unavailing, the telephone companies converted to balanced circuits, which had the incidental benefit of reducing attenuation, hence increasing range.

As electrical power distribution became more commonplace, this measure proved inadequate. Two wires, strung on either side of cross bars on utility poles, shared the route with electrical power lines. Within a few years the growing use of electricity again brought an increase of interference, so engineers devised a method called wire transposition, to cancel out the interference. In wire transposition, the wires exchange position once every several poles. In this way, the two wires would receive similar EMI from power lines. This represented an early implementation of twisting, with a twist rate of about four twists per kilometre, or six per mile. Such open-wire balanced lines with periodic transpositions still survives today in some rural areas.

Twisted pair cables were invented by Alexander Graham Bell in 1881. By 1900, the entire American telephone line network was either twisted pair or open wire with transposition to guard against interference. Today, most of the millions of kilometres of twisted pairs in the world are outdoor landlines, owned by telephone companies, used for voice service, and only handled or even seen by telephone workers.

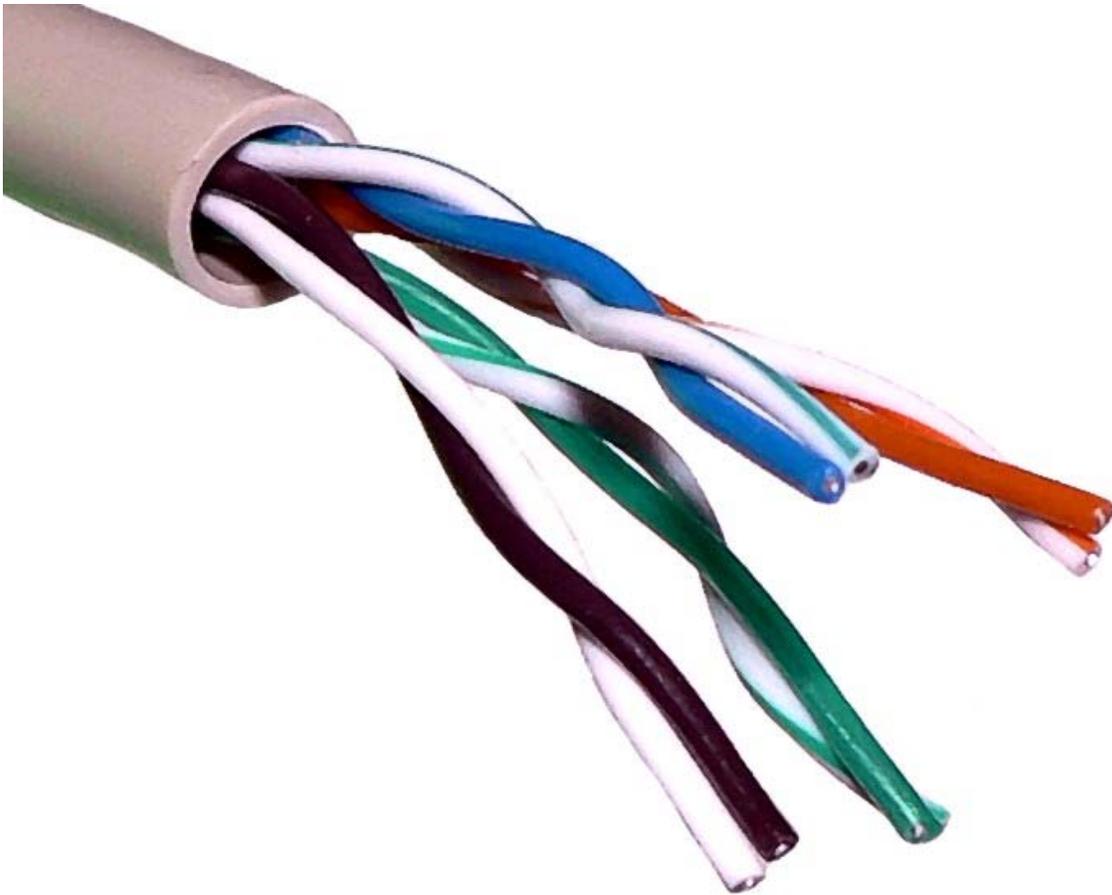## Unshielded twisted pair (UTP)

# UTP
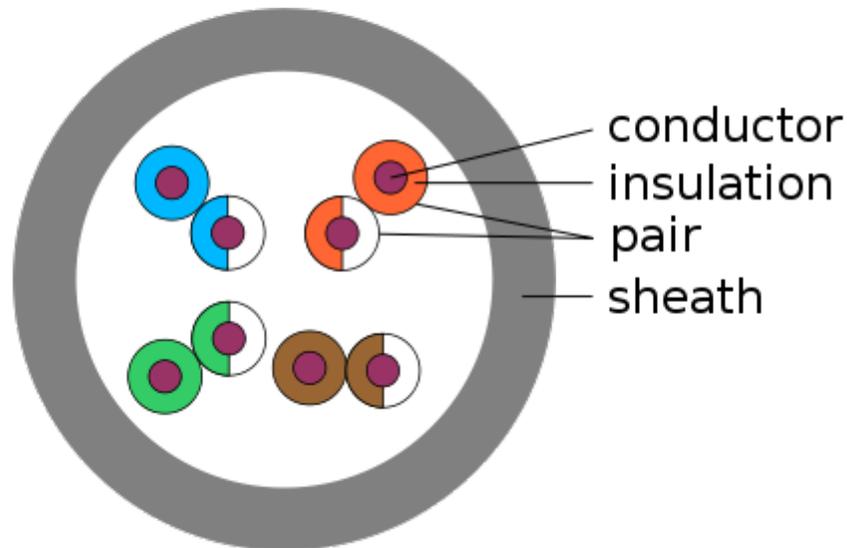


Unshielded twisted pair

UTP cables are found in many Ethernet networks and telephone systems. For indoor telephone applications, UTP is often grouped into sets of 25 pairs according to a standard 25-pair color code originally developed by AT&T. A typical subset of these colors (white/blue, blue/white, white/orange, orange/white) shows up in most UTP cables.

For urban outdoor telephone cables containing hundreds or thousands of pairs, the cable is divided into smaller but identical bundles. Each bundle consists of twisted pairs that have different twist rates. The bundles are in turn twisted together to make up the cable. Pairs having the same twist rate within the cable can still experience some degree of crosstalk. Wire pairs are selected carefully to minimize crosstalk within a large cable.

Unshielded twisted pair cable with different twist rates

UTP cable is also the most common cable used in computer networking. Modern Ethernet, the most common data networking standard, utilizes UTP cables. Twisted pair cabling is often used in data networks for short and medium length connections because of its relatively lower costs compared to optical fiber and coaxial cable.

UTP is also finding increasing use in video applications, primarily in security cameras. Many middle to high-end cameras include a UTP output with setscrew terminals. This is made possible by the fact that UTP cable bandwidth has improved to match the baseband of television signals. While the video recorder most likely still has unbalanced BNC connectors for standard coaxial cable, a balun is used to convert from 100-ohm balanced UTP to 75-ohm unbalanced. A balun can also be used at the camera end for ones without a UTP output. Only one pair is necessary for each video signal.
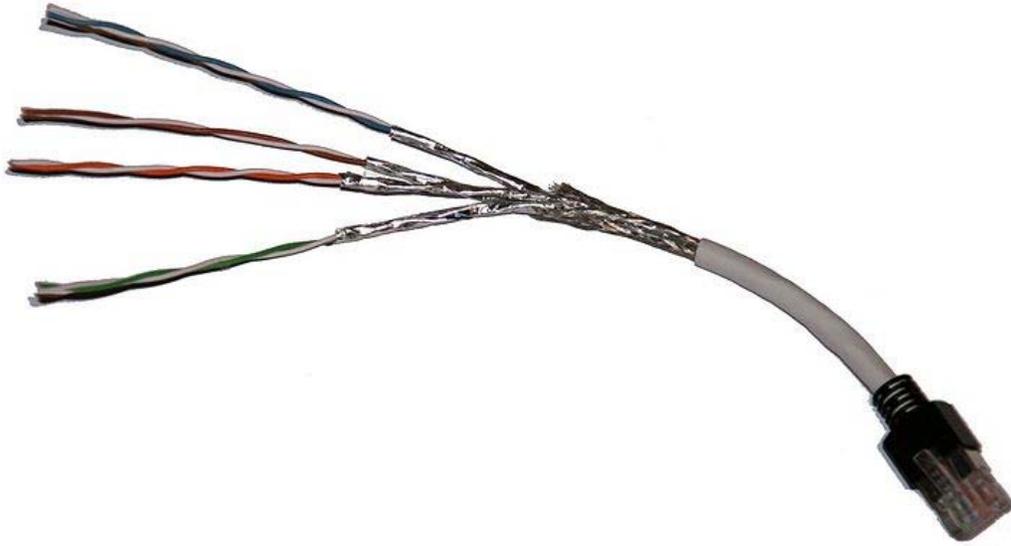
***Cable shielding***



S/UTP, also known as FTP

# STP



conductor
insulation
pair
pair shield
sheath
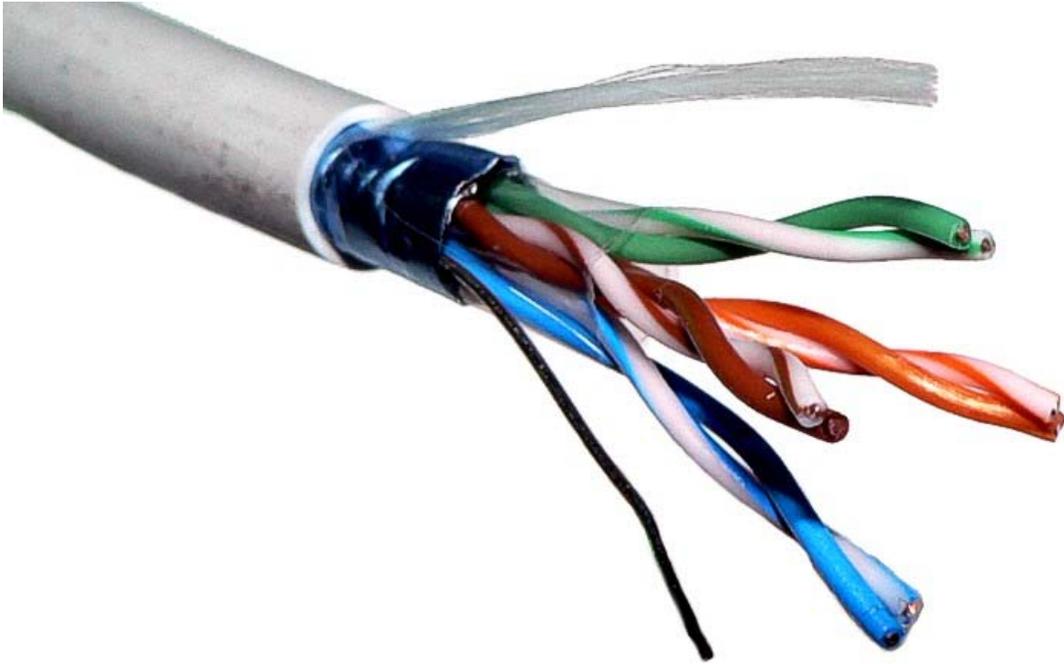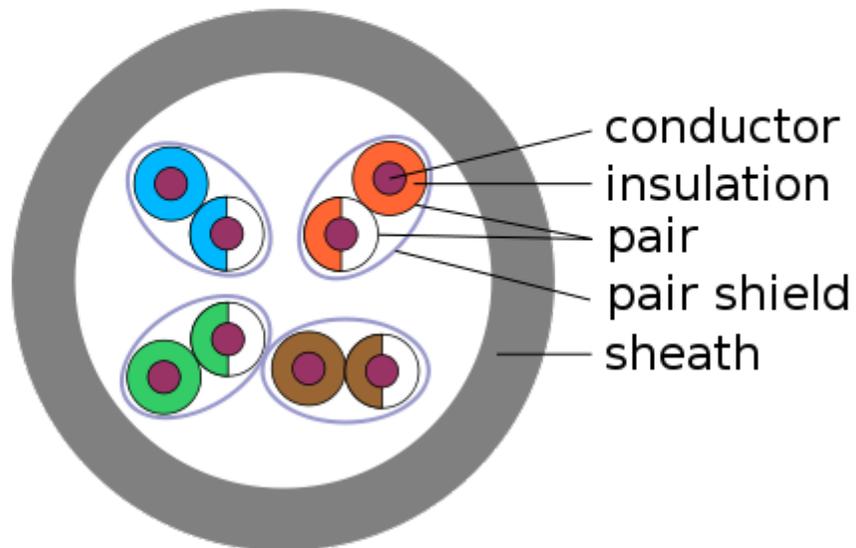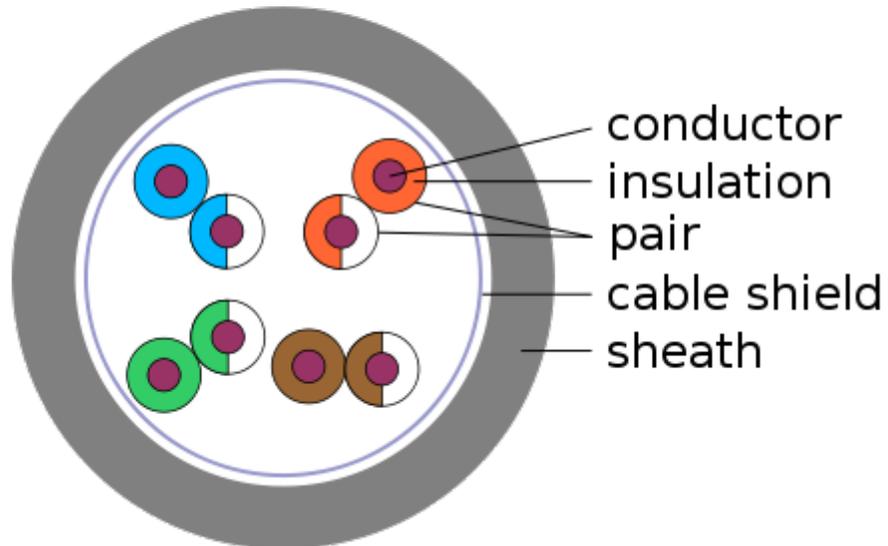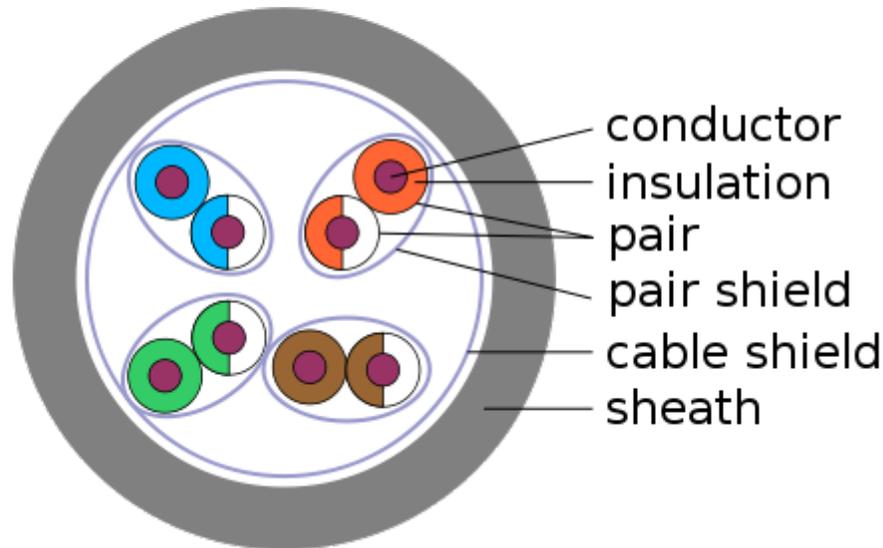
STP cable format

S/STP, also known as S/FTP.



S/UTP cable format

# S/STP



S/STP cable format

Twisted pair cables are often shielded in an attempt to prevent electromagnetic interference. Because the shielding is made of metal, it may also serve as a ground. However, usually a shielded or a screened twisted pair cable has a special grounding wire added called a drain wire. This shielding can be applied to individual pairs, or to the collection of pairs. When shielding is applied to the collection of pairs, this is referred to as screening. The shielding must be grounded for the shielding to work.

Shielded twisted pair (STP or STP-A)
> STP cabling includes metal shielding over each individual pair of copper wires. This type of shielding protects cable from external EMI. e.g. the 150 ohm shielded twisted pair cables defined by the IBM Cabling System specifications and used with token ring networks.

Screened unshielded twisted pair (S/UTP)
> Also known as Foiled Twisted Pair (FTP), is a screened UTP cable (ScTP).

