Foundations

1.1 INTRODUCTION

The purpose of a measurement system is to provide an observer with a numerical value corresponding to the variable being measured. In general, the measured value will not equal the true value of the variable but will be statistically distributed about an average or mean value. Statistics lies at the heart of any measurement and is presented more fully in a separate module of the Radiometrics series. In these lectures on Nuclear Instrumentation, we shall be dealing mainly with the principles of operation of the electronics used in the measurement system. The effects of statistical fluctuations on electrical signals are presented briefly in Lecture 3, under Electronic Noise.

1.2 ELEMENTS OF THE BASIC MEASUREMENT SYSTEM

Any measurement system can be decomposed into several elements or blocks. In general, it is possible to identify four types of elements.

Sensing element

This is the element in contact with the process. The sensing element gives an output, which depends on the variable to be measured. In a radiation detection system, it corresponds to the detector element.

Signal conditioning element

Takes the output of the sensor and converts it to a form suitable for additional processing. An example is the preamplifier, which converts charge into voltage.

Signal processing element

Converts the output of the conditioning element into a form suitable for presentation. For example, an analog-to-digital converter (adc) converts a voltage to a digital form for input to a computer or multichannel analyzer.

Data presentation element

Presents the measured value in an easily recognized form to the observer, e.g. a spectrum.

In this module, we will be concerned mainly with the properties of signal conditioning and processing elements (and their interconnections) that are commonly used in radiation detection systems. The properties of the sensing elements (detectors) are discussed in detail in other modules.

1.3 CONCEPTS

We begin with a discussion of the methods used to extract information from the voltage/current pulses produced by radiation detectors.

1.3.1 Device Impedance

A basic concept involved in the processing of pulses from radiation detectors is the impedance of the elements that comprise the measurement chain. A simple representation of the input and output impedances of a typical component is shown in Figure 1.1.

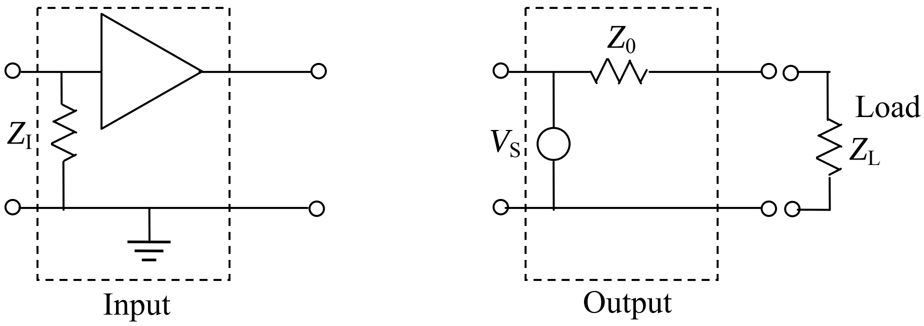


Figure 1.1 Idealized input and output configurations.

The **input impedance** Z_I represents the amount by which the device loads a signal source.

A high input impedance element will draw very little current from the source and, therefore, presents only a slight load. For example, the input impedance of an oscilloscope is often very high (about 1 MΩ) to avoid perturbing the signals that are being observed.

- For most applications, the input impedances of devices are kept **high**. However, there are exceptions.

The **output impedance** can be considered as an internal resistance in series with a voltage source.

- For most applications, the output impedance is kept **low** to minimize signal loss when the output is loaded with a subsequent component.

In Figure 1.1, the voltage V_L appearing across the load impedance Z_L is given by

$$V_L = V_S \frac{Z_L}{Z_L + Z_0}. \tag{1.1}$$

The open circuit voltage at the output is just V_S and to preserve the maximum signal strength, we want V_L to be as large a fraction as possible.

If the output impedance is small compared to the load (i.e. when $Z_0 << Z_L$) then,

$$V_L \approx V_S \tag{1.2}$$

and essentially all the signal voltage is transmitted to the load.

