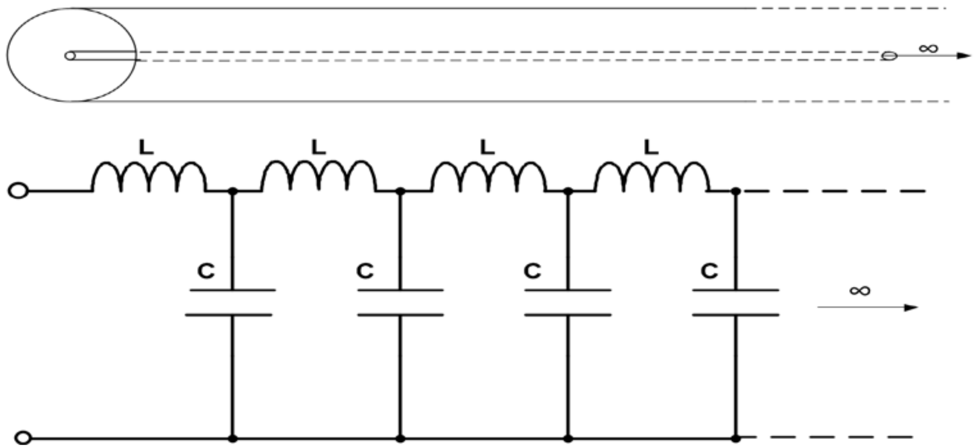
Coaxial Cables

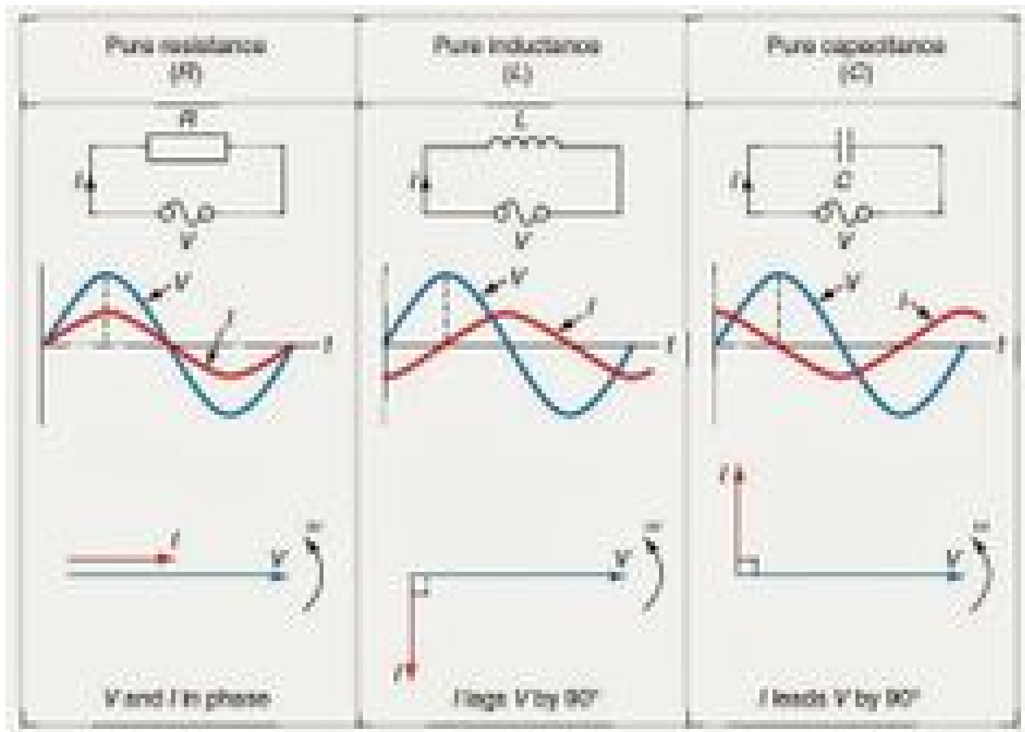
Reflections and Terminations
with Pulse Signals