Screened shielded twisted pair (S/STP or S/FTP)
> S/STP cabling, also known as Screened Fully shielded Twisted Pair (S/FTP), is both individually shielded (like STP cabling) and also has an outer metal shielding covering the entire group of shielded copper pairs (like S/UTP). This type of cabling offers the best protection from interference from external sources, and also eliminates *alien crosstalk*.

Note that different vendors and authors use different terminology (i.e. STP has been used to denote both STP-A, S/STP, and S/UTP).

**Comparison of some old and new abbreviations, according to ISO/IEC 11801:**

| Old name | New name | cable screening | pair shielding |
|---|---|---|---|
| UTP | U/UTP | none | none |
| FTP | F/UTP | foil | none |
| STP | U/FTP | none | foil |
| S-FTP | SF/UTP | foil, braiding | none |
| S-STP | S/FTP | braiding | foil |

The code before the slash designates the shielding for the cable itself, while the code after the slash determines the shielding for the individual pairs:

TP = twisted pair
U = unshielded
F = foil shielding
S = braided shielding

## *Most common cable categories*

| Category | Bandwidth | Applications | Notes |
|---|---|---|---|
| Cat1 | 0.4 MHz | Telephone and modem lines | Not described in EIA/TIA recommmendations. Unsuitable for modern systems. |
| Cat2 | ? MHz | Older terminal systems, e.g. IBM 3270 | Not described in EIA/TIA recommmendations. Unsuitable for modern systems. |
| Cat3 | 16MHz | 10BASE-T and 100BASE-T4 Ethernet | Described in EIA/TIA-568. Unsuitable for speeds above 16 Mbit/s. |
| Cat4 | 20MHz | 16 Mbit/s Token Ring | |
| Cat5 | 100MHz | 100BASE-TX & 1000BASE-T Ethernet | |
| Cat5e | 100MHz | 100BASE-TX & 1000BASE-T Ethernet | Enhanced Cat5. Practically the same as Cat5, but with better testing standards so Gigabit Ethernet works reliably. |
| Cat6 | 250MHz | 1000BASE-T Ethernet | Most commonly installed cable in Finland according to the 2002 standard. SFS-EN 50173-1 |
| Cat6e | 250MHz (500MHz according to some) | 10GBASE-T (under development) Ethernet | Not a standard; a cable maker's own label. |

| Cat6a | 500MHz | 10GBASE-T (under development) Ethernet | Standard under development (ISO/IEC 11801:2002 Amendment 2). |
|---|---|---|---|
| Cat7 | 600MHz | No applications yet. | Four pairs, U/FTP (shielded pairs). Standard under development. |
| Cat7a | 1000MHz | Telephone, CATV, 1000BASE-T in the same cable. | Four pairs, S/FTP (shielded pairs, braid-screened cable). Standard under development. |
| Cat8 | 1200MHz | Under development, no applications yet. | Four pairs, S/FTP (shielded pairs, braid-screened cable). Standard under development. |

## Solid core cable vs stranded cable

Solid core cable is supposed to be used for permanently installed runs. It is less flexible than stranded cable and is more prone to failure if repeatedly flexed. Stranded cable is used for fly leads at patch panel and for connections from wall-ports to end devices, as it resists cracking of the conductors. Stranded core is generally more expensive than solid core.

Connectors need to be designed differently for solid core than for stranded. Use of a connector with the wrong cable type is likely to lead to unreliable cabling. Plugs designed for solid and stranded core are readily available, and some vendors even offer plugs designed for use with both types. The punch-down blocks on patch-panel and wall port jacks are designed for use with solid core cable.

## Manufacture

Copper Rod Breakdown

The first step in low voltage cable production is copper rod breakdown. Copper is sent to the factory in 5,000 lb coils. These copper coils are continuously drawn through diamond dies that drastically reduce the diameter of the copper to 10 or 12 gauge. Lubrication is used during this process to reduce the amount of friction and heat on the copper cable. Once completed, the copper is stacked in vertical coils, called *stem packs*. These stem packs are then transferred to another drawing operation that further reduces the gauge of the copper. During this stage, the copper is also charged with an electrical current. This anneals the copper, which is a softening process. Once annealed and cooled off, the copper runs through a laser measurement system, to verify it is within manufacturing specifications.

Copper Insulation Process

The copper insulation process is continually monitored and controlled up to +/- .0001". Once the copper is insulated, it runs through a water cooling trough, allowing the wire jacket to harden properly.

Copper Twisting

Twisting helps reduce crosstalk between the individual pairs of wire. Some Cat6 premises cables include a center spline, or wire separator, to further reduce

crosstalk and increase performance. Copper twisting is accomplished by running each individual wire through multiple faceplates. This helps control pair position. Once twisted, this is known as a *cable unit*.

Jacketing

The cable unit then goes through the jacketing process. This step varies, depending on the type of cable being manufactured. OSP cable typically uses a black polyethylene or UV rated polyvinyl chloride (PVC). For Cat3, Cat5e and Cat6 premises cable, varying grades of PVC are used, depending on flame safety rating requirements. This step starts off with molten plastic being extruded at high pressure and formed around the moving cable core. Shielding, ripcords, armoring and water blocking compound may also be applied at this step. Cables that require dual shielding or double armor will need to repeat this process. Once completed, the cable passed through a long cooling bath, then through a laser micrometer to verify the final diameter.

Printing

Printing is done just before the cable is put in its final packaging. For OSP cable, a hot foil printing process is used, that leaves an indented print in the cable jacket. For premises cable, a high speed ink jet printer is used. Some cable manufacturers print distance marking from 1000–0 ft, or from 305–0 m making it very easy to determine how much cable is left in the box, or for measuring out cable runs. Other manufacturers use a six digit distance mark, making the process a little harder.

Coiling

The completed cable is then wound onto a reel or coil. The coiling process requires very precise tension controls to ensure the cable won't tangle when being pulled out of its box.

Final Testing

Once the cable is printed and coiled, it goes through one last set of tests. The manufacturer will test it against a large set of mechanical and electrical performance specifications. Once tested, the cable is ready for shipment.

## Advantages

- It is a thin, flexible cable that is easy to string between walls.
- More lines can be run through the same wiring ducts.
- UTP costs less per meter/foot than any other type of LAN cable.

## Disadvantages

- Twisted pair's susceptibility to electromagnetic interference greatly depends on the pair twisting schemes (usually patented by the manufacturers) staying intact during the installation. As a result, twisted pair cables usually have stringent requirements for maximum pulling tension as well as minimum bend radius. This relative fragility of twisted pair cables makes the installation practices an important part of ensuring the cable's performance.

- In video applications that send information across multiple parallel signal wires, twisted pair cabling can introduce signaling delays known as skew which results in subtle color defects and ghosting due to the image components not aligning correctly when recombined in the display device. The skew occurs because twisted pairs within the same cable often use a different number of twists per meter so as to prevent common-mode crosstalk between pairs with identical numbers of twists. The skew can be compensated by varying the length of pairs in the termination box, so as to introduce delay lines that take up the slack between shorter and longer pairs, though the precise lengths required are difficult to calculate and vary depending on the overall cable length.

### *Minor twisted pair variants*

- **Loaded twisted pair**: A twisted pair that has intentionally added inductance, common practice on telecommunication lines, except those carrying higher than voiceband frequencies. The added inductors are known as load coils and reduce distortion.
- **Unloaded twisted pair**: A twisted pair that has no added load coils.
- **Bonded twisted pair**: A twisted pair variant in which the pairs are individually bonded to increase robustness of the cable. Pioneered by Belden, it means the electrical specifications of the cable are maintained despite rough handling.
- **Twisted ribbon cable**: A variant of standard ribbon cable in which adjacent pairs of conductors are bonded and twisted together. The twisted pairs are then lightly bonded to each other in a ribbon format. Periodically along the ribbon there are short sections with no twisting to enable connectors and pcb headers to be terminated using the usual ribbon cable IDC techniques.

# Chapter 8

# Electronic test Equipment
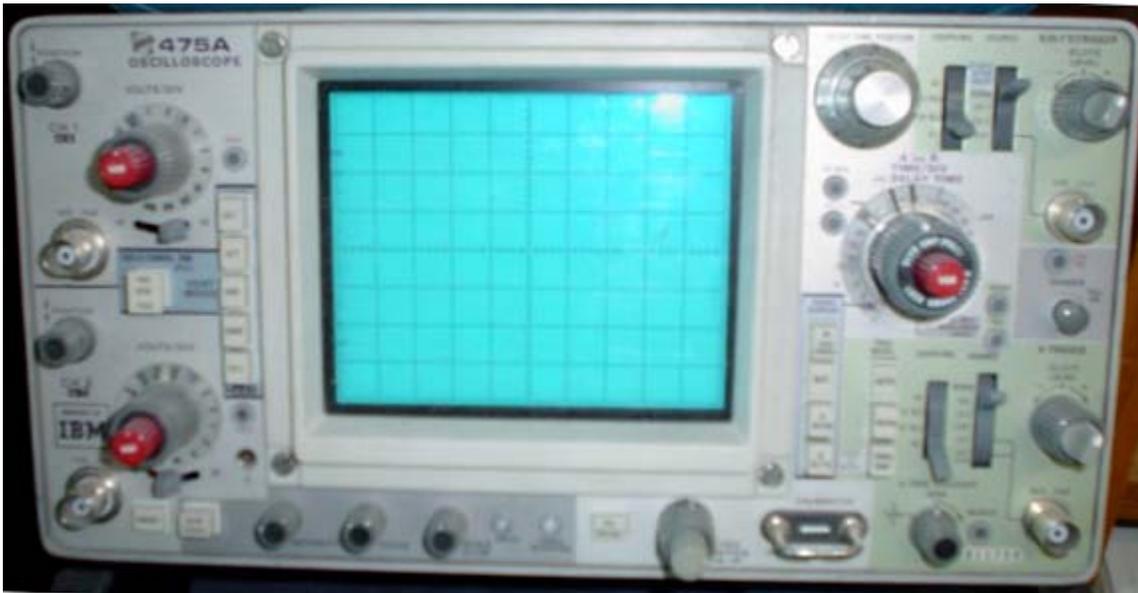


A Tektronix model 475A portable analogue oscilloscope

**Electronic test equipment** (sometimes called "testgear" or "bench top") is used to create signals and capture responses from electronic Devices Under Test (DUTs). In this way, the proper operation of the DUT can be proven or faults in the device can be traced and repaired. Use of electronic test equipment is essential to any serious work on electronics systems.

Practical electronics engineering and assembly requires the use of many different kinds of electronic test equipment ranging from the very simple and inexpensive (such as a test light consisting of just a light bulb and a test lead) to extremely complex and sophisticated such as Automatic Test Equipment. ATE often includes many of these instruments in real and simulated forms.

Generally, more advanced test gear is necessary when developing circuits and systems than is needed when doing production testing or when troubleshooting existing production units in the field.

## *Test Equipment Switching*

The addition of a high-speed switching system to a test system's configuration allows for faster, more cost-effective testing of multiple devices, and is designed to reduce both test errors and costs. Designing a test system's switching configuration requires an understanding of the signals to be switched and the tests to be performed, as well as the switching hardware form factors available.

## *Types of test equipment*

## Basic equipment
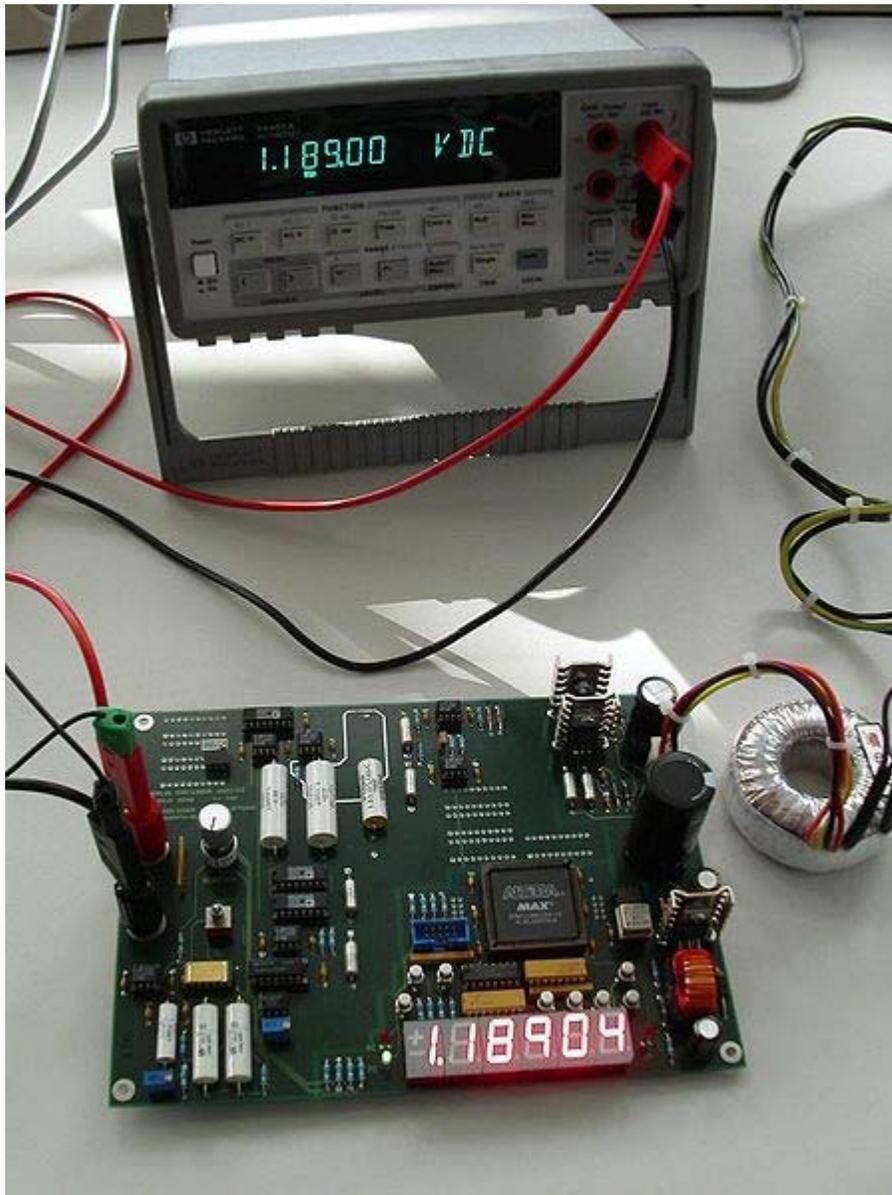


Agilent commercial digital voltmeter checking a prototype

The following items are used for basic measurement of voltages, currents, and components in the circuit under test.

- Voltmeter (Measures voltage)
- Ohmmeter (Measures resistance)
- Ammeter, e.g. Galvanometer or Milliameter (Measures current)

- Multimeter e.g., VOM (Volt-Ohm-Milliameter) or DMM (Digital Multimeter) (Measures all of the above)

The following are used for stimulus of the circuit under test:

- Power supplies
- Signal generator
- Digital pattern generator
- Pulse generator



Howard piA digital multimeter

The following analyze the response of the circuit under test:

- Oscilloscope (Measures all of the above as they change over time)
- Frequency counter (Measures frequency)

And connecting it all together:

- Test probes

## Advanced or less commonly used equipment

### Meters

- Solenoid voltmeter (*Wiggy*)
- Clamp meter (current transducer)
- Wheatstone bridge (Precisely measures resistance)
- Capacitance meter (Measures capacitance)
- LCR meter (Measures inductance, capacitance, resistance and combinations thereof)
- EMF Meter (Measures Electric and Magnetic Fields)
- Electrometer (Measures charge)

## Probes



A multimeter with a built in clampfacility. Pushing the large button at the bottom opens the lower jaw of the clamp, allowing the clamp to be placed around a conductor (wire).

- RF probe
- Signal tracer

## Analyzers

- Logic analyzer (Tests digital circuits)

- Spectrum analyzer (SA) (Measures spectral energy of signals)
- Protocol analyzer (Tests functionality, performance and conformance of protocols)
- Vector signal analyzer (VSA) (Like the SA but it can also perform many more useful digital demodulation functions)
- Time-domain reflectometer (Tests integrity of long cables)
- Semiconductor curve tracer

## Signal-generating devices



Leader Instruments LSG-15 signal generator.