On the other hand, if the output impedance is approximately equal to the load then

$$V_L = V_S/2 \tag{1.3}$$

and only half the unloaded output voltage of the device appears across the load.

- Therefore, to have output stages with low-output impedance is often an important design goal.

A typical output impedance of a circuit element might be 0.1 Ω.

1.3.2 Signal Chains

When several processing devices are connected in a signal chain, the load Z_L presented to a given component is just the input impedance Z_I for the next element. Therefore, if all output impedances are low compared to input impedances, the maximum signal level is preserved throughout the chain. This is a desirable condition for nuclear pulse processing systems, and is a major design criterion, because any attenuation of signal usually leads to a deterioration in signal quality (e.g. energy resolution).

1.4 COAXIAL CABLES AND SHIELDING:

Essentially all interconnections between elements of a signal chain are made using shielded coaxial cables. A typical coaxial cable consists of:

- A **central conductor**, which is separated by
- an **insulating dielectric** from a
- **braided wire shield** with
- an **insulating sheath** on the outside.

The braided shielding is designed to minimize noise pickup from stray fields. The effectiveness of the shielding against low-frequency electric fields is determined by the tightness of the braided metal shield, while high-frequency fields are shielded by the skin effect.

1.4.1 Propagation speed

The speed of propagation for pulses along a coaxial cable is determined by the dielectric material separating the inner and outer conductors.

The propagation speed is inversely proportional to the square root of the dielectric constant,

i.e. $$v_p = \frac{1}{\sqrt{\mu\varepsilon}} \propto \frac{1}{\sqrt{\varepsilon}} \tag{1.4}$$

Where ε is the permittivity and μ is the permeability of the dielectric. Another way to consider this is that the quantity on the bottom line is simply the refractive index of the medium.

Some cables use air or some other gas as the dielectric material. For these cables, the pulse propagation speed can be very close to the speed of light (3.0×10^8 m/s). Most general-duty cables use a solid, such as polyethylene, as a dielectric, in which case, the pulse propagation speed is about 66% that of the speed of light.

As an aside, a convenient approximation for the speed of light is a foot per nanosecond. Specialized cables have been developed to have specific pulse propagation properties.

- Cables using polyethylene foam as dielectric, for example, have a somewhat faster propagation speed than standard coaxial cable.
- At the other extreme, special delay cables have been developed where the pulse propagation speed is reduced by factors of 100 or more!

1.4.2 Attenuation

Real cables are never perfect transmission lines. There are always dissipative losses due to imperfect dielectrics and the resistance of the central conductor. Such losses result in signal attenuation and distortion. Pulse-shape distortion is especially important for the high-frequency components of pulses.

Such effects usually can be ignored for cables shorter than a few tens of meters. However, for longer cables or for applications involving the transmission of pulses with fast rise times, attention needs to be paid to the high-frequency attenuation specifications of the cable in order to minimize the distortion of the transmitted pulse. For example, the distortion of a 1 ns leading-edge pulse is easily observed in an oscilloscope after transmission through 3 meters of standard 50 Ω cable.

For signal cables, the important specifications, usually, are the

- characteristic impedance (see later),
- capacitance per unit length
- maximum voltage rating.

1.5 NOISE PICKUP AND COMPONENT GROUNDING

1.5.1 Common ground and ground loops

The outer braid or shield of the cable also connects the chassis to each component and to each other and, hence, can serve as a common-ground connection. When components are mounted in the same rack or panel, this connection is often redundant. However, when components are physically separated (as is often the case in nuclear applications when the detector is separated from the counting area), the shield acts as an important common-ground connection.

It is often the case that if all components are not grounded internally to the same point, some dc current will flow in the shield in order to maintain the common potential. Sometimes, this ground current is small enough to have no practical consequences. However, in the case where elements are widely separated and internally grounded under widely different conditions, the ground current can be quite large and its fluctuations can induce significant noise in the cable with subsequent negative effects on the system performance.