Consider a coaxial cable of infinite length and its equivalent circuit

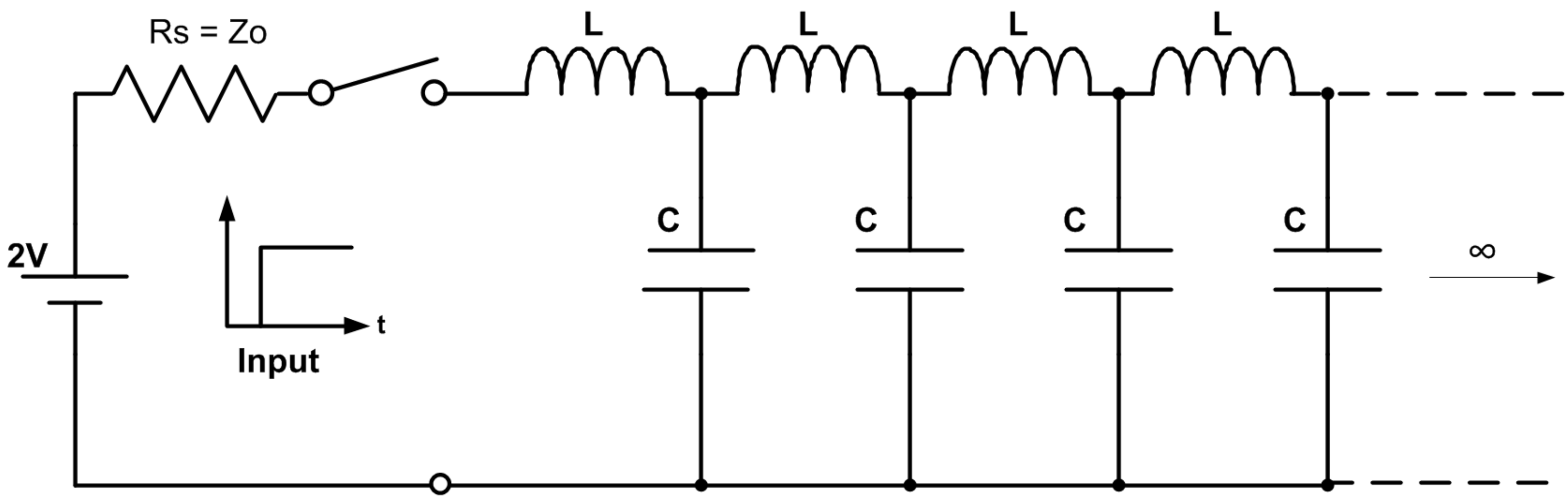


- L is the inductance per unit length between the inner and outer conductors and C is the capacitance per unit length between the two conductors.
- If we measure the impedance of this infinite cable at the input we find that it is purely resistive and equal to $Z_o = \sqrt{L/C}$. This is known as its characteristic impedance and is between 50 to 100 ohms for cables of about 5 mm diameter.
- If a step voltage V is applied to the input it travels down the line at about 2/3 the speed of light (~ 5ns/m) and charges up the cable capacitance to V as it goes down the line.
- The time taken to travel a unit length is $T_d = \sqrt{LC}$

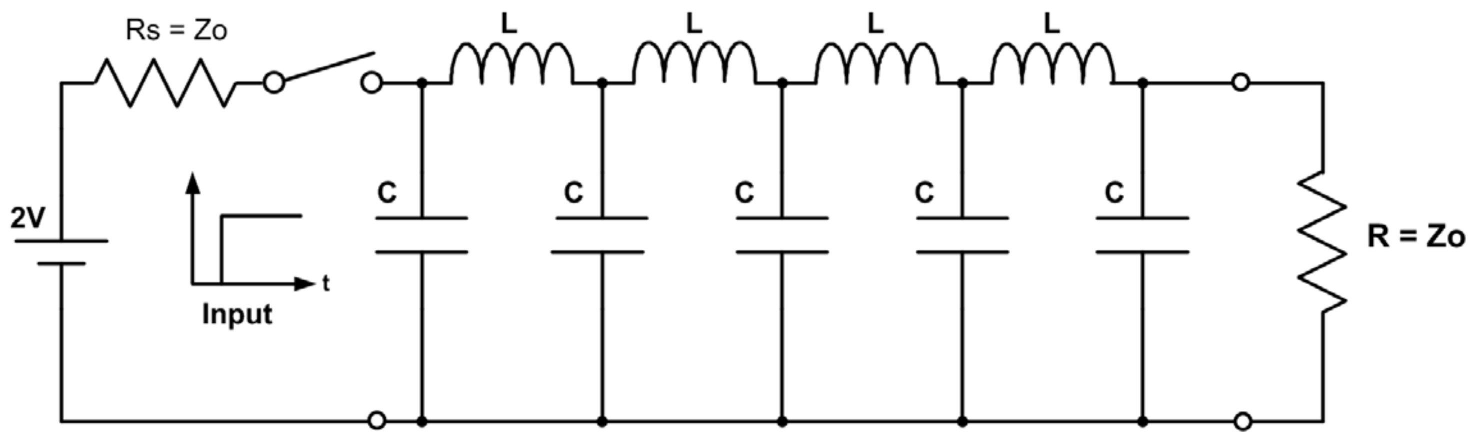
Concept of Resistive, Inductive, Capacitive circuits.