- Signal generator
- Frequency synthesiser
- Function generator
- Digital pattern generator
- Pulse generator
- Signal injector

## Miscellaneous devices

- Continuity tester
- Cable tester
- Hipot tester
- Network analyzer (used to characterize components or complete computer networks)

- Test light
- Transistor tester
- Tube tester
- Electrical tester pen
- Receptacle tester

## *Test Equipment Platforms*



Keithley Instruments Series 4200 CVU

Several modular electronic instrumentation platforms are currently in common use for configuring automated electronic test and measurement systems. These systems are widely employed for incoming inspection, quality assurance, and production testing of electronic devices and subassemblies. Industry-standard communication interfaces link signal sources with measurement instruments in "rack-and-stack" or chassis-/mainframe-based systems, often under the control of a custom software application running on an external PC.

### GPIB/IEEE-488

The General Purpose Interface Bus (GPIB) is an IEEE-488 (a standard created by the Institute of Electrical and Electronics Engineers) standard parallel interface used for attaching sensors and programmable instruments to a computer. GPIB is a digital 8-bit parallel communications interface capable of achieving data transfers of more than 8 Mbytes/s. It allows daisy-chaining up to 14 instruments to a system controller using a 24-pin connector. It is one of the most common I/O interfaces present in instruments and is designed specifically for instrument control applications. The IEEE-488 specifications standardized this bus and defined its electrical, mechanical, and functional specifications, while also defining its basic software communication rules. GPIB works best for applications in industrial settings that require a rugged connection for instrument control.

The original GPIB standard was developed in the late 1960s by Hewlett-Packard to connect and control the programmable instruments the company manufactured. The introduction of digital controllers and programmable test equipment created a need for a

standard, high-speed interface for communication between instruments and controllers from various vendors. In 1975, the IEEE published ANSI/IEEE Standard 488-1975, IEEE Standard Digital Interface for Programmable Instrumentation, which contained the electrical, mechanical, and functional specifications of an interfacing system. This standard was subsequently revised in 1978 (IEEE-488.1) and 1990 (IEEE-488.2). The IEEE 488.2 specification includes the Standard Commands for Programmable Instrumentation (SCPI), which define specific commands that each instrument class must obey. SCPI ensures compatibility and configurability among these instruments.

The IEEE-488 bus has long been popular because it is simple to use and takes advantage of a large selection of programmable instruments and stimuli. Large systems, however, have the following limitations:

- **Driver fanout** capacity limits the system to 14 devices plus a controller.
- **Cable length** limits the controller-device distance to two meters per device or 20 meters total, whichever is less. This imposes transmission problems on systems spread out in a room or on systems that require remote measurements.
- **Primary addresses** limit the system to 30 devices with primary addresses. Modern instruments rarely use secondary addresses so this puts a 30-device limit on system size.

## LAN eXtensions for Instrumentation (LXI)

The LXI Standard defines the communication protocols for instrumentation and data acquisition systems using Ethernet. These systems are based on small, modular instruments, using low-cost, open-standard LAN (Ethernet). LXI-compliant instruments offer the size and integration advantages of modular instruments without the cost and form factor constraints of card-cage architectures. Through the use of Ethernet communications, the LXI Standard allows for flexible packaging, high-speed I/O, and standardized use of LAN connectivity in a broad range of commercial, industrial, aerospace, and military applications. Every LXI-compliant instrument includes an Interchangeable Virtual Instrument (IVI) driver to simplify communication with non-LXI instruments, so LXI-compliant devices can communicate with devices that are not themselves LXI compliant (i.e., instruments that employ GPIB, VXI, PXI, etc.). This simplifies building and operating hybrid configurations of instruments.

LXI instruments sometimes employ scripting using embedded test script processors for configuring test and measurement applications. Script-based instruments provide architectural flexibility, improved performance, and lower cost for many applications. Scripting enhances the benefits of LXI instruments, and LXI offers features that both enable and enhance scripting. Although the current LXI standards for instrumentation do not require that instruments be programmable or implement scripting, several features in the LXI specification anticipate programmable instruments and provide useful functionality that enhances scripting's capabilities on LXI-compliant instruments.

### VME eXtensions for Instrumentation (VXI)

The VXI bus architecture is an open standard platform for automated test based on the VMEbus. Introduced in 1987, VXI uses all Eurocard form factors and adds trigger lines, a local bus, and other functions suited for measurement applications. VXI systems are based on a mainframe or chassis with up to 13 slots into which various VXI instrument modules can be installed. The chassis also provides all the power supply and cooling requirements for the chassis and the instruments it contains. VXI bus modules are typically 6U in height.

### PCI eXtensions for Instrumentation (PXI)

PXI is a peripheral bus specialized for data acquisition and real-time control systems. Introduced in 1997, PXI uses the CompactPCI 3U and 6U form factors and adds trigger lines, a local bus, and other functions suited for measurement applications. PXI hardware and software specifications are developed and maintained by the PXI Systems Alliance. More than 50 manufacturers around the world produce PXI hardware.

### Universal Serial Bus (USB)

The USB connects peripheral devices, such as keyboards and mice, to PCs. The USB is a Plug and Play bus that can handle up to 127 devices on one port, and has a theoretical maximum throughput of 480 Mb/s (high-speed USB defined by the USB 2.0 specification). Because USB ports are standard features of PCs, they are a natural evolution of conventional serial port technology. However, it is not widely used in building industrial test and measurement systems for a number of reasons; for example, USB cables are not industrial grade, are noise sensitive, can accidentally become detached, and the maximum distance between the controller and the device is 30 m. Like RS-232, USB is useful for applications in a laboratory setting that do not require a rugged bus connection.

### RS-232

RS-232 is a specification for serial communication that is popular in analytical and scientific instruments, as well for controlling peripherals such as printers. Unlike GPIB, with the RS-232 interface, it is possible to connect and control only one device at a time. RS-232 is also a relatively slow interface with typical data rates of less than 20 kbytes/s. RS-232 is best suited for laboratory applications compatible with a slower, less rugged connection.

### Test Script Processors and a Channel Expansion Bus

One of the most recently developed test system platforms employs instrumentation equipped with onboard test script processors combined with a high-speed bus. In this approach, one "master" instrument runs a test script (a small program) that controls the

operation of the various "slave" instruments in the test system, to which it is linked via a high-speed LAN-based trigger synchronization and inter-unit communication bus. Scripting is writing programs in a scripting language to coordinate a sequence of actions.

This approach is optimized for small message transfers that are characteristic of test and measurement applications. With very little network overhead and a 100Mbit/sec data rate, it is significantly faster than GPIB and 100BaseT Ethernet in real applications.

The advantage of this platform is that all connected instruments behave as one tightly integrated multi-channel system, so users can scale their test system to fit their required channel counts cost-effectively. A system configured on this type of platform can stand alone as a complete measurement and automation solution, with the master unit controlling sourcing, measuring, pass/fail decisions, test sequence flow control, binning, and the component handler or prober. Support for dedicated trigger lines means that synchronous operations between multiple instruments equipped with onboard Test Script Processors that are linked by this high speed bus can be achieved without the need for additional trigger connections.

# Chapter 9

# Electric Field Screening

**Screening** is the damping of electric fields caused by the presence of mobile charge carriers. It is an important part of the behavior of charge-carrying fluids, such as ionized gases (classical plasmas) and conduction electrons in semiconductors and metals. In a fluid composed of electrically charged constituent particles, each pair of particles interact through the Coulomb force,

$$\mathbf{F} = \frac{q_1 q_2}{4\pi\epsilon_0 \left|\mathbf{r}\right|^2}\hat{\mathbf{r}}$$
.

This interaction complicates the theoretical treatment of the fluid. For example, a naive quantum mechanical calculation of the ground-state energy density yields infinity, which is unreasonable. The difficulty lies in the fact that even though the Coulomb force diminishes with distance as $1/r^2$, the average number of particles at each distance $r$ is proportional to $r^2$, assuming the fluid is fairly isotropic. As a result, a charge fluctuation at any one point has non-negligible effects at large distances.

In reality, these long-range effects are suppressed by the flow of the fluid particles in response to electric fields. This flow reduces the *effective* interaction between particles to a short-range "screened" Coulomb interaction.

For example, consider a fluid composed of electrons. Each electron possesses an electric field which repels other electrons. As a result, it is surrounded by a region in which the density of electrons is lower than usual. This region can be treated as a positively-charged "screening hole". Viewed from a large distance, this screening hole has the effect of an overlaid positive charge which cancels the electric field produced by the electron. Only at short distances, inside the hole region, can the electron's field be detected.

## *Electrostatic screening*

The first theoretical treatment of screening, due to Debye and Hückel (1923), dealt with a stationary point charge embedded in a fluid. This is known as **electrostatic screening**.

Consider a fluid of electrons in a background of heavy, positively-charged ions. For simplicity, we ignore the motion and spatial distribution of the ions, approximating them as a uniform background charge. This is permissible since the electrons are lighter and more mobile than the ions, provided we consider distances much larger than the ionic separation. In condensed matter physics, this model is referred to as jellium.

Let $\rho$ denote the number density of electrons, and $\varphi$ the electric potential. At first, the electrons are evenly distributed so that there is zero net charge at every point. Therefore, $\varphi$ is initially a constant as well.

We now introduce a fixed point charge $Q$ at the origin. The associated charge density is $Q\delta(r)$, where $\delta(r)$ is the Dirac delta function. After the system has returned to equilibrium, let the change in the electron density and electric potential be $\Delta\rho(r)$ and $\Delta\varphi(r)$ respectively. The charge density and electric potential are related by the first of Maxwell's equations, which gives

$$-\nabla^2[\Delta\phi(r)] = \frac{1}{\epsilon_0}[Q\delta(r) - e\Delta\rho(r)]$$

.

To proceed, we must find a second independent equation relating $\Delta\rho$ and $\Delta\varphi$. We consider two possible approximations, under which the two quantities are proportional: the Debye-Hückel approximation, valid at high temperatures, and the Fermi-Thomas approximation, valid at low temperatures.

## Debye-Hückel approximation

In the Debye-Hückel approximation, we maintain the system in thermodynamic equilibrium, at a temperature $T$ high enough that the fluid particles obey Maxwell-Boltzmann statistics. At each point in space, the density of electrons with energy $j$ has the form

$$\rho_j(r) = \rho_j^{(0)}(r) \, \exp\left[\frac{e\phi(r)}{k_B T}\right]$$

where $k_B$ is Boltzmann's constant. Perturbing in $\varphi$ and expanding the exponential to first order, we obtain

$$e\Delta\rho \simeq \epsilon_0 k_0^2 \Delta\phi$$

where

$$k_0 \overset{\text{def}}{=} \sqrt{\frac{\rho e^2}{\epsilon_0 k_B T}}$$

The associated length $\lambda_D \equiv 1/k_0$ is called the Debye length. The Debye length is the fundamental length scale of a classical plasma.

## Fermi-Thomas approximation

In the Fermi-Thomas approximation, we maintain the system at a constant chemical potential and at low temperatures. (The former condition corresponds, in a real experiment, to keeping the fluid in electrical contact at a fixed potential difference with ground.) The chemical potential $\mu$ is, by definition, the energy of adding an extra electron to the fluid. This energy may be decomposed into a kinetic energy $T$ and the potential energy $-e\varphi$. Since the chemical potential is kept constant,

$$\Delta\mu = \Delta T - e\Delta\varphi = 0.$$

If the temperature is extremely low, the behavior of the electrons comes close to the quantum mechanical model of a free electron gas. We thus approximate $T$ by the kinetic energy of an additional electron in the free electron gas, which is simply the Fermi energy $E_F$. The Fermi energy is related to the density of electrons (including spin degeneracy) by

$$\rho = 2\frac{1}{(2\pi)^3}\frac{4}{3}\pi k_F^3 \quad , \quad E_F = \frac{\hbar^2 k_F^2}{2m} \quad , \quad \rho \propto E_F^{3/2}.$$

Perturbing to first order, we find that

$$\Delta\rho \simeq \frac{3\rho}{2E_F}\Delta E_F.$$

Inserting this into the above equation for $\Delta\mu$ yields

$$e\Delta\rho \simeq \epsilon_0 k_0^2 \Delta\phi$$

where

$$k_0 \overset{\text{def}}{=} \sqrt{\frac{3e^2\rho}{2\epsilon_0 E_F}} = \sqrt{\frac{me^2 k_f}{\epsilon_0 \pi^2 \hbar^2}}$$

is called the Fermi-Thomas screening wave vector.

This follows from a previous result for the free electron gas, which is a model of non-interacting electrons, whereas the fluid which we are studying contains a Coulomb interaction. Therefore, the Fermi-Thomas approximation is only valid when the electron density is high, so that the particle interactions are relatively weak.

## Screened Coulomb interactions

Our results from the Debye-Hückel or Fermi-Thomas approximation may now be inserted into the first Maxwell equation. The result is

$$\left[\nabla^2 - k_0^2\right]\phi(r) = -\frac{Q}{\epsilon_0}\delta(r)$$

which is known as the screened Poisson equation. The solution is

$$\phi(r) = \frac{Q}{4\pi\epsilon_0 r}e^{-k_0 r}$$

which is called a screened Coulomb potential. It is a Coulomb potential multiplied by an exponential damping term, with the strength of the damping factor given by the magnitude of $k_0$, the Debye or Fermi-Thomas wave vector. Note that this potential has the same form as the Yukawa potential. This screening yields a dielectric function $\epsilon(r) = e^{k_0 r}$.

## Quantum-mechanical screening

In real metals, electrical screening is more complex than described above in the Fermi-Thomas theory. This is because Fermi-Thomas theory assumes that the mobile charges (electrons) can respond at any wave-vector. However, it is not energetically possible for an electron within or on a Fermi surface to respond at wave-vectors shorter than the Fermi wave-vector. This is related to the Gibbs phenomenon, where fourier series for functions that vary rapidly in space are not good approximations unless a very large number of terms in the series are retained. In physics this is known as Friedel oscillations, and applies both to surface and bulk screening. In each case the net electric field does not fall off exponentially in space, but rather as an inverse power law multiplied by an oscillatory term. The area of many-body physics devotes considerable effort to quantum-mechanical screening, which is very relevant to condensed matter physics.

# Chapter 10

# Electromagnetic Shielding
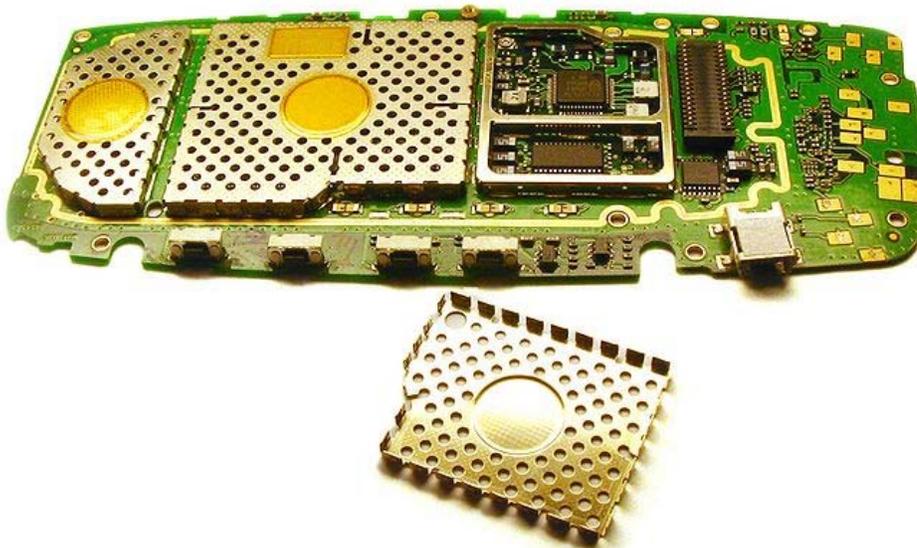
Electromagnetic shielding cages inside a disassembled mobile phone.

**Electromagnetic shielding** is the process of reducing the electromagnetic field in a space by blocking the field with barriers made of conductive and/or magnetic materials. Shielding is typically applied (1) to enclosures to isolate electrical devices from the 'outside world' and (2) to cables to isolate wires from the environment through which the cable runs. Electromagnetic shielding that blocks radio frequency electromagnetic radiation is also known as **RF shielding**.

The shielding can reduce the coupling of radio waves, electromagnetic fields and electrostatic fields, though not static or low-frequency magnetic fields (a conductive enclosure used to block electrostatic fields is also known as a Faraday cage). The amount of reduction depends very much upon the material used, its thickness, the size of the shielded volume and the frequency of the fields of interest and the size, shape and orientation of apertures in a shield to an incident electromagnetic field.

## Materials used

Typical materials used for electromagnetic shielding include sheet metal, metal screen, and metal foam. Any holes in the shield or mesh must be significantly smaller than the wavelength of the radiation that is being kept out, or the enclosure will not effectively approximate an unbroken conducting surface.

