Appendix 3: Shielding Techniques and Cables

The lab environment has many sources of electromagnetic interference, which must be avoided for sensitive electrical measurements. This appendix describes some of the most important sources of interference and summarizes cabling and shielding techniques used to reduce pickup.

ELECTROSTATIC PICKUP

Electric fields from unshielded power lines and power cords are one of the largest sources of interference. These electric fields capacitively couple any wiring they intercept to the sinusoidal power line voltage at \(120V_{\text{rms}}\) and 60 Hz frequency. The effective coupling capacitance for 60 Hz pickup is determined by the location of the wiring relative to power lines, and falls off with distance. One can estimate the magnitude of this capacitive pickup by simply using the voltage divider rule for the impedance of the pickup capacitance in series with the effective impedance to ground of the wiring of interest. For example, for \(C_p = 10 \text{ pF}\) the magnitude of the corresponding impedance is \(Z = 1/\Box C_p \sim 300 \text{M} \Omega\). If the impedance to ground is \(1 \text{ M} \Omega\), the 60 Hz electrostatic pickup will be roughly \((1 \text{M} \Box /300 \text{M} \Box )120 \text{V} \sim 0.4 \text{V}\), which is comparable to or larger than many signals of interest. On the other hand, if the impedance to ground is only \(1 \Box\), then the pickup will be only \(0.4 \mu \text{V}\). Thus high impedance circuits are most sensitive to electrostatic pickup.

Electrostatic pickup can be reduced substantially by completely enclosing the circuit of interest inside a grounded conductive shield, which intercepts stray electric field lines from external sources. The cases of electronic equipment are commonly made from metal or other conductive material, which is grounded to the power line ground for this purpose. Connections between instruments should be made using cables with flexible conductive shields as described below.

MAGNETIC PICKUP

Stray magnetic fields cause interference via the electromotive force around loops in a
circuit induced by changes in magnetic flux. The sources of magnetic interference typically originate from ac power. Currents flowing in power lines directly create ac magnetic fields that inductively couple into circuitry causing a sinusoidal 60 Hz pickup. Usually magnetic pickup has a strong 3rd harmonic content at 180 Hz. The magnetic fields responsible for this pickup originate from ac motors in vacuum pumps and air handling equipment, and from the transformers used in power supplies. Harmonic generation occurs in the iron cores of motors and transformers as the magnetization begins to saturate. The coupling of a circuit for magnetic pickup is determined by the mutual inductance between the circuit and the source of magnetic field, and falls off with distance and decreases with the area of any loops in the circuit. Sources of magnetic pickup at higher frequencies include the CRT’s used in televisions and computer terminals which scan the electron beam magnetically, and small high efficiency switching power supplies. These should be kept away from sensitive electronics.

Magnetic fields are difficult to shield because they penetrate the metal cases of most electronic equipment. A continuous shield constructed of high permeability material such as mu-metal can be used to divert magnetic field lines away from an enclosed circuit. However, mu-metal is expensive and loses its high permeability with mechanical deformation. Mu-metal shields are used to protect the electron beam in oscilloscope CRT’s and to shield the most sensitive preamplifiers. An easier and less expensive way to reduce magnetic pickup is to reduce the area of sensitive loops in the circuit by keeping the leads close together. Twisting pairs of wires together further reduces magnetic pickup, because the total flux linked alternates in sign and averages to zero. Coaxial cables are relatively insensitive to magnetic pickup, because the average flux linked is very small due to their cylindrical symmetry.

CABLES

Several types of cables are available in the lab to make connections between electronic equipment. Their properties and recommended uses are summarized below:

Test leads. These are unshielded insulated leads used to make quick measurements of a circuit with a multimeter. They usually have a test probe at one end and a banana plug at
the other. Some have banana plugs at both ends. These connections are suitable for the measurement of fairly large voltages (> 0.1 Volt) on low impedance circuits, but should not be used for sensitive measurements.

**BNC coaxial cables.** The most common type of connector cable in the lab is a coaxial cable with male BNC connectors at both ends. The coaxial cable consists of a center conductor surrounded by a cylindrical shield made of braided copper wire, which is usually grounded. Using adapters it is possible to connect two cables end to end, two cables to the same point (tee), or go from one cable to test leads. Coaxial cables are dual purpose: 1) they provide electrostatic shielding and minimize magnetic pickup for sensitive measurements at low frequencies, and 2) they transmit fast pulses with little attenuation or distortion near the speed of light, about 1 foot per nanosecond. Coaxial cables have a characteristic impedance, which is 50Ω for most coaxial cables used in the lab. For fast pulse transmission applications, it is important to match the impedance of the cable with the instruments to which it is connected. Otherwise pulses are reflected from the ends of the cable and bounce back and forth in the cable, distorting the signal. One can accomplish this by terminating the cable with a tee and a 50Ω terminator.