Infinite Cable with a step input of V volts

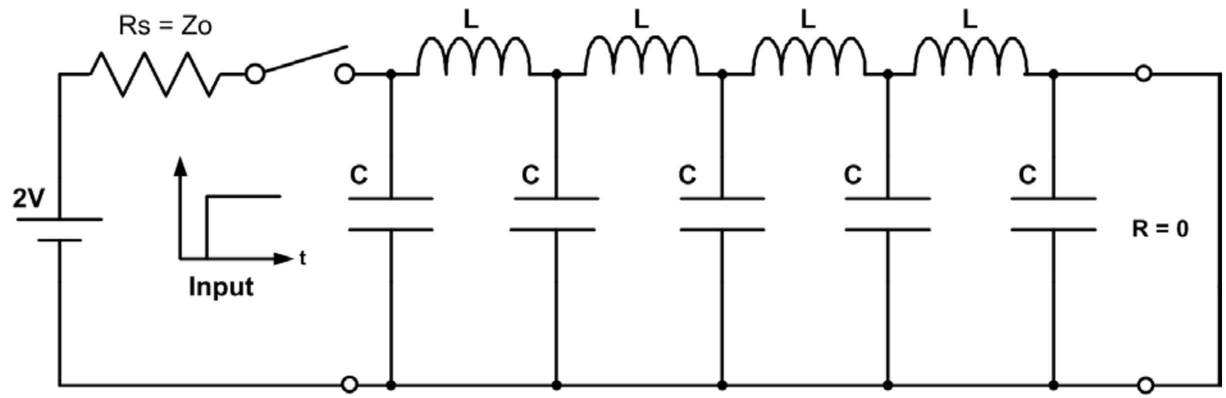


Finite cable terminated with R = Zo



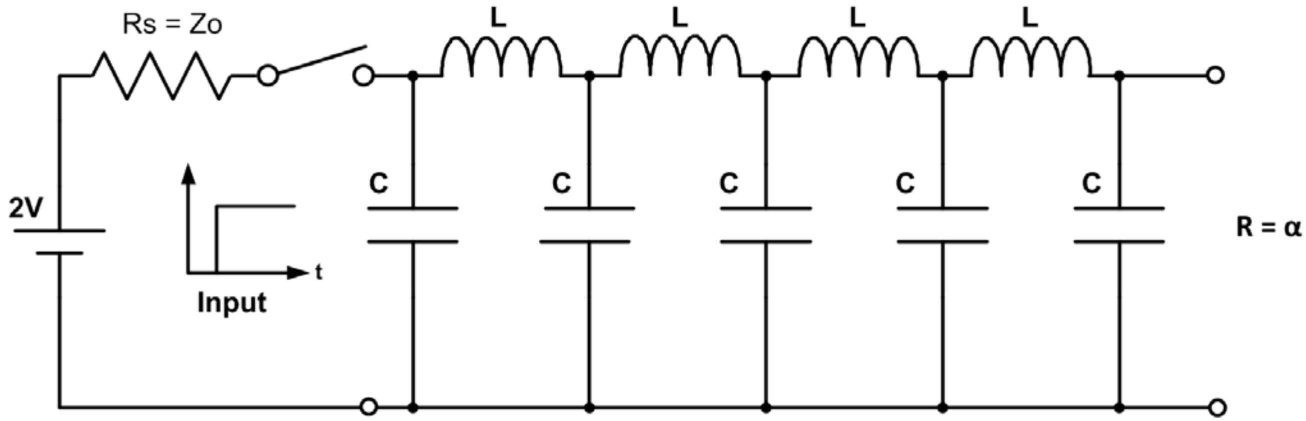
- If we now cut the cable and connect a resistor R equal to Zo across the output it still appears is an infinite line from the point of view of the input voltage. The step voltage V will travel down the line as though it were an infinite line of characteristic impedance Zo, charging the capacitors to V. When it reaches the end the voltage across R will become V and the current though it will be the same current that would flow down the rest of an infinite cable (V/Zo). There will be no reflections as in an infinite line. The step waveshape energy will be completely absorbed in R.