Another commonly used shielding method, especially with electronic goods housed in plastic enclosures, is to coat the inside of the enclosure with a metallic ink or similar material. The ink consists of a carrier material loaded with a suitable metal, typically copper or nickel, in the form of very small particulates. It is sprayed on to the enclosure and, once dry, produces a continuous conductive layer of metal, which can be electrically connected to the chassis ground of the equipment, thus providing effective shielding.

## Example applications
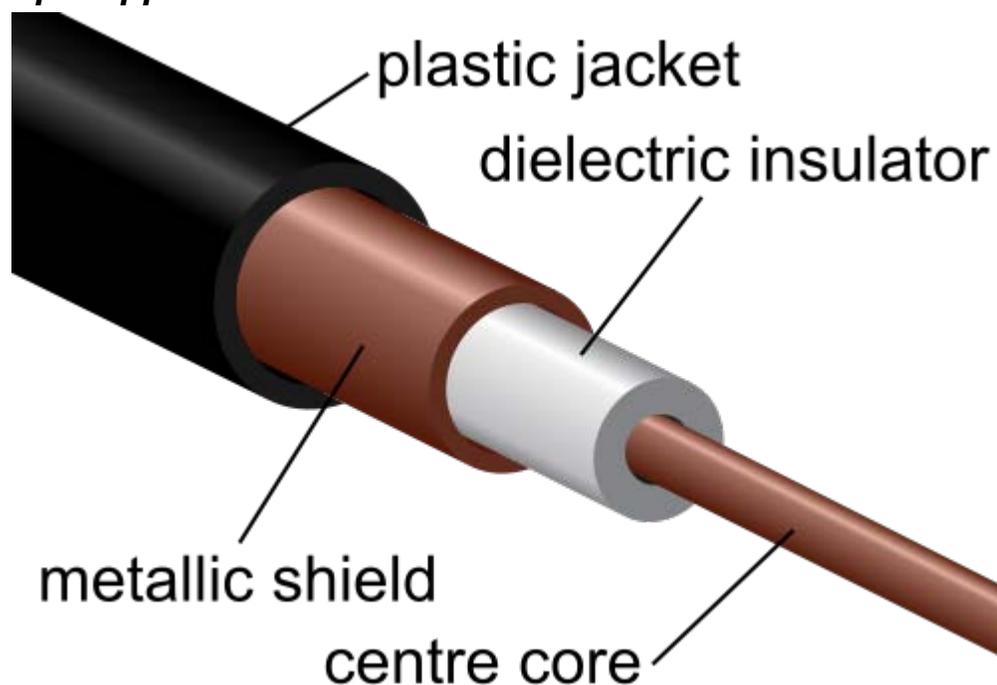


Cross-section through a coaxial cable showing shielding and other layers

One example is a shielded cable, which has electromagnetic shielding in the form of a wire mesh surrounding an inner core conductor. The shielding impedes the escape of any

signal from the core conductor, and also signals from being added to the core conductor. Some cables have two separate coaxial screens, one connected at both ends, the other at one end only, to maximize shielding of both electromagnetic and electrostatic fields.

The door of a microwave oven has a screen built into the window. From the perspective of microwaves (with wavelengths of 12 cm) this screen finishes a Faraday cage formed by the oven's metal housing. Visible light, with wavelengths ranging between 400 nm and 700 nm, passes easily between the wires.

RF shielding is also used to prevent access to data stored on RFID chips embedded in various devices, such as biometric passports.

NATO specifies electromagnetic shielding for computers and keyboards to prevent passive monitoring of keyboard emissions that would allow passwords to be captured; consumer keyboards do not offer this protection primarily because of the prohibitive cost.

RF shielding is also used to protect medical and laboratory equipment to provide protection against interfering signals, including AM, FM, TV, emergency services, dispatch, pagers, ESMR, cellular, and PCS. It can also be used to protect the equipment at the AM, FM or TV broadcast facilities.

## How electromagnetic shielding works

Electromagnetic radiation consists of coupled electric and magnetic fields. The electric field produces forces on the charge carriers (i.e., electrons) within the conductor. As soon as an electric field is applied to the surface of an ideal conductor, it induces a current that causes displacement of charge inside the conductor that cancels the applied field inside, at which point the current stops.

Similarly, *varying* magnetic fields generate eddy currents that act to cancel the applied magnetic field. (The conductor does not respond to static magnetic fields unless the conductor is moving relative to the magnetic field.) The result is that electromagnetic radiation is reflected from the surface of the conductor: internal fields stay inside, and external fields stay outside.

Several factors serve to limit the shielding capability of real RF shields. One is that, due to the electrical resistance of the conductor, the excited field does not completely cancel the incident field. Also, most conductors exhibit a ferromagnetic response to low-frequency magnetic fields, so that such fields are not fully attenuated by the conductor. Any holes in the shield force current to flow around them, so that fields passing through the holes do not excite opposing electromagnetic fields. These effects reduce the field-reflecting capability of the shield.

In the case of high-frequency electromagnetic radiation, the above-mentioned adjustments take a non-negligible amount of time. But then the radiation energy, as far as it is not reflected, is absorbed by the skin (unless it is extremely thin), so in this case there

is no electromagnetic field inside either. This is called the skin effect. A measure for the depth to which radiation can penetrate the shield is the so-called skin depth.

## *Magnetic shielding*

Equipment sometimes requires isolation from external magnetic fields. For static or slowly varying magnetic fields (below about 100 kHz) the Faraday shielding described above is ineffective. There exists a limited possibility of passively isolating a volume magnetically by using shields made of high magnetic permeability metal alloys such as large crystalline grain structure foils or sheet metals of Permalloy and Mu-metal, or with nanocrystalline grain structure ferromagnetic metal coatings. These materials don't block the magnetic field, as with electric shielding, but rather draw the field into themselves, providing a path for the magnetic field lines around the shielded volume. The best shape for magnetic shields is thus a closed container. The effectiveness of this type of shielding decreases with the material's permeability, which generally drops off at both very low magnetic field strengths, and also at high field strengths where the material becomes saturated. So to achieve low residual fields, magnetic shields often consist of several enclosures one inside the other, each of which successively reduces the field inside it.

Because of the above limitations of passive shielding, an alternative used with static fields is active shielding; using a field created by another magnet to cancel out the ambient field within a volume. Solenoids designed to do this are called Helmholtz coils.

# Chapter 11

# Immunity Aware Programming

When writing firmware for an embedded system, **immunity aware programming** is a set of programming techniques used in an attempt to tolerate transient errors in the program counter or other modules of a program that would otherwise lead to failure. Immunity aware programming is an example for defensive programming and also for EMC Aware Programming.

Such transient errors in a "victim" device may be caused by single event upsets, insufficient power, or by strong electromagnetic signals transmitted by some other "source" device.

Most of these techniques apply to the software in the "victim" device to make it more reliable. A few of these techniques apply to software in the "source" device to make it emit less unwanted noise.

## *Task and objectives*

Microcontrollers' firmware can inexpensively improve the electromagnetic compatibility of an embedded system.

Embedded systems firmware is usually not considered to be a source of radio frequency interference. Radio emissions are often caused by harmonic frequencies of the system clock and switching currents. The pulses on these wires can have fast rise and fall times, causing their wires to act as radio transmitters. This effect is increased by badly designed printed circuit boards. These effects are reduced by using microcontroller output drivers with slower rise times, or by turning off system components.

The microcontroller is easy to control. It is also susceptible to faults from radio frequency interference. Therefore, making the microcontroller's software resist such errors can cheaply improve the system's tolerance for electromagnetic interference, by reducing the need for hardware alterations.

## *Possible Interferences of microcontroller-based systems*

CMOS microcontrollers have specific weak spots which can be strengthened by software that works against electromagnetic interference. Failure modes and effects analysis of a system and its requirements is often required. Electromagnetic compatibility issues can easily be added to such an analysis.

## The Power Supply

Slow changes of power supply voltage do not cause significant disturbances but rapid changes can make unpredictable trouble. If a voltage exceeds parameters in the controller's data sheet by 150 percent it can cause the input port or the output port to get hung in one state, also known as CMOS latch-up . Without internal current control, latch-up causes the microcontroller to burn out. The standard solution is a mix of software and hardware changes. Most embedded systems have a software watchdog. This watchdog should be external to the microcontroller, and immune to any plausible electromagnetic interference. It should reset the power supply, briefly switching it off. The watchdog period should be half or less of the time and power required to burn out the microcontroller. The power supply design should also be well-grounded and decoupled using capacitors and inductors close to the microcontroller; some typical values are 100uF and 0.1uF in parallel.

Low power can cause serious malfunctions in most microcontrollers. For the CPU to successfully decode and execute instructions, the supplied voltage must not drop below the minimum voltage level. When the supplied voltage drops below this level, the CPU may start to execute some instructions incorrectly. The result is unexpected activity on the internal data and control lines. This activity may cause:

- CPU register corruption
- I/O register corruption
- I/O pin random toggling
- SRAM corruption
- EEPROM corruption

Brownout detection solves most of those problems in most systems by causing the system to shut down when mains power is unreliable. One typical system retriggers a timer each time that the AC mains voltage exceeds 90% of its rated voltage. If the timer expires, it interrupts the microcontroller, which then shuts down its system. Also, many systems measure the power supply voltages, to guard against slow power supply degradation.

## The oscillator

The input ports of CMOS oscillators have high impedances and are thus very susceptible to transient disturbances. According to Ohm's law, high impedance causes high voltage differences. They also are very sensitive to short circuits, from moisture or dust.

One typical failure is when the oscillators' stability is affected. This can cause it to stop, or change its period. The normal system hedges are to have an auxiliary oscillator using some cheap, robust scheme such as a ring of inverters or a resistor-capacitor one-shot timer. After a reset (perhaps caused by a software watchdog), the system may default to these, only switching in the sensitive crystal oscillator once timing measurements have proven it to be stable. It's also common in high-reliability systems to measure the clock frequency by comparing it to an external standard, usually a communications clock, the power line, or a resistor-capacitor timer.

Bursts of electromagnetic interference can shorten clock periods or cause runt pulses that lead to incorrect data access or command execution. The result is wrong memory content or program pointers. The standard method of overcoming this in hardware is to use an on-chip phase locked loop to generate the microcontroller's actual clock signal. Software can periodically verify data structures, and read critical ports using voting, distributing the reads in time or space.

## The I/O-ports

Input/Output ports—including address lines and data lines—connected by long lines or external peripherals are the antennae that permit disturbances to have effects. Electromagnetic interference can lead to incorrect data and addresses on these lines. Strong fluctuations can cause the computer to misread I/O registers or even stop communication with these ports. Electrostatic discharge can actually destroy ports or cause malfunctions.

Most microcontrollers' pins are high impedance inputs or mixed inputs and outputs. High impedance input pins are sensitive to noise and can register false levels if not properly terminated. Pins that are not terminated insode an IC need resistors attached. These have to be connected to ground or supply ensuring a known logic state.
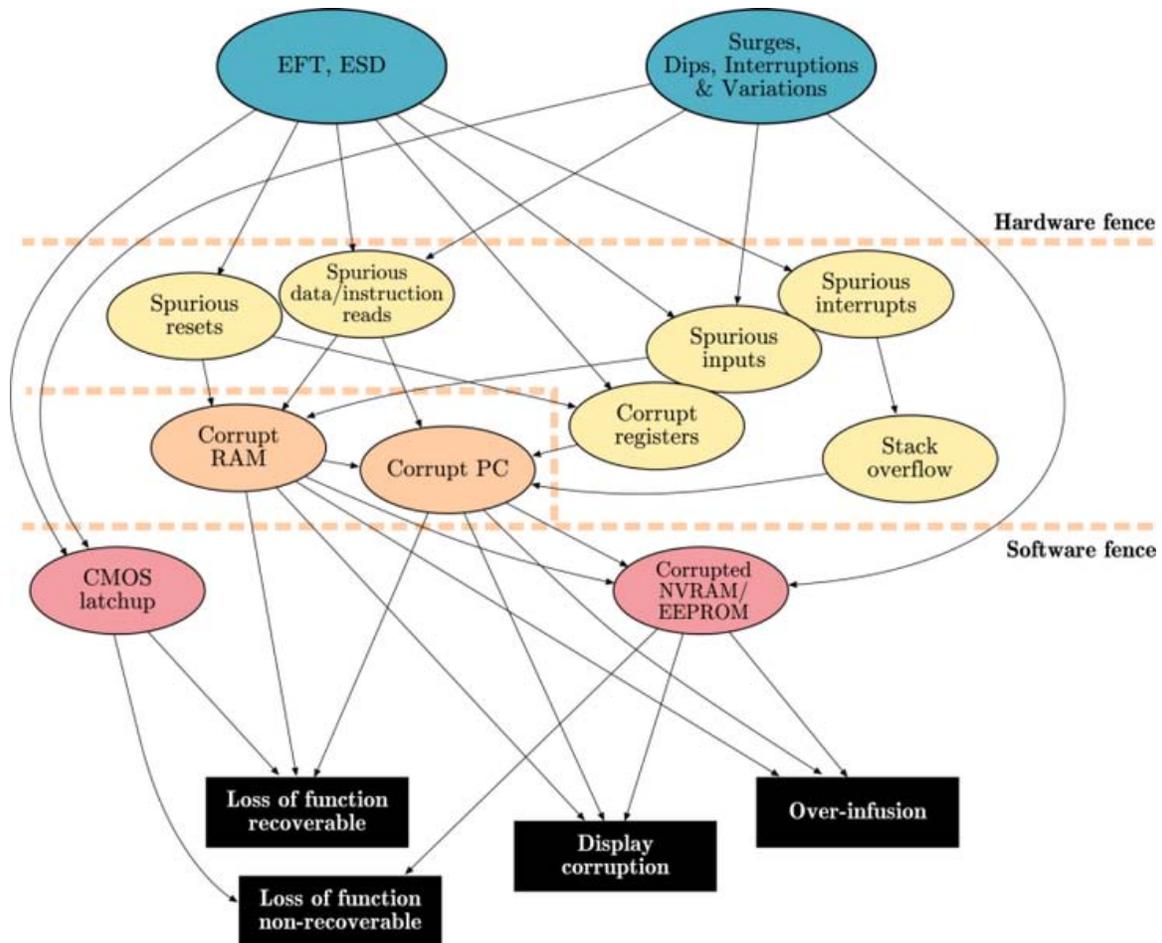
Cause and effect figure. The cause must be determined, so the problem can be fixed.

## *Corrective actions*

An analysis of possible errors before correction is very important. The cause must be determined so that the problem can be fixed.

The Motor Industry Software Reliability Association identifies the required steps in case of an error as follows:

- Information/warning the user
- Store the faulty data until a defined reset can be carried out
- Keep the system in a defined state until the error can be corrected

### Instruction Pointer (IP) Error Management

A disturbed instruction pointer can lead to serious errors, such as an undefined jump to an arbitrary point in the memory where illegal instructions are read. The state of the system will be undefined. IP errors can be handled by use of software based solutions such as function tokens and an NOP slide(s).

Many processors, such as the Motorola 680x0, feature a hardware trap upon encountering an illegal instruction. A correct instruction, defined in the trap vector, is executed, rather than the random one. Traps can handle a larger range errors than function tokens and NOP slides. Supplementary to illegal instructions hardware traps securely handle memory access violations, overflows, or a division by zero.

## Token Passing (Function Token)
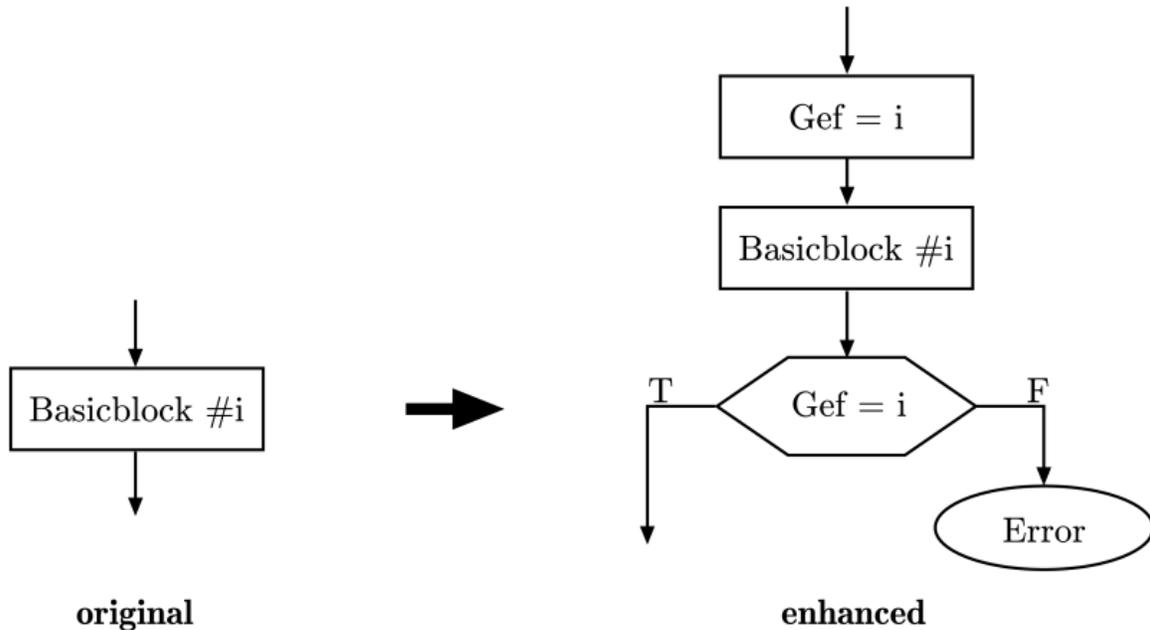


Token Passing as Execution Flow Control

```c
/*****************************************
// Token Passing with global function ID
*****************************************/
char gFunctionId = 0;
void FunktionA(void);

void main(){
    gFunctionId = 'A';
    FunktionA();
    if(gFunctionId != 'M') Print("Invalid IP");
}

void FunktionA(void){
    if(gFunctionId != 'A') Print("Invalid IP");
    DoSomething();
    gFunctionId = 'M';
}
```

C Source: Token Passing with Global Function ID.