For example, ground loops can significantly degrade the energy resolution obtained using high-resolution germanium detectors. Under these circumstances, the ground-loop currents **must be eliminated** by ensuring that all components are grounded only to a single common point for the entire system.

Transient pulses can also be induced in cable shields if nearby equipment involves the fast switching of electric currents.

1.5.2 Common Mode Rejection

A technique known as common mode rejection is sometimes helpful in reducing the effects of noise pickup in cables. In this case, the receiving device (often a linear amplifier) is designed with a differential input. The signal amplitude is determined by measuring one input relative to a reference voltage on the other input. The two inputs are fed by identical cables that run side by side to the signal source (often the preamplifier). Only the first cable is connected to the signal source while the second is left open at the sending end. In principle, the same pickup will appear on both cables and hence will be eliminated by the differential input.

1.6 CHARACTERISTIC IMPEDANCE AND CABLE REFLECTIONS

1.6.1 Fast and slow pulses

We consider two extreme cases for transmission of pulses along cables:

- Slow pulses.
- Fast pulses.

The distinction between fast and slow pulses depends on a comparison of the fastest component of the pulse (usually the rise or fall time) with the transit time of the pulse through the cable. As mentioned above, the propagation speed is roughly two thirds of a foot per nanosecond so that the transit time through a 1 m cable is about 5 ns (sorry about the mixed units).

Pulses with rise times that are slow compared to the transit time are considered slow, while those with rise times comparable with the transit time (or faster) are considered fast pulses. Most pulses derived from `timing or fast logic electronic modules' (e.g leading-edge or constant-fraction discriminators) are fast pulses, while those from linear devices (e.g. amplifiers) are slow.

Slow pulses: In this case, the cable acts as a simple conductor connecting the components. Its important properties are its series resistance and its capacitance to ground. Since the resistance of the central conductor is small for moderate-size cables (less than a few hundred meters), the capacitance usually dominates. The capacitative loading increases with cable length. In particular, it is important to keep the cable length to a minimum between the detector and preamplifier because:

(a) the noise characteristics of the preamplifier deteriorate with increasing input capacitance and

(b) at this point in the signal chain, the signal size is smallest and hence most vulnerable to additional noise.

For most other cases, the choice of cable for slow pulses is not critical.

Fast pulses: Other considerations become important for fast pulses. Perhaps the most important is the **characteristic impedance** Z_0 of the cable. The characteristic impedance depends on the dielectric and on the diameters of the inner conductor and outer braid but is independent of the length of the cable. To illustrate, consider the situation shown in Figure 1.2, which shows a cable

and a voltage generator capable of generating a step voltage change from zero to V_0. When this voltage step is applied to the input of the cable, it will travel down the length of the cable with the propagation speed of the cable.

While the voltage step is travelling down the cable, current is being drawn from the signal source because a finite charge per unit length is required to raise the voltage of the central conductor to V_0. If the cable were infinitely long, then this current would continue to be drawn from the source.

The characteristic impedance Z_0 is simply the ratio of the voltage to the current drawn by the infinitely long cable.

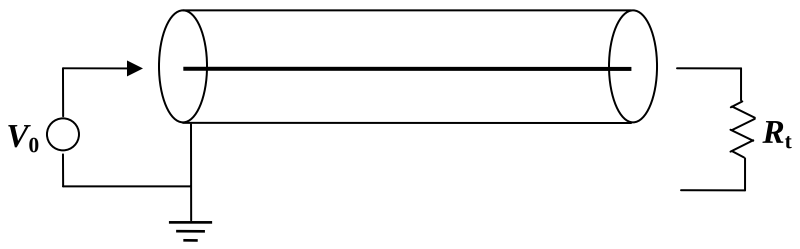


Figure 1.2 Schematic diagram of a step voltage being applied to a cable.