What happens if the resistor is not equal to Zo?
e.g. if R = 0



- If R = 0 there is a short circuit at the end of the cable and the voltage at the output must be zero at all times. When the switch is closed the step voltage V will still be applied to the input and charge the first capacitor. The voltage will travel down the line charging all the capacitors to V until it reaches the last capacitor which cannot charge due to the short circuit. The current will flow through the short circuit instead. The previous, second to the last, capacitor will now discharge from V to zero volts through the short circuit . Then the capacitor before that until eventually the first capacitor has zero volts across it. This is what you would expect if a coaxial cable is short circuit at the output – the input must be zero as well, after a time 2TD. (The time to travel down any cable length D is TD)
- We can say that the step voltage has travelled down the line charging capacitors to V until it reached the short circuit. Then the step voltage was reflected and inverted to become –V and travelled back towards the input discharging capacitors. The incident and reflected step voltages V and –V cancel out to zero.

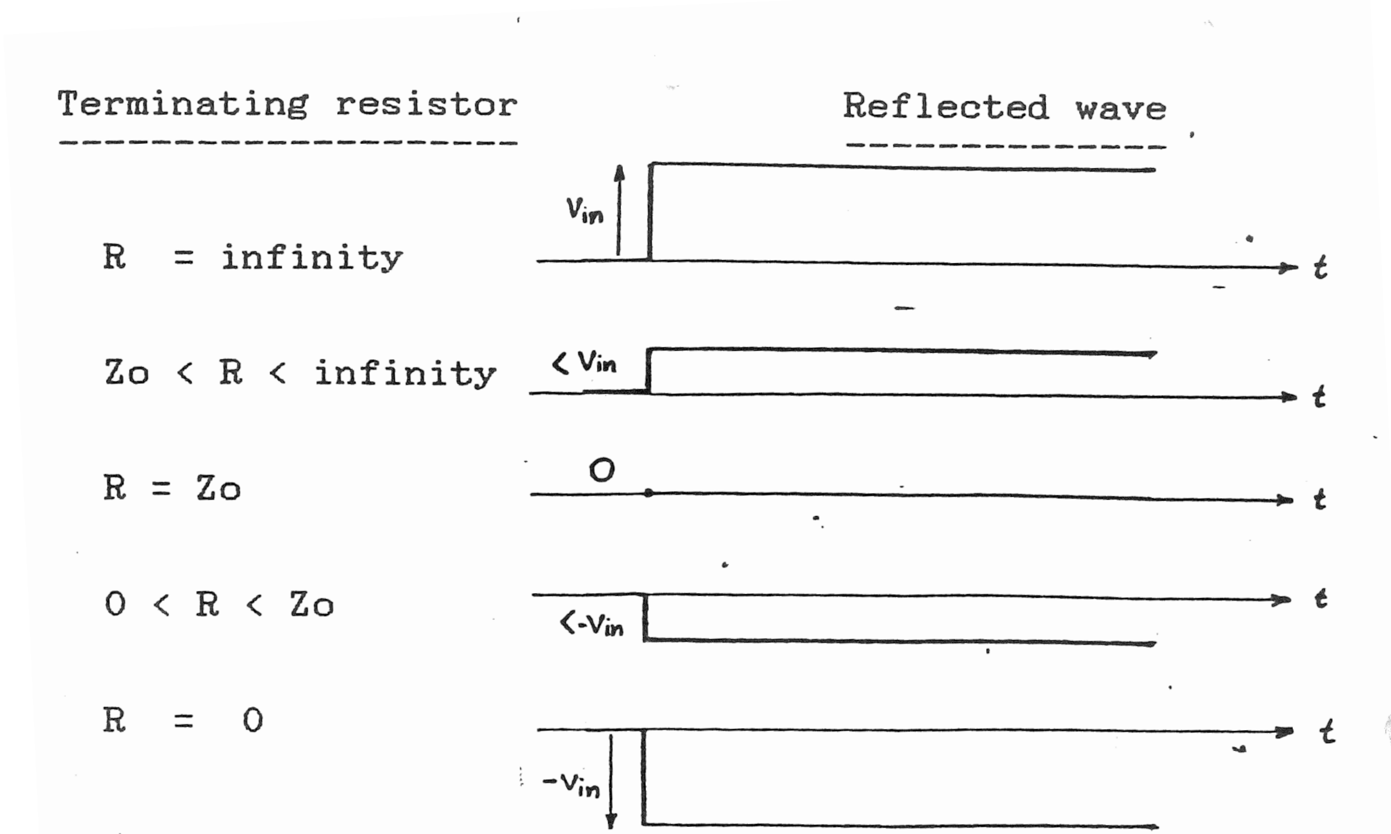
What happens if the resistor is equal to infinity?