Improved noise immunity can be achieved by execution flow control known as token passing. The figure to the right shows the functional principle schematically. This method deals with program flow errors caused by the instruction pointers.

The implementation is simple and efficient. Every function is tagged with a unique function ID. When the function is called the function ID is saved in a global variable. The function is only executed if the function ID in the global variable and the ID of the function match. If the IDs do not match an instruction pointer error has occurred and specific corrective actions can be taken. A sample implementation of token passing using a global variable programmed in C is stated in the following source listing.

The implementation of function tokens increases the program code size by 10 to 20% and slows down the performance. To improve the implementation, instead of global variables like above, the function ID can be passed as an argument within the functions header as shown in the code sample below.

```
1   /*****************************************
2   // Token Passing with function parameters
3   /*****************************************/
4   #define FUNCTION_MAIN 'm'
5   #define FUNCTION_A    'a'
6   #define FUNCTION_B    'b'
7   #define ERROR         -1
8
9   char FunctionA(char caller, char callee);
10  char FunctionB(char caller, char callee);
11
12  int main(){
13      // call of FunctionA and check for correct return of call
14      if(FunctionA(FUNCTION_MAIN, FUNCTION_A)!=FUNCTION_MAIN)
15          Print("ERROR: Invalid Function Call"); return ERROR;
16
17      return 0:
18  }
19
20  char FunctionA(char caller, char callee){
21      // check for intended call of FunctionA
22      if(callee != FUNCTION_A)
23          Print("ERROR: Invalid Function Call"); return ERROR;
24      // call of FunctionB and check for correct return of call
25      if(FunctionB(FUNCTION_A, FUNCTION_B)!=FUNCTION_A)
26          Print("ERROR: Invalid Function Call"); return ERROR;
27
28      return caller;
29  }
30
31  char FunctionB(char caller, char callee){
32      // check for intended call of FunctionB
33      if(callee != FUNCTION_B)
34          Print("ERROR: Invalid Function Call"); return ERROR;
35      // the call was correct, data can be processed
36      .
37      .
38      .
39      process something...
40      .
41      .
42
43      return caller;
44  }
```

C Source: Token Passing with Function Parameters.

## NOP slide

With NOP-Fills the reliability of a system in case of a disturbed instruction pointer can be improved in some cases. The entire program memory that is not used by the program code is filled with No-Operation (NOP) instructions. In machine code a NOP instruction is often represented by 0x00 (e.g. Intel 8051, ATMega16 etc.). The system is kept in a defined state. At the end of the physical program memory an instruction pointer error handling (IPEH IP-Error-Handler) has to be implemented. In some cases this can be a simple reset.

If an instruction pointer error occurs during the execution and a program points to a memory segment filled with NOP instructions inevitably an error occurred and is recognized.

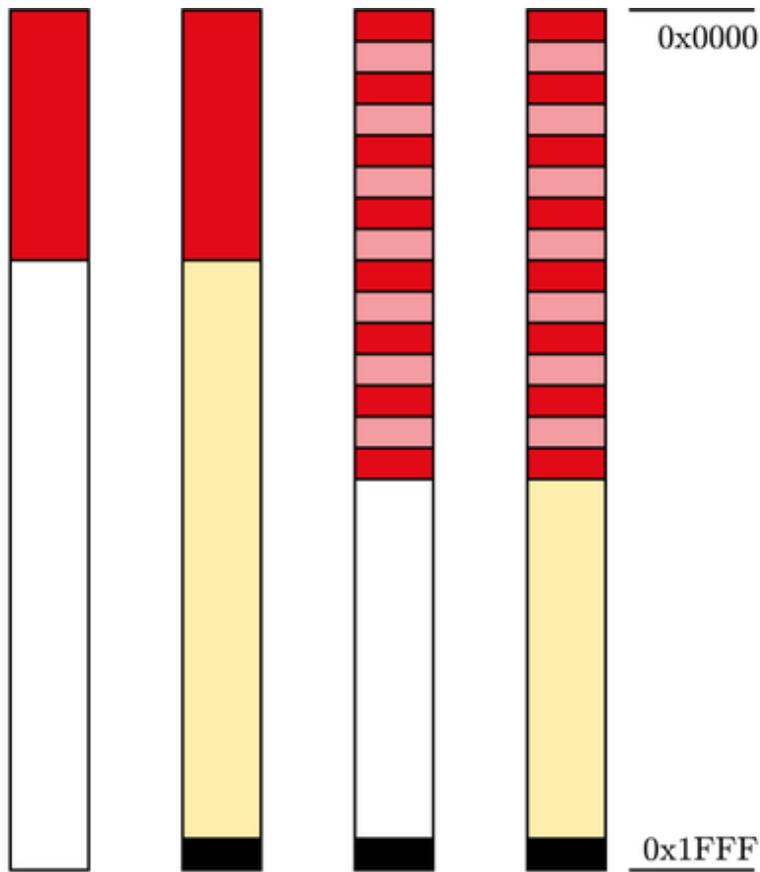Two methods of implementing NOP-Fills are applicable.

- In the first method the unused physical memory is set to 0x00 manually by search and replace in the (HEX) program file. The drawback of this method is that this has to be done after every compilation.



| Programm code | NOP Fill region | IPEH |
| --- | --- | --- |

0x0000          0x0700          0x0F00    0x0FFF
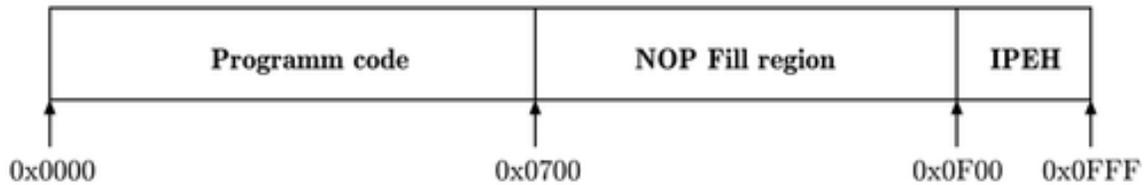
Program Memory Filled with Code, NOPs and Error Handler.

- The second method is to include a corresponding number of NOP assembler directives directly in the program code.

When using the CodevisionAVR C compiler, NOP fills can be implemented easily. The chip-programmer offers the feature to edit the program flash and eeprom to fill it with a specific value. Using an Atmel ATMega16 no jump to reset address 0x00 needs to be implemented as the overflow of the instruction pointer automatically sets its value to 0x00. Unfortunately resets due to overflow are not equivalent to intentional reset. During the intended reset all necessary MC registers are reset by hardware which is not done by a jump to 0x00. So this method will not be applied in the following tests.

Memory before and after the implementation of both Function Token and NOP-Fills.

## I/O Register Errors

Microcontroller architecture requires the I/O leads to be placed at the outer edge of the silicon die. Thus I/O contacts are affected strongly by transient disturbances on their way to the silicon core and I/O registers are one of the most vulnerable parts of the microcontroller. Wrongly read I/O registers may lead to incorrect system state. Most serious errors can occur at the reset port and interrupt input ports. Disturbed data direction registers (DDR) may inhibit writing to the bus. These disturbances can be prevented as following:

**1. Cyclic update of the most important registers**

By cyclically updating of the most important register and the data in the data direction registers in shortest possible intervals errors can be reduced. Thus a wrongly set bit can be corrected before it can have negative effects.

**2. Multiple read of input registers**

A further method of filtering disturbances is multiple read of input registers. The read in values are then checked for consistency. If the values are consistent they can be considered valid. A definition of a value range and/or the calculation of a mean value can improve the results for some applications.

**Side Effect**: Increased Activity

A drawback is the increased activity due to permanent updates and read outs of peripherals. This activity may add additional emissions and failures.

**External Interrupt Ports; Stack Overflow**

External interrupts are triggered by falling/rising edges or high/low potential at the interrupt port leading to an interrupt request (IRQ) in the controller. Hardware interrupts are divided into maskable interrupts and non-maskable interrupts (NMI). The triggering of maskable interrupts can be stopped in some time-critical functions. If an interrupt is called the current instruction pointer (IP) is saved on the stack and the stack pointer (SP) is decremented. The address of the interrupt service routine (ISR) is read from the interrupt vector table and loaded to the IP register and the ISR is executed as a consequence.

If interrupts—due to disturbances—are generated faster than processed, the stack grows until all memory is used. Data on the stack or other data might be overwritten. A defensive software strategy can be applied. The stack pointer (SP) can be watched. The growing of the stack beyond a defined address can then be stopped. The value of the stack pointer can be checked at the start of the interrupt service routine. If the SP points to an address outside the defined stack limits a reset can be executed.

## Data Redundancy

In systems without error detection and correction units the reliability of the system can be improved by providing protection through software. Protecting the entire memory (code and data) may not be practical in software as it causes an unacceptable amount of overhead but it is a software implemented low-cost solution for code segments.

Another elementary requirement of digital systems is the faultless transmission of data. Communication with other components can be the weak point and a source of errors of a system. A well thought-out transmission protocol is very important. The techniques described below can also be applied to data transmitted and hence increasing transmission reliability.

## Cyclic Redundancy and Parity Check

A cyclic redundancy check is a type of hash function used to produce a checksum which is a small integer from a large block of data, such as network traffic or computer files. CRCs are calculated before and after transmission or duplication, and compared to confirm that they are equal. A CRC detects all one or two bit errors, all odd errors, all burst errors if the burst is smaller than the CRC, and most of the wide burst errors. Parity Checks can be applied to single characters (VRC—vertical redundancy check) resulting an additional parity bit or to a block of data (LRC—longitudinal redundancy check) issuing a block check character. Both methods can be implemented rather easily by using an XOR operation. A trade off is that less errors can be detected than with the CRC. Parity Checks only detect odd numbers of flipped bits. The even numbers of bit errors stay undetected. A possible improvement is the usage of both, VRC and LRC, called Double Parity or Optimal Rectangular Code (ORC).

Some microcontrollers feature a hardware CRC unit.

## Different Kinds of Duplication

A specific way of data redundancy is the duplication which can be applied in several ways as described in the following:

- **Data Duplication**

  To cope with the corruption of data, multiple copies of important registers and variables can be stored. Consistency checks between memory locations storing the same values, or voting techniques can then be performed when accessing the data.
  Two different modifications to the source code need to be implemented.

  - The first one corresponds to duplicating some or all of the program variables in order to introduce data redundancy and modifying all the operators to manage the introduced replica of the variables.

  - The second modification introduces consistency checks in the control flow so that consistency between the two copies of each variable is verified.

When the data is read out the two sets of data are compared. A disturbance is detected if the two data sets are not equal. An error can be reported. If both sets of data are corrupted a significant error can be reported and the system can react accordingly.

In most cases, safety-critical applications have strict constraints in terms of memory occupation and system performance. The duplication of the whole set of variables and the introduction of a consistency check before every read operation represent the optimum choice from the fault coverage point of view. The duplication of the whole set of variables enables an extremely high percentage of faults to be covered by this software

redundancy technique. On the other side, by duplicating a lower percentage of variables one can trade-off the obtained fault coverage with the CPU time overhead.
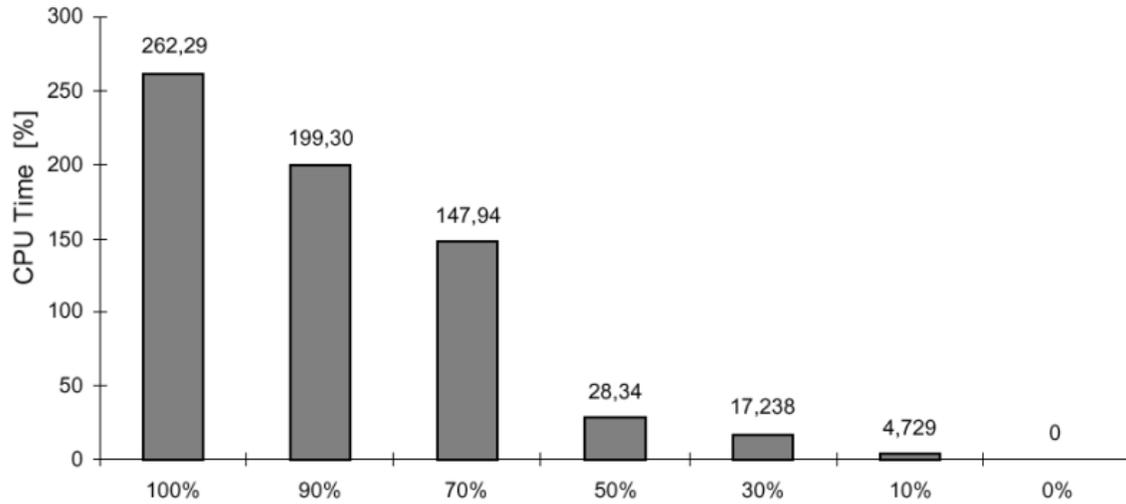


An experimental analysis of CPU time overhead and the amount of duplicated variables.

The experimental result shows that duplicating only 50% of the variables is enough to cover 85% of faults with a CPU time overhead of just 28%.

Attention should also be paid to the implementation of the consistency check as it is usually carried out after each read operation or at the end of each variables life period. Carefully implementing this check can minimize the CPU time and code size for this application.

```
1   /*********************
2   // Original Function
3   /*********************/
4   int a = 0;
5   int result = 0;
6
7   // Function Call
8   result = AddOne(a);
9
10  // Function Implementation
11  int AddOne(int data){
12
13      data = data + 1;
14
15      return data;
16  }
17
18
19  /*************************************************
20  // Improved Function Call with Duplicated Parameters
21  /*************************************************/
22  int a1 = 0;
23  int a2 = 0;
24  int result1 = 0;
25  int result2 = 0;
26
27  // Function Call
28  AddOne(a1, a2, &result1, &result2);
29  // Check for Consistency
30  if(result1 != result2) Error();
31
32  // Improved Function Implementation
33  void AddOne(int data1, int data2, int * result1, int * result2){
34
35      data1 = data1 + 1;
36      data2 = data2 + 1;
37
38      if(data1 != data2) Error();
39
40      *result1 = data1;
41      *result2 = data2;
42  }
```

C Sample Code: Function Parameter Duplication.

```
1   /************************
2   //  Original  Test  Condition
3   /***********************/
4   if(condition){
5       DoSomething();
6   }else{
7       DoSomethingElse();
8   }
9
10  /***********************
11  //  Improved  Test  Condition
12  /**********************/
13  if(condition){
14      if(!condition){
15          Error();
16      }
17      DoSomething();
18  }else{
19      if(condition){
20          Error();
21      }
22      DoSomethingElse();
23  }
```

C Sample Code: Duplication of Test Conditions.

- **Function Parameter Duplication**

As the detection of errors in data is achieved through duplicating all variables and adding consistency checks after every read operation special considerations have to be applied according to the procedure interfaces. Parameters passed to procedures as well as return values are considered to be variables. Hence, every procedure parameter is duplicated as well as the return values. A procedure is still called only once, but it returns two results, which must hold the same value. The source listing to the right shows a sample implementation of function parameter duplication.

- **Test Duplication**

To duplicate a test is one of the most robust methods that exist for generic soft error detection. A drawback is that no strict assumption on the cause of the errors (EMI, ESD etc.), nor on the type of errors to expect (errors affecting the control flow, errors affecting data etc.) can be made. Erroneous bit-changes in data-bytes while stored in memory, cache, register, or transmitted on a bus are known. These data-bytes could be operation codes (instructions), memory addresses, or data. Thus, this method is able to detect a wide range of faults and is not limited to a specific fault model. Using this method, memory increases about 4 times and execution time is about 2.5 times as long as the same program without test duplication. Source listing to the right shows a sample implementation of the duplication of test conditions.