1.6.2 Cable Reflections

For finite-length cables, the conditions that exist at the far end of the cable need to be considered. There are many possibilities for terminating the end of a cable.

The cable is terminated by the effective resistance R_t, which appears between the central conductor and the outer shield of the cable.

(i) If the cable is connected to an electronic component, the termination resistance is effectively the input impedance of the component, $R_t = Z_I$.

(ii) If the cable is left unconnected, its termination resistance is infinite (large).

(iii) The cable can be terminated by connecting a resistor (imaginatively called a terminator) between the central conductor and the outer shield. Usually, the resistance R_t of this terminator is chosen to match the characteristic impedance of the cable.

(iv) If it is desired to terminate a cable, which is connected to a high input impedance device, with a lower termination resistance, a resistor to ground (shunt termination) can be inserted parallel to the input so that the effective termination is just the parallel combination of the input impedance and the terminator.

For example, consider what happens when a Z_0 = 50 Ω cable is terminated by a 50 Ω terminator. If a 5 V step is applied to the input end, a current of 100 mA is drawn from the source while the step is propagating along the cable. Note that no power is being dissipated at this stage. The current simply goes into charging successive elements of the cable as the step propagates. When the step reaches the far end of the cable, the situation changes. Current no longer goes into charging the cable (it is now fully charged). However, the 50 Ω terminator now sees a 5 V potential and begins to draw a current of 100 mA to ground. If the signal source is to hold the 5 V potential, it must be capable of supplying this current indefinitely.

- Therefore, as far as the source is concerned, a cable terminated in its own impedance behaves like an infinitely long cable of the same impedance.

Suppose the cable is not terminated by its own characteristic impedance. In this case, there will be an abrupt change in the properties of the medium through which the step pulse is propagating and reflections will be generated from the end of the cable.

- Cable shorted: ($R_t = 0$): The step is inverted and reflected with the same amplitude.
- Cable unterminated (R_t = infinite): The step is reflected with the same polarity and amplitude.

Table 1.1

Termination Resistance R_t	Reflected Step Amplitude
0	$-V$
Between 0 and Z_0	Between $-V$ and 0
Z_0	0
Between Z_0 and infinity	Between 0 and $+V$
Infinity	$+V$

Various other termination possibilities are summarized in Tables 1.1 and 1.2. In general, the ratio of reflected to incident amplitude is given by

$$\frac{V_r}{V_i} = \frac{R_t - Z_0}{R_t + Z_0} \tag{1.5}$$

Reflections are very undesirable when transmitting fast pulses since they can lead to distortion of the pulse shape and to the generation of spurious pulses (i.e. going above threshold in a discriminator because of a reflected pulse). Therefore, careful attention needs to be paid to the termination at each end of the cable.

The majority of cables used in nuclear instrumentation systems have a characteristic impedance of 50 or 93 Ω. Therefore, most commercial boxes intended for fast pulse applications are designed to have input impedances of 50 or 93 Ω

If the device impedance does not match the cable impedance, external terminators need to be used where the cable connects to the device. Several possible scenarios for proper termination are dealt with in Figure 1.3 and Table 1.2. The usual form of termination is shunt termination at the receiving end of the cable.

Table 1.2 Proper steps to terminate a cable.