- If R = α there is an open circuit at the end of the cable. When the switch is closed the step voltage V will still be applied to the input and charge the first capacitor. The voltage will travel down the line charging the capacitors to V until it reaches and charges the last capacitor. The current, which would have continued flowing down an infinite line, now cannot and so it puts additional charge on the last capacitor charging it above V volts, in fact to 2V. Then the previous, second to the last, capacitor will charge from V to 2V volts. Then the capacitor before that until eventually the first capacitor has 2V volts across it. This is what you would expect if a coaxial cable is open circuit at the output – the input must be the same as the output, after a time 2TD.
- We can say that the step voltage has travelled down the line charging capacitors to V until it reached the open circuit. Then the step voltage was reflected (non-inverted) and travelled back towards the input charging capacitors more. The incident and reflected step voltages V and V add up to 2V. The reflected wave sees Rs=Zo terminating the input and there are no further reflections.

So if the termination is α we get a reflection equal to the input
If the termination is = Zo we get no reflection
And if the termination is zero we get an inverted reflection

What happens if the termination is < Zo ? Or if it is > Zo but < α ?



So if the termination is < Zo we get a reflection less than the input V
And if it is > Zo but < α we get an inverted reflection but less than the input V

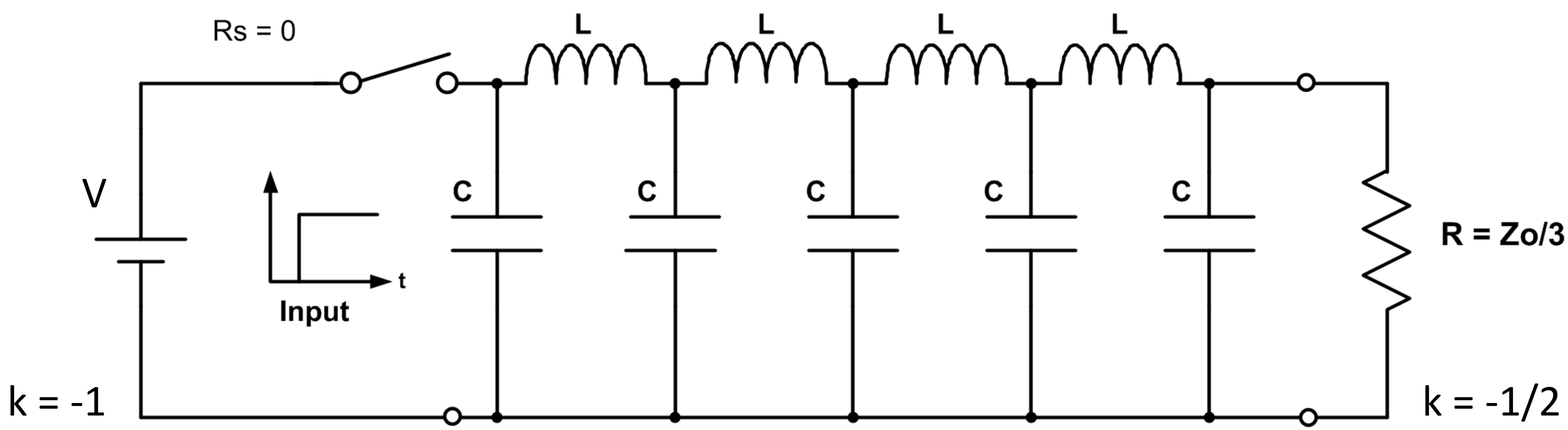
- The amplitude and polarity of a reflected wave can be calculated from

$$k = (R - Zo)/(R + Zo)$$

where k is the fraction of the incident wave that is reflected.