- **Branching Duplication**



original      enhanced
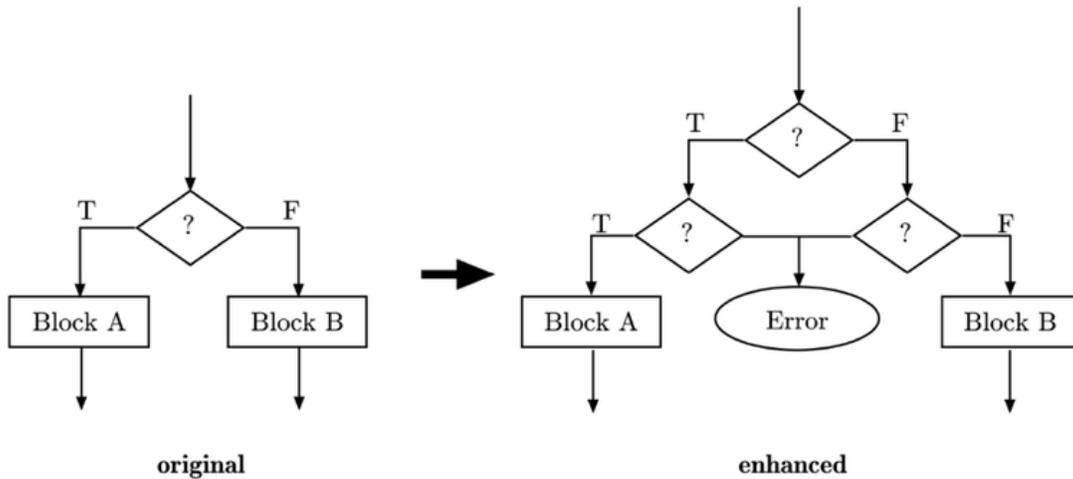
Branch Duplication.

Compared to Test Duplication, where one condition is cross-checked, with branching duplication the condition is duplicated.

For every conditional test in the program the condition and the resulting jump should be reevaluated as shown in the figure. Only if the condition is met again the jump is executed else an error has occurred.

- **Instruction Duplication and Diversity in Implementation**

What is the benefit of when data, tests, and brunches are duplicated when the result is calculated incorrect? One solution is to duplicate an instruction entirely but implement them differently. So two different programs with the same functionality but with different sets of data, and different implementations are executed. Their outputs are compared and must be equal. This methods cover not just bit-flips or processor faults but also programming errors (bugs). If it is intended to especially handle hardware (CPU) faults the software can be implemented using different parts of the hardware, for example one implementation uses a hardware multiply and the other implementation multiplies by shifting or adding. This causes a significant overhead (more than a factor of 2 for the size of the code). On the other hand the results are outstanding accurately.

## Ports

## Reset Ports and Interrupt Ports

Reset ports and interrupts are very important as they can be triggered by rising/falling edges or high/low potential at the interrupt port. Transient disturbances can lead to unwanted resets, or trigger interrupts and thus cause the entire system to crash. For every

triggered interrupt the instruction pointer is saved on the stack and the stack pointer is decremented.

Try to reduce the amount of edge-triggered interrupts. If interrupts can be triggered only with a level, then this helps to ensure that noise on an interrupt pin will not cause an undesired operation. It must be kept in mind that, level-triggered interrupts can lead to repeated interrupts as long as the level stays high. In the implementation, this characteristic must be considered, repeated unwanted interrupts must be disabled in the ISR. If this is not possible, then on immediate entry of an edge-triggered interrupt, a software check on the pin to determine if the level is correct should suffice.

For all unused interrupts an error handling routine has to be implemented to keep the system in a defined state after an unintended interrupt.

Unintentional resets disturb the correct program execution and are not acceptable for extensive applications or safety critical systems.

## Reset differentiation (Cold/Warm start)

A frequent system requirement is the automatic resumption of work after a disturbance/disruption. It can be useful to record the state of a system at shut down and to save the data in a non-volatile memory. At startup the system can evaluate if the system restarts due to disturbance or failure (warm start) and the system status can be restored or an error can be indicated. In case of a cold start the saved data in the memory can be considered valid.

**External Current Consumption Measurement**
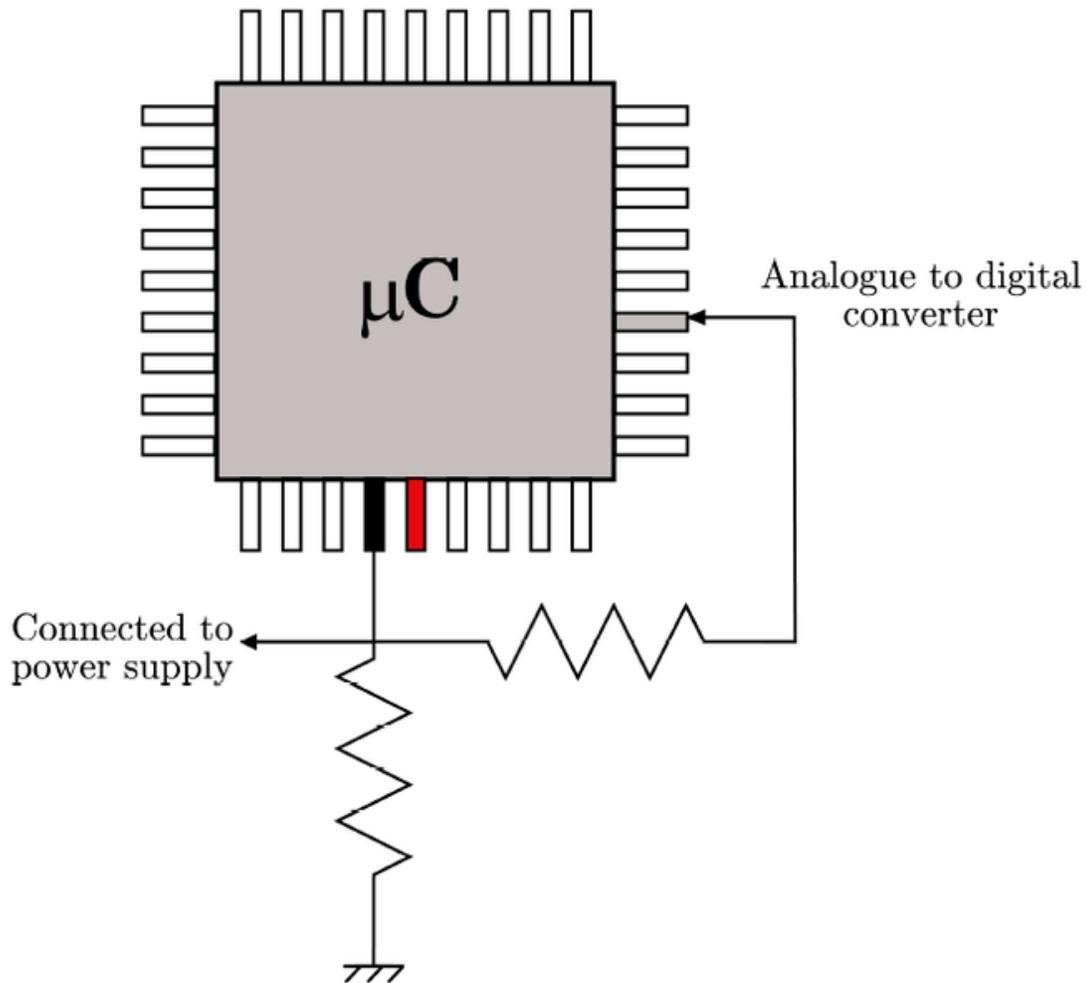


Hard- and Software Combination: Detection of Power Supply Fluctuation using an AD-converter.

This method is a combination of hard- and software implementations. It proposes a simple circuit to detect an electromagnetic interference using the own resources of the device. Most microcontrollers, like the ATMega16, integrate analog to digital converters (ADCs) which could be used to detect unusual power supply fluctuations caused by interferences.

When an interference is detected by the software, the microcontroller could enter a safe state while waiting for the aggression to pass. During this safe state, no critical executions are allowed. The graphic presents how interference detection can be performed. This technique can easily be used with any microcontroller that features an AD-converter.

## Watchdog

Watchdog timers significantly improve the reliability of a microcontroller in electromagnetically influenced environment. They are often integrated on the chip. A watchdog timer is an independent parallel component which detects software errors and hardware errors reliably.

The software informs the watchdog in regular intervals that it is still working properly. If the watchdog is not informed it means that the software does not work as specified anymore. Then the watchdog resets the system to a defined state. During the reset, the device is not able to process data and does not react to calls.

As the strategy to reset the watchdog timer is very important two requirements have to be attended:

- The watchdog may only be reset if all routines work properly.

- The reset must be executed as quickly as possible.

Simple activation of the watchdog and regular resets of the timer do not make optimal use of a watchdog. For best results the refresh cycle of the timer must be set as short as possible and called from the main() function, so a reset can be performed before damage is caused or an error occurred. If a microcontroller does not have an internal watchdog a similar functionality can be implemented by the use of a timer interrupt or an external device.

## Brown-Out

A Brown-Out circuit monitors the VCC level during operation by comparing it to a fixed trigger level. When VCC drops below the trigger level, the Brown-out Reset is immediately activated. When VCC rises again, the MCU is restarted after a certain delay.

# Chapter 12

# Wireless Energy Transfer

**Wireless energy transfer** or **wireless power** is the transmission of electrical energy from a power source to an electrical load without interconnecting wires. Wireless transmission is useful in cases where interconnecting wires are inconvenient, hazardous, or impossible. The problem of wireless power transmission differs from that of wireless telecommunications, such as radio. In the latter, the proportion of energy received becomes critical only if it is too low for the signal to be distinguished from the background noise. With wireless power, efficiency is the more significant parameter. A large part of the energy sent out by the generating plant must arrive at the receiver or receivers to make the system economical.

The most common form of wireless power transmission is carried out using direct induction followed by resonant magnetic induction. Other methods under consideration include electromagnetic radiation in the form of microwaves or lasers.

## *Electric energy transfer*

An electric current flowing through a conductor carries electrical energy. When an electric current passes through a circuit there is an electric field in the dielectric surrounding the conductor; magnetic field lines around the conductor and lines of electric force radially about the conductor.

In a direct current circuit, if the current is continuous, the fields are constant; there is a condition of stress in the space surrounding the conductor, which represents stored electric and magnetic energy, just as a compressed spring or a moving mass represents stored energy. In an alternating current circuit, the fields also alternate; that is, with every half wave of current and of voltage, the magnetic and the electric field start at the conductor and run outwards into space with the velocity of light. Where these alternating fields impinge on another conductor a voltage and a current are induced.

Any change in the electrical conditions of the circuit, whether internal or external involves a readjustment of the stored magnetic and electric field energy of the circuit, that is, a so-called transient. A transient is of the general character of a condenser discharge through an inductive circuit. The phenomenon of the condenser discharge through an

inductive circuit therefore is of the greatest importance to the engineer, as the foremost cause of high-voltage and high-frequency troubles in electric circuits.

Electromagnetic induction is proportional to the intensity of the current and voltage in the conductor which produces the fields and to the frequency. The higher the frequency the more intense the induction effect. Energy is transferred from a conductor that produces the fields (the primary) to any conductor on which the fields impinge (the secondary). Part of the energy of the primary conductor passes inductively across space into secondary conductor and the energy decreases rapidly along the primary conductor. A high frequency current does not pass for long distances along a conductor but rapidly transfers its energy by induction to adjacent conductors. Higher induction resulting from the higher frequency is the explanation of the apparent difference in the propagation of high frequency disturbances from the propagation of the low frequency power of alternating current systems. The higher the frequency the more preponderant become the inductive effects that transfer energy from circuit to circuit across space. The more rapidly the energy decreases and the current dies out along the circuit, the more local is the phenomenon.

The flow of electric energy thus comprises phenomena inside of the conductor and phenomena in the space outside of the conductor—the electric field—which, in a continuous current circuit, is a condition of steady magnetic and dielectric stress, and in an alternating current circuit is alternating, that is, an electric wave launched by the conductor to become far-field electromagnetic radiation traveling through space with the velocity of light.

In electric power transmission and distribution, the phenomena inside of the conductor are of main importance, and the electric field of the conductor is usually observed only incidentally. Inversely, in the use of electric power for *radio* telecommunications it is only the electric and magnetic fields outside of the conductor, that is electromagnetic radiation, which is of importance in transmitting the message. The phenomenon in the conductor, the current in the launching structure, is not used.

The electric charge displacement in the conductor produces a magnetic field and resultant lines of electric force. The magnetic field is a maximum in the direction concentric, or approximately so, to the conductor. That is, a ferromagnetic body tends to set itself in a direction at right angles to the conductor. The electric field has a maximum in a direction radial, or approximately so, to the conductor. The electric field component tends in a direction radial to the conductor and dielectric bodies may be attracted or repelled radially to the conductor.

The electric field of a circuit over which energy flows has three main axes at right angles with each other:

1. The *magnetic field*, concentric with the conductor.
2. The *lines of electric force*, radial to the conductor.
3. The *power gradient*, parallel to the conductor.

Where the electric circuit consists of several conductors, the electric fields of the conductors superimpose upon each other, and the resultant magnetic field lines and lines of electric force are not concentric and radial respectively, except *approximately in the immediate neighborhood* of the conductor. Between parallel conductors they are conjugate of circles. Neither the power consumption in the conductor, nor the magnetic field, nor the electric field, are proportional to the flow of energy through the circuit. However, the product of the intensity of the magnetic field and the intensity of the electric field is proportional to the flow of energy or the power, and the power is therefore resolved into a product of the two components **i** and **e**, which are chosen proportional respectively to the intensity of the magnetic field and of the electric field. The component called the current is defined as that factor of the electric power which is proportional to the magnetic field, and the other component, called the voltage, is defined as that factor of the electric power which is proportional to the electric field.

In *radio* telecommunications the electric field of the transmit antenna propagates through space as a radio wave and impinges upon the receive antenna where it is observed by its magnetic and electric effect. Radio waves, microwaves, infrared radiation, visible light, ultraviolet radiation, X rays and gamma rays are shown to be the same electromagnetic radiation phenomenon, differing one from the other only in frequency of vibration.

## Electromagnetic induction

Energy transfer by electromagnetic induction is typically magnetic but capacitive coupling can also be achieved.

## Electrodynamic induction method

The electrodynamic induction wireless transmission technique is near field over distances up to about one-sixth of the wavelength used. Near field energy itself is non-radiative but some radiative losses do occur. In addition there are usually resistive losses. With electrodynamic induction, electric current flowing through a primary coil creates a magnetic field that acts on a secondary coil producing a current within it. Coupling must be tight in order to achieve high efficiency. As the distance from the primary is increased, more and more of the magnetic field misses the secondary. Even over a relatively short range the inductive coupling is grossly inefficient, wasting much of the transmitted energy.

This action of an electrical transformer is the simplest form of wireless power transmission. The primary and secondary circuits of a transformer are not directly connected. Energy transfer takes place through a process known as mutual induction. Principal functions are stepping the primary voltage either up or down and electrical isolation. Mobile phone and electric toothbrush battery chargers, and electrical power distribution transformers are examples of how this principle is used. Induction cookers use this method. The main drawback to this basic form of wireless transmission is short range. The receiver must be directly adjacent to the transmitter or induction unit in order to efficiently couple with it.

The application of resonance improves the situation somewhat. When resonant coupling is used the transmitter and receiver inductors are tuned to a mutual frequency and the drive current is modified from a sinusoidal to a nonsinusoidal transient waveform. Pulse power transfer occurs over multiple cycles. In this way significant power may be transmitted over a distance of up to a few times the size of the primary coil. Transmitting and receiving coils are usually single layer solenoids or flat spirals with series capacitors, which, in combination, allow the receiving element to be tuned to the transmitter frequency.

Common uses of resonance-enhanced electrodynamic induction are charging the batteries of portable devices such as laptop computers and cell phones, medical implants and electric vehicles. A localized charging technique  selects the appropriate transmitting coil in a multilayer winding array structure. Resonance is used in both the wireless charging pad (the transmitter circuit) and the receiver module (embedded in the load) to maximize energy transfer efficiency. This approach is suitable for universal wireless charging pads for portable electronics such as mobile phones. It has been adopted as part of the Qi wireless charging standard.

It is also used for powering devices having no batteries, such as RFID patches and contactless smartcards, and to couple electrical energy from the primary inductor to the helical resonator of Tesla coil wireless power transmitters.