Original Conditions			Termination Conditions			
Z_0 Source Output Impedance	Z_i Load Input Impedance	Signal Level at Load	Location	Type	Term. Resist.	Sig. Level at Load
50Ω	50Ω	$V_s/2$	Properly Terminated			
50Ω	High (≫50Ω)	V_S	Receiving end	Shunt	50Ω	$V_S/2$
50Ω	Low (≈ $F \times 50\Omega$) $F \ll 1$	$V_S \cdot (\frac{F}{1+F})$ $\approx V_S \cdot F$	Receiving end	Series	$50(1-F)$ Ω	$V_S(F/2)$
Low (≈ $F \cdot 50\Omega$) $F \ll 1$	50Ω	$\sim V_S$	Sending end	Series	$50(1-F)$ Ω	$\sim V_S/2$
High (≈ $K \cdot 50\Omega$) $K \gg 1$	50Ω	$V_S \cdot (\frac{1}{1+K})$ $\approx V_S/K$	Sending	Shunt	50Ω	$\sim V_S/2K$
Low (≪50Ω)	High (≫50Ω)	V_S	Sending Receiving	Series Shunt	50Ω 50Ω	$\sim V_S/2$
			(both required for termination of both ends of the cable)			
All the terminations listed above lead to proper termination of both ends of the cable. Below are two conditions in which only one end is terminated. (Compare with last entry above.)						
Low	High	V_S	Sending	Series	50Ω	V_S
Low	High	V_S	Receiving	Shunt	50Ω	V_S

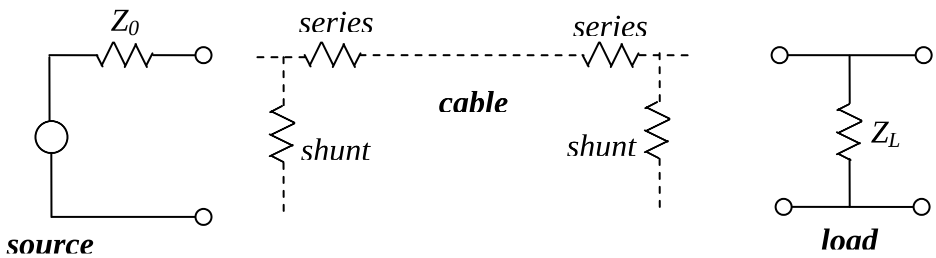


Figure 1.3 Various possible methods of termination at either end of a coaxial cable.

1.7 CABLE ACCESSORIES

Some of this may seem obvious, but it is worth going through the details just once to ensure familiarity with some common terminology.

1.7.1 Connectors.

Connectors are either plugs or jacks corresponding to male and female types, respectively. If in doubt, the innermost element of the connector is the one used to determine its sex (I'll let you use your imagination from there). The normal convention is to use plugs on the ends of the cable and jacks on the boxes the cables plug into.

Connectors are connected to the cable either by hand assembly and soldering or (probably better) by use of a crimping tool. Jacks, intended for mounting on equipment, can be either panel jacks, which screw through the front panel, or bulkhead jacks, which are tightened to the panel using a nut and lock washer.

Broadly speaking, connectors can be either signal connectors or high-voltage connectors, with some obvious differences. The high-voltage rating (breakdown) of signal connectors is usually not very high, or important (typically 500 V). The properties of some commonly used connectors are summarized in Table 1.3.

Probably, the BNC connector is still the most commonly used for nuclear applications, although it is being replaced by lemo or ribbon cables for some applications. The BNC connector is the standard connector specified by the NIM instrumentation standard. The standard BNC connector has a 50 Ω impedance and a maximum voltage rating of 500 V.

Table 1.3 Properties of common cable connectors.

	Maximum Voltage	Characteristic Impedance in Ohms	Maximum Frequency (GHz)	Relative Cost	Coupling
UHF	500	Nonconstant	0.3	Low	Threaded
BNC	500	50	10	Low	Bayonet
TNC	500	50	10	Med.	Threaded
General Radio APC-7	1000	50	18	High	Spring-action and threaded
Microdot	1500	50, 70, or 93	2	Med.	Threaded
50 CM	500	50	4	Med.	Push-on, self-locking
HN	5000	50	4	Med.	Threaded
MHV	5000	Nonconstant	0.1	Med.	Bayonet
SHV	5000	50	10	Med.	Bayonet

Data largely obtained from:
Coaxial Connectors, Catalog CC-6, Amphenol RF Division, Amphenol Corp.
Terminal and Connector Handbook, American Pamcor, Inc.
Coaxial Connector Catalog 100-2, MALCO, Microdot Company