Consider the case when the reflected pulse is – V/2

- Consider the case when the signal source impedance is zero (Rs=0), and the reflected pulse is half Vin, and inverted so that k = -1/2 (i.e. R = Zo/3).



When V is first applied it travels down the line charging up the capacitance to V as it goes. At a time TD it reaches the output where half V is reflected and inverted. The resultant output at this time is then V - V/2 = V/2.

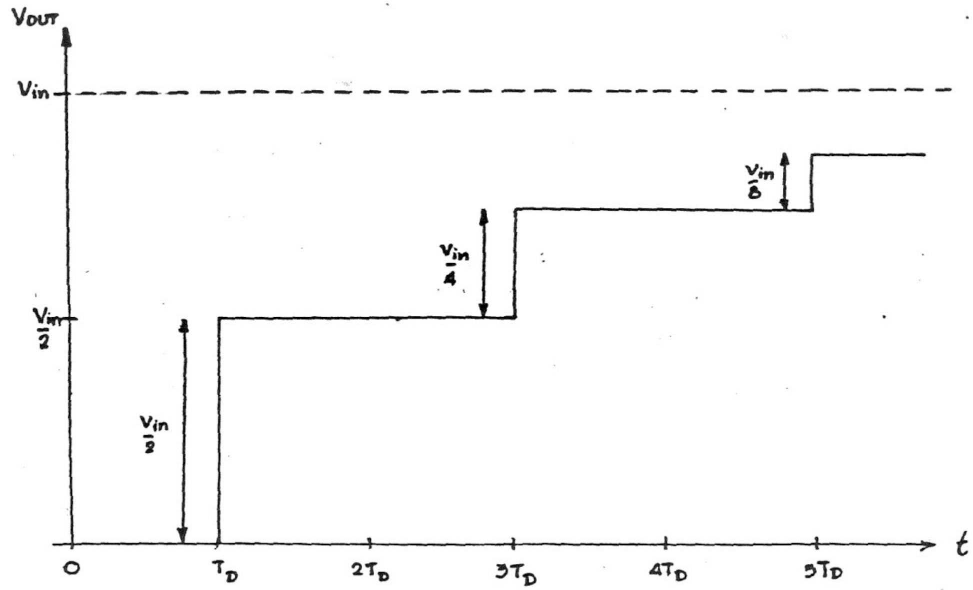


Fig. 6.5 Output waveshape for R = Zo/3. (Vin = V)

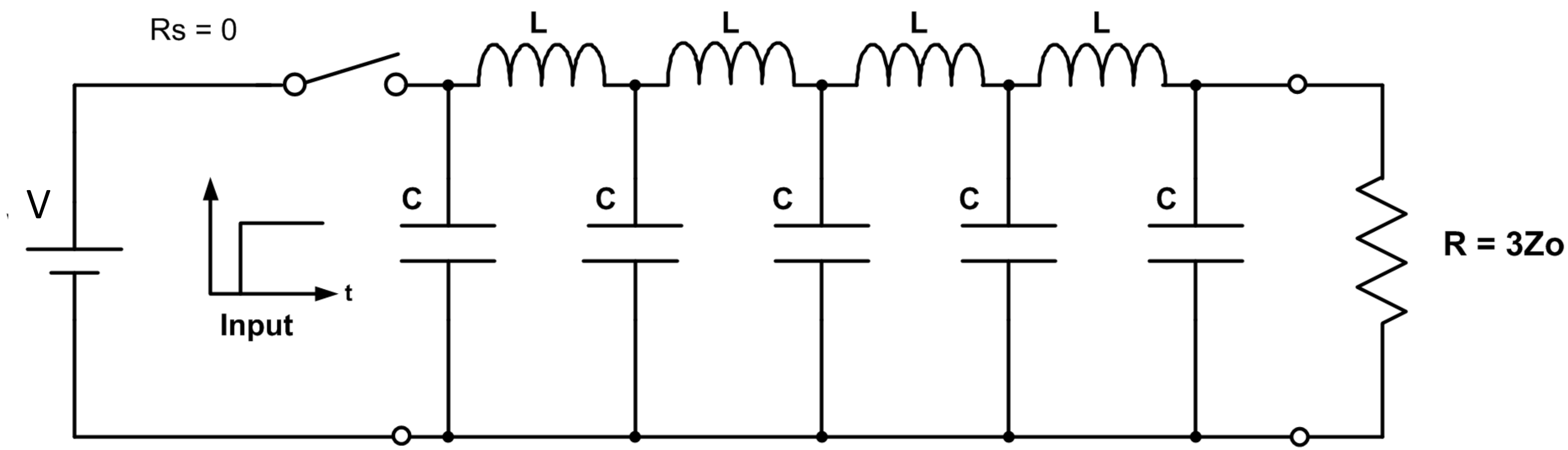
- The reflected wave travels back towards the input reducing the charge on the capacitors to V/2 all along the line. When it gets to the input it sees a short circuit (the voltage generator internal resistance is zero) so the reflected wave of - V/2 is reflected again and re-inverted to become +V/2. This travels back towards the output charging the capacitance up to V = (V/2 + V/2) again, but when the travelling wave of +V/2 reaches the output at time 3TD half of it is reflected inverted, so the total output at this time is V - V/4 = 3V/4.
- Similarly after another time interval 2TD later, i.e. at 5 TD, V/8 will be subtracted from V as shown. After about 10TD Vout almost equals V.