## Electrostatic induction method
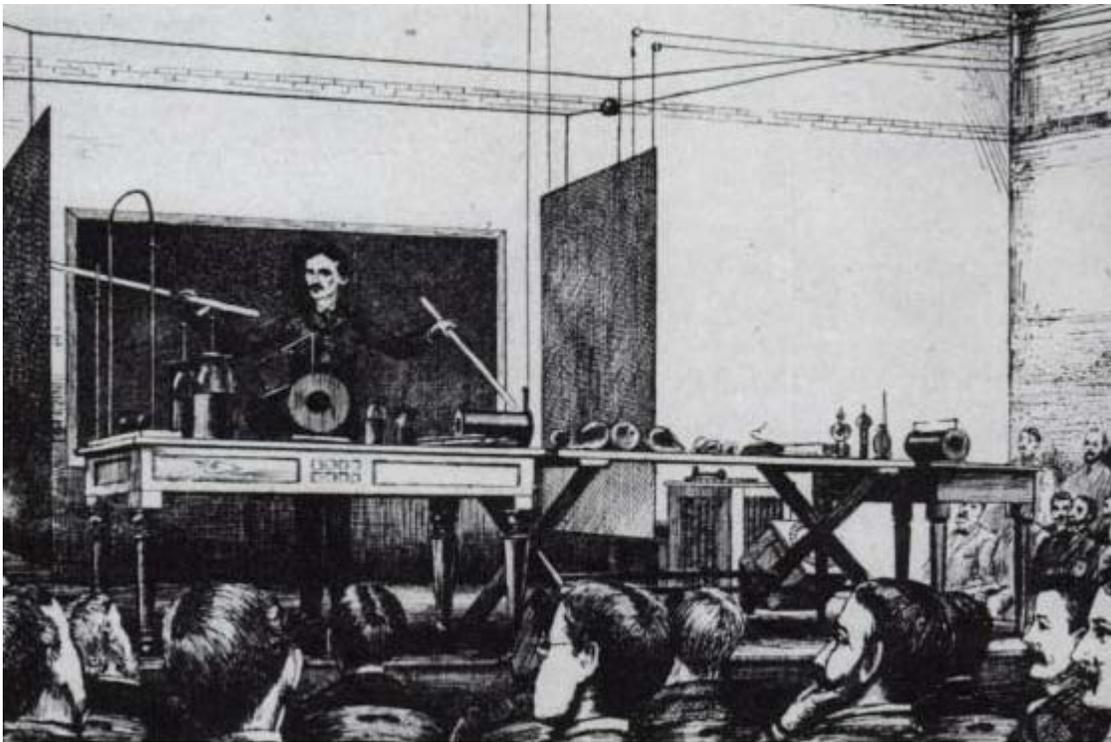


The **Tesla effect**. is the illumination of two exhausted tubes by means of a powerful, rapidly alternating electrostatic field created between two vertical metal sheets suspended from the ceiling on insulating cords. It exploits the physics of electrostatic induction.

Electrostatic or capacitive coupling is the passage of electrical energy through a dielectric. In practice it is an electric field gradient or differential capacitance between two or more insulated terminals, plates, electrodes, or nodes that are elevated over a conducting ground plane. The electric field is created by an alternating current of high potential and high frequency. The capacitance between fixed plates and the powered device form a voltage divider.

The electric energy transmitted through the atmosphere can be utilized by receiving devices. Tesla demonstrated the illumination of wireless lamps by energy that was coupled to them through an alternating electric field.

"Instead of depending on *electrodynamic induction* at a distance to light the tube . . . [the] ideal way of lighting a hall or room would . . . be to produce such a condition in it that an illuminating device could be moved and put anywhere, and that it is lighted, no matter where it is put and without being electrically connected to anything. I have been able to produce such a condition by creating in the room a powerful, *rapidly alternating electrostatic field*. For this purpose I suspend a sheet of metal a distance from the ceiling on insulating cords and connect it to one terminal of the induction coil, the other terminal being preferably connected to the ground. Or else I suspend two sheets . . . each sheet being connected with one of the terminals of the coil, and their size being carefully determined. An exhausted tube may then be carried in the hand anywhere between the sheets or placed anywhere, even a certain distance beyond them; it remains always luminous."

The principle of electrostatic induction is applicable to the electrical conduction wireless transmission method.

## Electromagnetic radiation

Far field methods achieve longer ranges, often multiple kilometer ranges, where the distance is much greater than the diameter of the device(s). The main reason for longer ranges with radio wave and optical devices is the fact that electromagnetic radiation in the far-field can be made to match the shape of the receiving area (using high directivity antennas or well-collimated Laser Beam) thereby delivering almost all emitted power at long ranges. The maximum directivity for antennas is physically limited by diffraction.

## Beamed power, size, distance, and efficiency

The size of the components may be dictated by the distance from transmitter to receiver, the wavelength and the Rayleigh criterion or diffraction limit, used in standard radio frequency antenna design, which also applies to lasers. In addition to the Rayleigh criterion Airy's diffraction limit is also frequently used to determine an approximate spot size at an arbitrary distance from the aperture.

The Rayleigh criterion dictates that any radio wave, microwave or laser beam will spread and become weaker and diffuse over distance; the larger the transmitter antenna or laser

aperture compared to the wavelength of radiation, the tighter the beam and the less it will spread as a function of distance (and vice versa). Smaller antennae also suffer from excessive losses due to side lobes. However, the concept of laser aperture considerably differs from an antenna. Typically, a laser aperture much larger than the wavelength induces multi-moded radiation and mostly collimators are used before emitted radiation couples into a fiber or into space.

Ultimately, beamwidth is physically determined by diffraction due to the dish size in relation to the wavelength of the electromagnetic radiation used to make the beam. Microwave power beaming can be more efficient than lasers, and is less prone to atmospheric attenuation caused by dust or water vapor losing atmosphere to vaporize the water in contact.

Then the power levels are calculated by combining the above parameters together, and adding in the gains and losses due to the antenna characteristics and the transparency and dispersion of the medium through which the radiation passes. That process is known as calculating a link budget.

## Microwave method
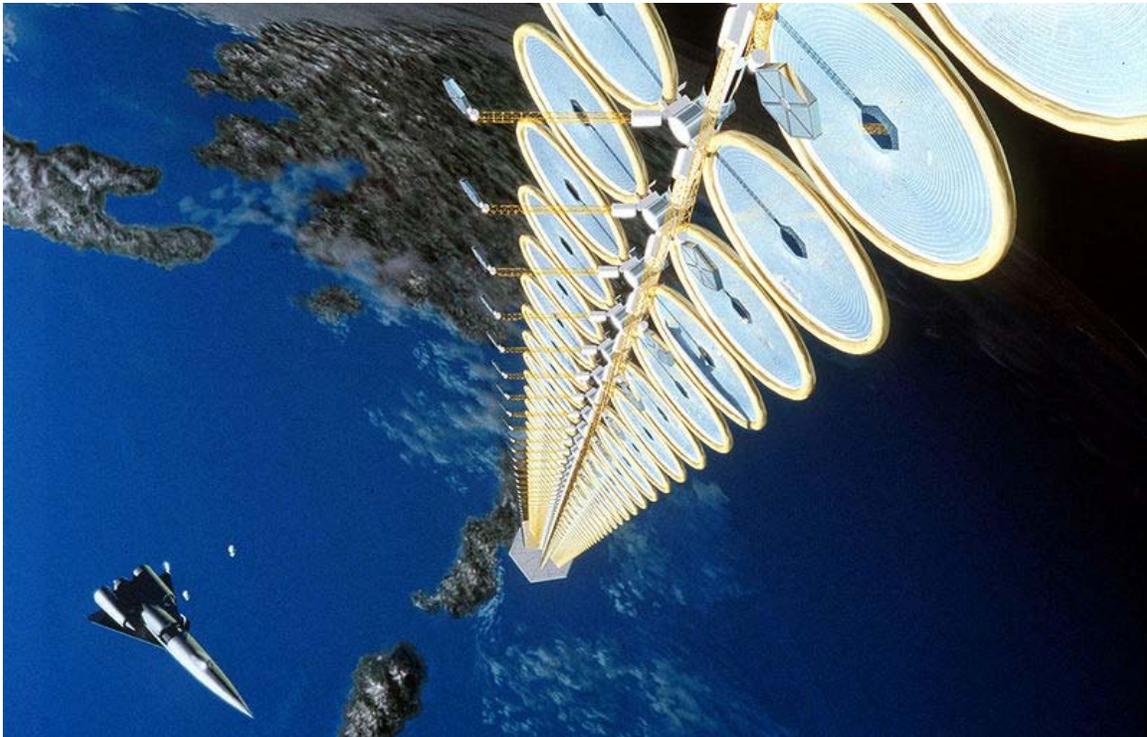


An artist's depiction of a solar satellite that could send electric energy by microwaves to a space vessel or planetary surface.

Power transmission via radio waves can be made more directional, allowing longer distance power beaming, with shorter wavelengths of electromagnetic radiation, typically in the microwave range. A rectenna may be used to convert the microwave energy back

into electricity. Rectenna conversion efficiencies exceeding 95% have been realized. Power beaming using microwaves has been proposed for the transmission of energy from orbiting solar power satellites to Earth and the beaming of power to spacecraft leaving orbit has been considered.

Power beaming by microwaves has the difficulty that for most space applications the required aperture sizes are very large due to diffraction limiting antenna directionality. For example, the 1978 NASA Study of solar power satellites required a 1-km diameter transmitting antenna, and a 10 km diameter receiving rectenna, for a microwave beam at 2.45 GHz. These sizes can be somewhat decreased by using shorter wavelengths, although short wavelengths may have difficulties with atmospheric absorption and beam blockage by rain or water droplets. Because of the "thinned array curse," it is not possible to make a narrower beam by combining the beams of several smaller satellites.

For earthbound applications a large area 10 km diameter receiving array allows large total power levels to be used while operating at the low power density suggested for human electromagnetic exposure safety. A human safe power density of 1 mW/cm$^2$ distributed across a 10 km diameter area corresponds to 750 megawatts total power level. This is the power level found in many modern electric power plants.

Following World War II, which saw the development of high-power microwave emitters known as cavity magnetrons, the idea of using microwaves to transmit power was researched. By 1964 a miniature helicopter propelled by microwave power had been demonstrated.

Japanese researcher Hidetsugu Yagi also investigated wireless energy transmission using a directional array antenna that he designed. In February 1926, Yagi and Uda published their first paper on the tuned high-gain directional array now known as the Yagi antenna. While it did not prove to be particularly useful for power transmission, this beam antenna has been widely adopted throughout the broadcasting and wireless telecommunications industries due to its excellent performance characteristics.

Wireless high power transmission using microwaves is well proven. Experiments in the tens of kilowatts have been performed at Goldstone in California in 1975 and more recently (1997) at Grand Bassin on Reunion Island. These methods achieve distances on the order of a kilometer.

# Laser method
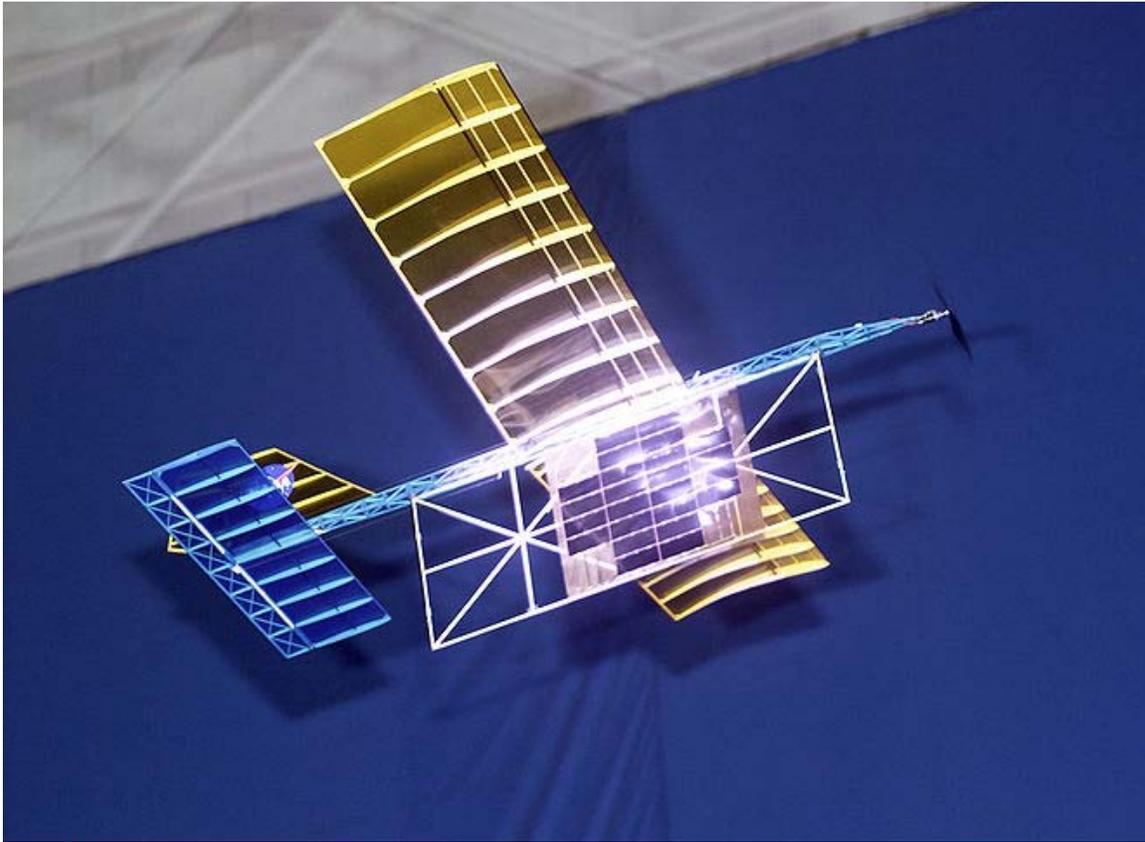


NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/Gallery/Photo/index.html
NASA Photo: ED03−0249−18   Date: September 18, 2003   Photo By: Tom Tschida

With a laser beam centered on its panel of photovoltaic cells, a model plane makes the first flight of an aircraft powered by a laser beam inside a building at NASA Marshall.

With a laser beam centered on its panel of photovoltaic cells, a lightweight model plane makes the first flight of an aircraft powered by a laser beam inside a building at NASA Marshall Space Flight Center.

In the case of electromagnetic radiation closer to visible region of spectrum (10s of microns (um) to 10s of nm), power can be transmitted by converting electricity into a laser beam that is then pointed at a solar cell receiver. This mechanism is generally known as "powerbeaming" because the power is beamed at a receiver that can convert it to usable electrical energy.

Advantages of laser based energy transfer compared with other wireless methods are:

1. collimated monochromatic wavefront propagation allows narrow beam cross-section area for energy transmission over large ranges.
2. compact size of solid state lasers-photovoltaics semiconductor diodes fit into into small products.

3. no radio-frequency interference to existing radio communication such as Wi-fi and cell phones.
4. control of access; only receivers illuminated by the laser receive power.

Its drawbacks are:

1. Conversion to light, such as with a laser, is inefficient
2. Conversion back into electricity is inefficient, with photovoltaic cells achieving 40%-50% efficiency. (Note that conversion efficiency is rather higher with monochromatic light than with insolation of solar panels).
3. Atmospheric absorption causes losses.
4. As with microwave beaming, this method requires a direct line of sight with the target.

The laser "powerbeaming" technology has been mostly explored in military weapons and aerospace applications and is now being developed for commercial and consumer electronics Low-Power applications. Wireless energy transfer system using laser for consumer space has to satisfy Laser safety requirements standardized under IEC 60825.

To develop an understanding of the trade-offs of Laser ("a special type of light wave"-based system):

1. Propagation of a laser beam (on how Laser beam propagation is much less affected by diffraction limits)
2. Coherence and the range limitation problem (on how spatial and spectral coherence characteristics of Lasers allows better distance-to-power capabilities )
3. Airy disk (on how wavelength fundamentally dictates the size of a disk with distance)
4. Applications of laser diodes (on how the laser sources are utilized in various industries and their sizes are reducing for better integration)

Geoffrey Landis is one of the pioneers of solar power satellite and laser-based transfer of energy especially for space and lunar missions. The continuously increasing demand for safe and frequent space missions has resulted in serious thoughts on a futuristic space elevator that would be powered by lasers. NASA's space elevator would need wireless power to be beamed to it for it to climb a tether.

NASA's Dryden Flight Research Center has demonstrated flight of a lightweight unmanned model plane powered by a laser beam. This proof-of-concept demonstrates the feasibility of periodic recharging using the laser beam system and the lack of need to return to ground.