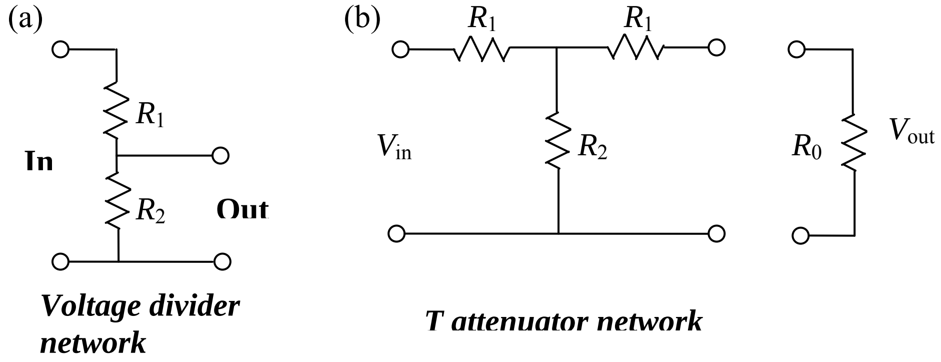
1.7.2 Pulse attenuators

Attenuators can be used in situations where it is necessary to reduce the amplitude of a pulse, for example, in order to match the input requirements of a component.

- **However, this situation should be avoided, if at all possible, when dealing with linear pulses (i.e. inputs/outputs of linear amplifiers) as attenuation inevitably hurts the signal-to-noise ratio.**

The simplest attenuator is the resistive voltage divider, shown in Figure 1.4(a). However, when using this divider, attention needs to be paid to input impedance and to its high-voltage performance. To provide a constant multiplication factor of $R_2/(R_1 + R_2)$, the divider must be used with a source impedance $Z_0 << R_1$ and the attenuated pulse must be applied to a following component with an input impedance $Z_I >> R_2$. In addition, because of non-ideal resistors and stray capacitance, a simple divider network is not suitable for pulses with fast rise or fall times (< 100 ns).

The T-attenuator, also shown in Figure 1.4, is more popular as a fast attenuator. It has the advantage of symmetric and equal input and output impedances, which allows for convenient matching to cables and devices. Attenuators of this type can have excellent high-frequency characteristics.



$$\alpha = \frac{V_{in}}{V_{out}} \qquad R_1 = R_0 \frac{1-\alpha}{1+\alpha} \qquad R_2 = R_0 \frac{2\alpha}{\alpha^2 - 1}$$

Figure 1.4 (a) A simple voltage-divider network to attenuate a pulse. (b) A T-attenuator network.

1.7.3 Pulse splitter

For slow pulses, where impedance matching is not so important, the familiar `tee' can be used to split the pulse chain into two branches without problems.

The circuit shown in Figure 1.5 can be used when impedance matching is required to prevent reflections or distortions. A pulse applied to any terminal will be supplied to the other two, while maintaining a constant impedance. For example, for a 50 Ω splitter, the resistance values should each be 16.6 Ω. In this case, the impedance `looking' into any terminal will be 50 Ω, if the other two terminals are connected to 50 Ω loads. The signal delivered to each load will be only half what it would be if the load were directly applied to the source.

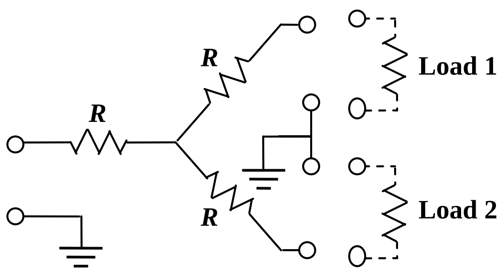


Figure 1.5 A symmetric pulse-splitter circuit. This can be used to supply two loads while maintaining matched impedance levels.