- A similar thing would happen for any other value of R less than Zo, but different fractions will be reflected each time, according to the value of k.

- If we have R>Zo then the reflected fraction is not inverted.

Consider the case when the reflected pulse is +1/2 Vin

- Consider the case of R = 3Zo below, so that k = +1/2.



k = -1

k = 1/2

The output waveshape then looks like Fig. 6.6. below

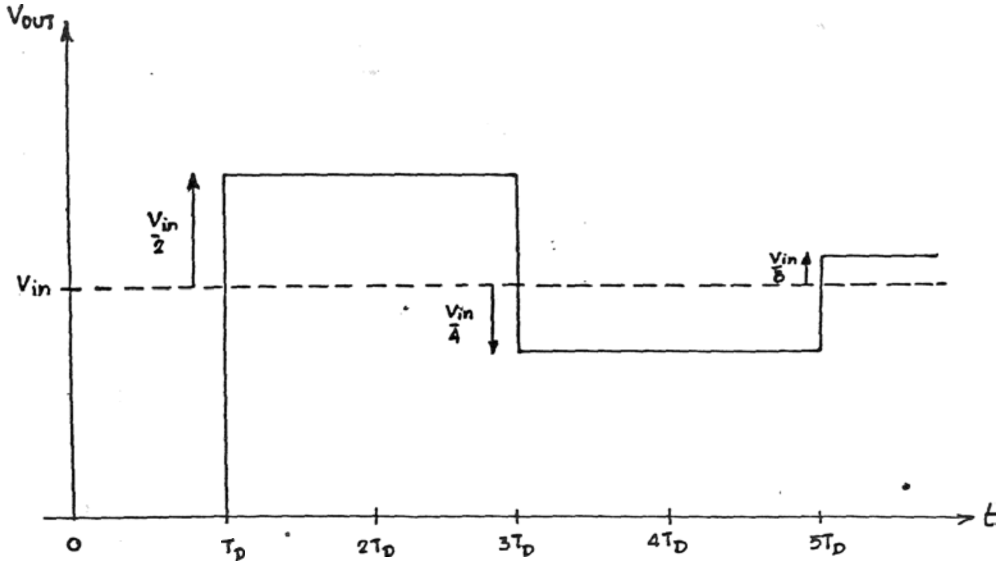


Fig. 6.6 Output waveshape for R = 3Zo. (Vin = V)

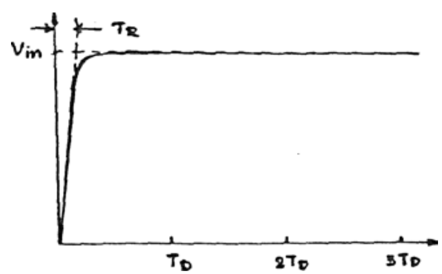
- Again when the step voltage is applied at the input it travels down the line charging the capacitance up to V as it goes. After a time TD it reaches the output and half V is reflected back down the line adding to the original voltage to produce 1.5 V at the output at time TD. The V/2 which is reflected down the line hits the input short circuit and is inverted and reflected, so -V/2 goes back to the output reducing the charge on the capacitance to 1.5 V - V/2 = V as it goes. When -V/2 reaches the output at time 3 TD half of it is reflected, but it is not re-inverted so -V/4 travels back to the input leaving Vin - V/4 = 3 V/4 at the output, at time 3 TD. Similarly V/8 is added to V at time 5 TD and at about 10 TD, Vout = V.