**Shielded twisted pair cables.** For low frequency applications, the pulse transmission characteristics of coaxial cable are not important, and one can obtain both electrostatic and magnetic shielding by using shielded twisted pairs of wires. Twisted pairs minimize the area of the loop for inductive coupling to stray magnetic fields, and a flexible shield intercepts stray electric field lines. Additional pickup reduction can be realized with twisted pair cables by using a differential amplifier to detect the signal: differential amplifiers are insensitive to "common mode" voltage present on both inputs and respond only to the difference in voltage between the inputs. Shielded twisted pair cables often end in a standard microphone connector, which consists of two pins surrounded by a metal casing, which is connected to the shield.

**Strip cables.** These are composed of many parallel, unshielded single wires molded in a wide plastic insulation strip. The wires are separated by grooves, so that a single wire
can be peeled away from the others. Strip cables were developed to interconnect many digital logic lines quickly and easily rather than to shield against stray electrostatic or magnetic pickup. Logic signals use a voltage change of several volts to signify the change of only one bit of information, and are quite insensitive to noise. However, due to their convenience, strip cables are now used in some applications for analog signals. In order to reduce pickup in these circumstances, it is common to ground every other wire in the cable to provide some shielding.

TRANSMISSION LINES

Objective: To understand the characteristics of coaxial cable transmission lines including propagation delay, impedance matching, and charging.

Equipment:
fast dual trace oscilloscope (50 MHz bandwidth or better)
fast pulse generator (risetime 10 nsec or less) with 50 Ohm source impedance
100 feet of high quality 50 Ohm coaxial cable with low attenuation and nearly 100% shield coverage - Ethernet cable
various termination resistors in Pomona boxes - 10, 20, 50, 100, 200, 500 Ohm

Procedure:
1) Velocity of propagation - Connect the coaxial cable between the two inputs of the oscilloscope, channel 1 and channel 2. Use a tee on channel 1 to connect this end of the cable to the pulse generator. Terminate the cable at the end connected to channel 2 with 50 Ohms to ground. Set up the pulse generator to produce single rectangular pulses with height \( V_p \sim 1 \text{ V} \) and widths in the range of 10 nsec to 1 \( \mu \text{sec} \) and repetition rates \( \sim 10\text{kHz} \) to 100 kHz. Set up the oscilloscope to trigger from the incoming pulse on channel 1, and to display both pulses, alternation between them. Compare the pulse shapes at both ends of the cable, and measure the propagation delay of the pulse down the cable. From the delay determine the velocity of propagation of the pulse down the transmission line and compare with the velocity of light.

2) Effect of impedance matching - Remove the 50 Ohm termination from the far end of the cable so that it is terminated only by the 1 MegaOhm input resistance of the}
oscilloscope, and observe the waveform at both ends simultaneously. The pulse will be reflected from the unterminated end of the cable with no change in sign. Before the reflected pulse arrives at the pulse generator, the output is the same as for 50 Ohm termination. After the reflected pulse arrives, the voltage doubles. Measure the pulse shapes on the oscilloscope. At the near (Ch. 1) end of the cable, the voltage should double after two transit times from Vp to 2Vp. At the far end (Ch. 2) the voltage should be 2Vp as soon as it arrives. Repeat these measurements with a shorting cap at the far (Ch. 2) end of the cable. In this case the reflected pulse has the opposite sign, and cancels the incoming pulse. Observed the shapes of the pulse at the near end (Ch. 1) of the cable: the voltage should go to zero after two transit times. At the far end, one should not observe a signal. Finally, use intermediate values of the termination resistors between 0 and 50 Ohms and for more than 50 Ohms, and compare the amplitude of the reflected wave with the theoretical expression.

3) Cable charging - Remove any termination from the far end of the cable and add series resistance to the pulse generator so that its effective source resistance is greater than 50 Ohms, perhaps 200 Ohms. Observe the waveform at the near end of the cable for a long rectangular step at the pulse generator. One should see the build up of voltage from a low value obtained by the resistive voltage divider formula (500 in series with 50 Ohms) to a steady state value of twice the set voltage via a series of steps separated by twice the transit time. One can calculate each step using the voltage divider formula iteratively and compare it with the continuous result which is of course a decaying exponential build up with time constant RC with R the total effective source resistance and C the total cable capacitance.