"Lasermotive" demonstrated laser powerbeaming at one kilometer during NASA's 2009 powerbeaming contest. Also "Lighthouse DEV" (a spin off of NASA Power Beaming Team) along with "University of Maryland" is developing an eye safe laser system to power a small UAV. Since 2006, "PowerBeam" which originally invented the eye-safe

technology and holds all crucial patents in this technology space, is developing commercially ready units for various consumer and industrial electronic products.

## Electrical conduction
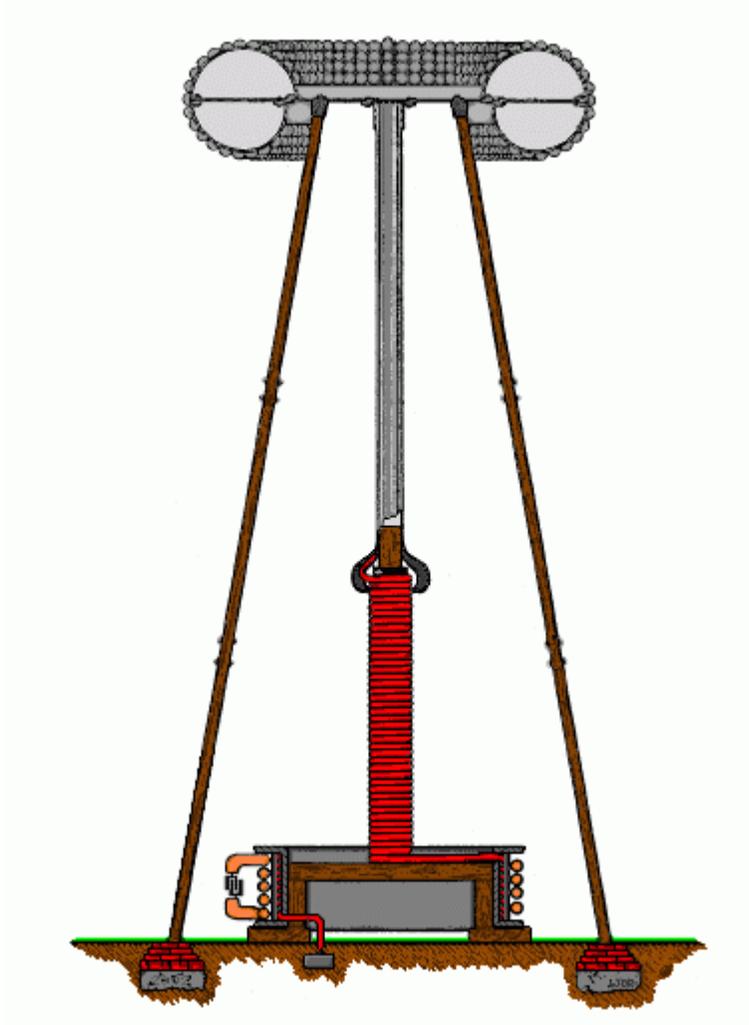


The Tesla coil wireless power transmitter **U.S. Patent 1,119,732**
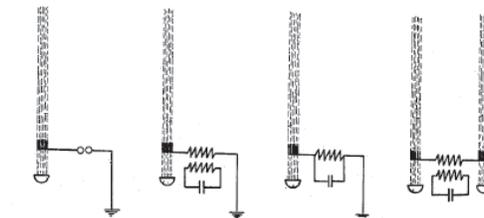


Means for long conductors of electricity forming part of an electric circuit and electrically connecting said ionized beam to an electric circuit. Hettinger 1917 -(U.S. Patent 1,309,031)

# Disturbed charge of ground and air method

Single wire with Earth return electrical power transmission systems rely on current flowing through the earth plus a single wire insulated from the earth to complete the circuit. In emergencies high-voltage direct current power transmission systems can also operate in the 'single wire with earth return' mode. Elimination of the raised insulated wire, and transmission of high-potential, high-frequency alternating current through the earth with an atmospheric return circuit has been investigated as a method of wireless electrical power transmission. Transmission of electrical energy through the earth alone, eliminating the second conductor is also being investigated.

Low frequency alternating current can be transmitted through the inhomogeneous earth with low loss because the net resistance between earth antipodes is considerably less than 1 ohm. The electrical displacement takes place predominantly by electrical conduction through the oceans, and metallic ore bodies and similar subsurface structures. The electrical displacement is also by means of electrostatic induction through the more dielectric regions such as quartz deposits and other non-conducting minerals.

Alternating current can be transmitted through atmospheric strata having a barometric pressure of less than 135 millimeters of mercury. Current flows by means of electrostatic induction through the lower atmosphere up to about two or three miles above the plants (this is the middle part in a three-space model) and the flow of ions, that is to say, electrical conduction through the ionized region above three miles. Intense vertical beams of ultraviolet light may be used to ionize the atmospheric gasses directly above the two elevated terminals resulting in the formation of plasma high-voltage electrical transmission lines leading up to the conducting atmospheric strata. The end result is a flow electrical current between the two elevated terminals by a path up to and through the troposphere and back down to the other facility. Electrical conduction through atmospheric strata is made possible by the creation of capacitively coupled discharge plasma through the process of atmospheric ionization.

### Terrestrial transmission line with atmospheric return

Tesla discovered that electrical energy can be transmitted through the earth and the atmosphere. In the course of his research he successfully lit lamps at moderate distances and was able to detect the transmitted energy at much greater distances. The Wardenclyffe Tower project was a commercial venture for trans-Atlantic wireless telephony and proof-of-concept demonstrations of global wireless power transmission. The facility was not completed because of insufficient funding.

Earth is a naturally conducting body and forms one conductor of the system. A second path is established through the upper troposphere and lower stratosphere starting at an elevation of approximately 4.5 miles (7.2 km).

A global system for "the transmission of electrical energy without wires" called the World Wireless System, dependent upon the high electrical conductivity of plasma and the high electrical conductivity of the earth, was proposed as early as 1904.

**Terrestrial single-conductor surface wave transmission line**

The same transmitter used for the atmospheric conduction method is used for the terrestrial single-conductor earth resonance method.

The fundamental earth resonance frequency is claimed to be approximately 11.78 Hz. With the earth resonance method some harmonic of this fundamental frequency is used. "I would say that the frequency should be smaller then twenty thousand per second, through shorter waves might be practicable" and on the low end, "a frequency of nine hundred and twenty-five per second" is used, "when it is indispensable to operate motors of the ordinary kind."

Observations have been made that may be inconsistent with a basic tenet of physics related to the scalar derivatives of the electromagnetic potentials that are presently considered to be *nonphysical.*

## *Timeline of wireless power*

- **1820**: André-Marie Ampère develops Ampere's law showing that electric current produces a magnetic field.
- **1831**: Michael Faraday develops Faraday's law of induction describing the electromagnetic force induced in a conductor by a time-varying magnetic flux.
- **1836**: Nicholas Callan invents the electrical transformer.
- **1864**: James Clerk Maxwell synthesizes the previous observations, experiments and equations of electricity, magnetism and optics into a consistent theory and mathematically models the behavior of electromagnetic radiation.
- **1888**: Heinrich Rudolf Hertz confirms the existence of electromagnetic radiation. Hertz's "*apparatus for generating electromagnetic waves*" was a VHF or UHF "radio wave" spark gap transmitter.
- **1891**: Tesla improves Hertz-wave wireless transmitter RF power supply or exciter in his patent No. 454,622, "System of Electric Lighting."
- **1893**: Tesla demonstrates the wireless illumination of phosphorescent lamps of his design at the World's Columbian Exposition in Chicago.
- **1893**: Tesla publicly demonstrates wireless power before a meeting of the National Electric Light Association in St. Louis.
- **1894**: Tesla lights incandescent lamps wirelessly at the 35 South Fifth Avenue laboratory in New York City by means of "electro-dynamic induction" or resonant inductive coupling.
- **1894**: Hutin & LeBlanc, espouse long held view that inductive energy transfer should be possible, they received U.S. Patent # 527,857 describing a system for power transmission at 3 kHz.

- **1894**: Jagdish Chandra Bose ignites gunpowder and rings a bell at a distance using electromagnetic waves, showing that communications signals can be sent without using wires.
- **1896**: Tesla demonstrates wireless transmission over a distance of about 48 kilometres (30 mi).
- **1897**: Tesla files his first patent application dealing specifically with wireless transmission.
- **1899**: Tesla continues his wireless power transmission research in Colorado Springs and writes, "the inferiority of the induction method would appear immense as compared with the *disturbed charge of ground and air method*."
- **1902**: Nikola Tesla vs. Reginald Fessenden - U.S. Patent Interference No. 21,701, System of Signaling (wireless); wireless power transmission, time and frequency domain spread spectrum telecommunications, electronic logic gates in general.
- **1904**: At the St. Louis World's Fair, a prize is offered for a successful attempt to drive a 0.1 horsepower (75 W) airship motor by energy transmitted through space at a distance of at least 100 feet (30 m).
- **1916**: Tesla states, "In my [*disturbed charge of ground and air*] system, you should free yourself of the idea that there is [electromagnetic] radiation, that energy is radiated. It is not radiated; it is conserved."
- **1917**: Tesla's Wardenclyffe tower is demolished. . . .

- **1926**: Shintaro Uda and Hidetsugu Yagi publish their first paper on Uda's *"tuned high-gain directional array"* better known as the Yagi antenna.

- **1961**: William C. Brown publishes an article exploring possibilities of microwave power transmission.
- **1964**: Brown demonstrates on CBS News with Walter Cronkite a model helicopter that receives all of the power needed for flight from a microwave beam. Between 1969 and 1975, Brown is technical director of a JPL Raytheon program that beams 30 kW over a distance of 1 mile at 84% efficiency.
- **1968**: Peter Glaser proposes wirelessly transmitting solar energy captured in space using "Powerbeaming" technology. This is usually recognized as the first description of a solar power satellite.
- **1971**: Prof. Don Otto develops a small trolley powered by induction at The University of Auckland, in New Zealand.
- **1973**: The world's first passive RFID system is demonstrated at Los-Alamos National Lab.
- **1975**: Goldstone Deep Space Communications Complex does experiments in the tens of kilowatts.
- **1988**: A power electronics group led by Prof. John Boys at The University of Auckland in New Zealand, develops an inverter using novel engineering materials and power electronics and conclude that power transmission by means of electrodynamic induction should be achievable. A first prototype for a contact-less power supply is built. Auckland Uniservices, the commercial company of The University of Auckland, patents the technology.

- **1989**: Daifuku, a Japanese company, engages Auckland Uniservices Ltd. to develop technology for car assembly plants and materials handling providing challenging technical requirements including multiplicity of vehicles.
- **1990**: Prof. John Boys team develops novel technology enabling multiple vehicles to run on the same inductive power loop and provide independent control of each vehicle. Auckland UniServices Patents the technology.
- **1996**: Auckland Uniservices develops an Electric Bus power system using electrodynamic induction to charge (30-60 kW) opportunistically commencing implementation in New Zealand. Prof John Boys Team commission 1st commercial IPT Bus in the world at Whakarewarewa, in New Zealand.
- **1998**: RFID tags are powered by electrodynamic induction over a few feet.
- **1999**: Dr. Herbert L. Becker powers a lamp and a hand held fan from a distance of 30 feet.
- **1999**: Prof. Shu Yuen (Ron) Hui and Mr. S.C. Tang of the City University of Hong Kong file a patent on "Coreless Printed-Circuit-Board (PCB) transformers and operating techniques", which form the basis for future planar charging surface with "vertical flux" leaving the planar surface. The circuit uses resonant circuits for wireless power transfer. EP(GB)0935263B
- **2000**: Prof. Shu Yuen (Ron) Hui invent a planar wireless charging pad using the "vertical flux" approach and resonant power transfer for charging portable consumer electronic products. A patent is filed on "Apparatus and method of an inductive battery charger," PCT Patent PCT/AU03/00 721, 2000.
- **2000**: Based on the coreless PCB transformer developed by Prof. Ron Hui, Prof. B. Choi and his team at Kyungpook National University publish a paper on "A new contactless battery charger for portable telecommunication/computing electronics," in Proc. ICCE'00 Int. Conf. Consumer Electron., 2000, pp. 58–59. The coreless PCB transformer is used to wirelessly charge a mobile phone.
- **2001** Prof. Shu Yuen (Ron) Hui and Dr. S.C. Tang file a patent on "Planar Printed-Circuit-Board Transformers with Effective Electromagnetic Interference (EMI) Shielding". The EM shield consists of a thin layer of ferrite and a thin layer of copper sheet. It enables the underneath of the future wireless charging pads to be shielded with a thin EM shield structure with thickness of typically 0.7mm or less. Patent: US6,501,364.
- **2001**: Prof. Ron Hui's team demonstrate that the coreless PCB transformer can transmit power close to 100W in 'A low-profile low-power converter with coreless PCB isolation transformer, IEEE Transactions on Power Electronics, Volume: 16 Issue: 3 , May 2001. A team of Philips Research Center Aachen, led by Dr. Eberhard Waffenschmidt, use it to power an 100W lighting device in their paper "Size advantage of coreless transformers in the MHz range" in the European Power Electronics Conference in Graz.
- **2001**: Splashpower formed in the UK. Uses coupled resonant coils in a flat "pad" style to transfer tens of watts into a variety of consumer devices, including lamp, phone, PDA, iPod etc.
- **2002**: Prof. Shu Yuen (Ron) Hui extends the planar wireless charging pad concept using the vertical flux approach to incorporate free-positioning feature for multiple loads. This is achieved by using a multilayer planar winding array

structure. Patent were granted as "Planar Inductive Battery Charger", GB2389720 and GB 2389767.

- **2004**: Electrodynamic induction used by 90 percent of the US$1 billion clean room industry for materials handling equipment in semiconductor, LCD and plasma screen manufacture.
- **2005**: Prof. Shu Yuen (Ron) Hui and Dr. W.C. Ho of City University of Hong Kong publish their work in the IEEE Transactions on a planar wireless charging platform with free-positioning feature. The planar wireless charging pad is able to charge several loads simultaneously on a flat surface.
- **2005**: Prof Boys' team at The University of Auckland, refines 3-phase IPT Highway and pick-up systems allowing transmission of power to moving vehicles in the lab.
- **2007**: A localized charging technique is reported by Dr. Xun Liu and Prof. Ron Hui for the wireless charging pad with free-positioning feature. With the aid of the double-layer EM shields enclosing the transmitter and receiver coils, the localized charging selects the right transmitter coil so as to minimize flux leakage and human exposure to radiation.
- **2007**: Using electrodynamic induction a physics research group, led by Prof. Marin Soljacic, at MIT, wirelessly power a 60W light bulb with 40% efficiency at a 2 metres (6.6 ft) distance with two 60 cm-diameter coils.
- **2008**: Bombardier offers a new wireless power transmission product PRIMOVE, a system for use on trams and light-rail vehicles.
- **2008**: Industrial designer Thanh Tran, at Brunel University make a wireless lamp incorporating a high efficiency 3W LED.
- **2008**: Intel reproduces Tesla's original 1894 implementation of electrodynamic induction and Prof. John Boys group's 1988 follow-up experiments by wirelessly powering a nearby light bulb with 75% efficiency.
- **2008**: Greg Leyh and Mike Kennan of the Nevada Lightning Laboratory publish a paper on Tesla's *disturbed charge of ground and air method* of wireless power transmission with circuit simulations and test results showing an efficiency greater than can be obtained using the electrodynamic induction method.
- **2009**: A Consortium of interested companies called the Wireless Power Consortium announce they are nearing completion for a new industry standard for low-power inductive charging
- **2009**: Palm (now a division HP) launches the Palm Pre smartphone with the Palm Touchstone wireless charger.
- **2009**: An Ex approved Torch and Charger aimed at the offshore market is introduced. This product is developed by Wireless Power & Communication, a Norway based company.
- **2009**: A simple analytical electrical model of electrodynamic induction power transmission is proposed and applied to a wireless power transfer system for implantable devices.
- **2009**: Lasermotive uses diode laser to win $900k NASA prize in power beaming, breaking several world records in power and distance, by transmitting over a kilowatt more than several hundred meters.

- **2009**: Sony shows a wireless electrodynamic-induction powered TV set, 60 W over 50 cm
- **2010**: Haier Group debuts "the world's first" completely wireless LCD television at CES 2010 based on Prof. Marin Soljacic's follow-up research on Tesla's electrodynamic induction wireless energy transmission method and the Wireless Home Digital Interface (WHDI).
- **2010**: System On Chip (SoC) group in University of British Columbia develops an optimization tool for the design of highly efficient wireless power transmission systems using multiple coils. The design is optimized for implantable applications and power transfer efficiency of 82% is achieved.