So now we can see when it is important to prevent reflections and when it is not necessary.

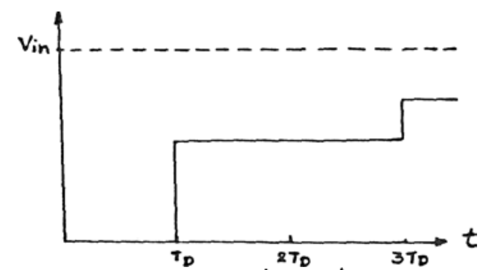
If Tr < 10 TD we need termination

If Tr ≥ 10 TD we do not need termination

- We assumed in the cases above that the rise time, Tr, of the input step was zero (or very small). For signal rise times which are small compared to TD we will get distortion of the input step like above, and we should prevent it by termination, either by putting Rs = Zo or R = Zo or both to eliminate reflections. See Fig. 6.7a below



input

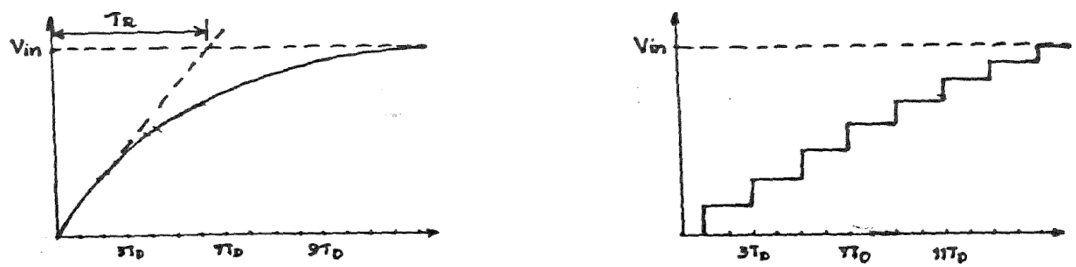


output

Fig.   6.7a. If Tr < 10 TD we will have distortion at the output and we need to terminate the cable with a resistance R = Zo (or Rs = Zo).

If Tr ≥ 10 TD we do not need termination

If the input signal rise time is equal or more than 10TD the reflections will occur in such a short time that they will not be noticed, so it makes no difference if we do not terminate the cable with its characteristic impedance. See Fig. 6.7b.

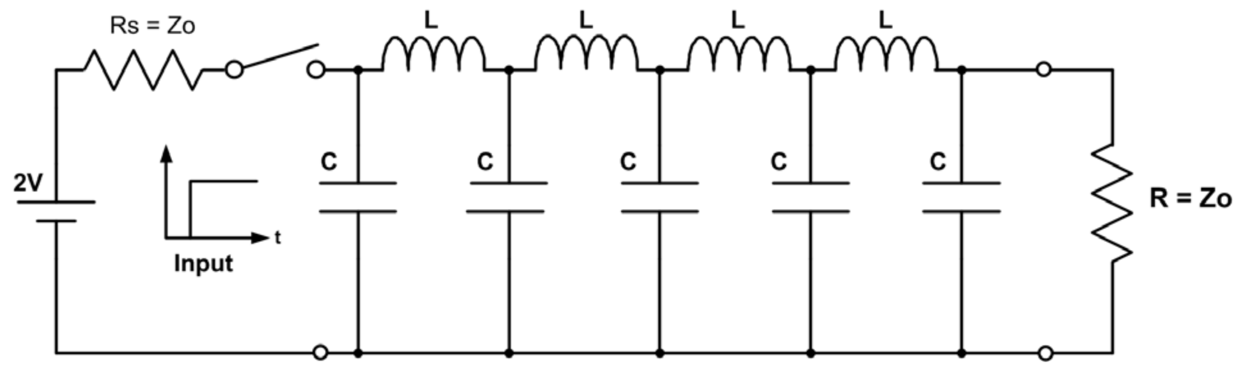


input **output**

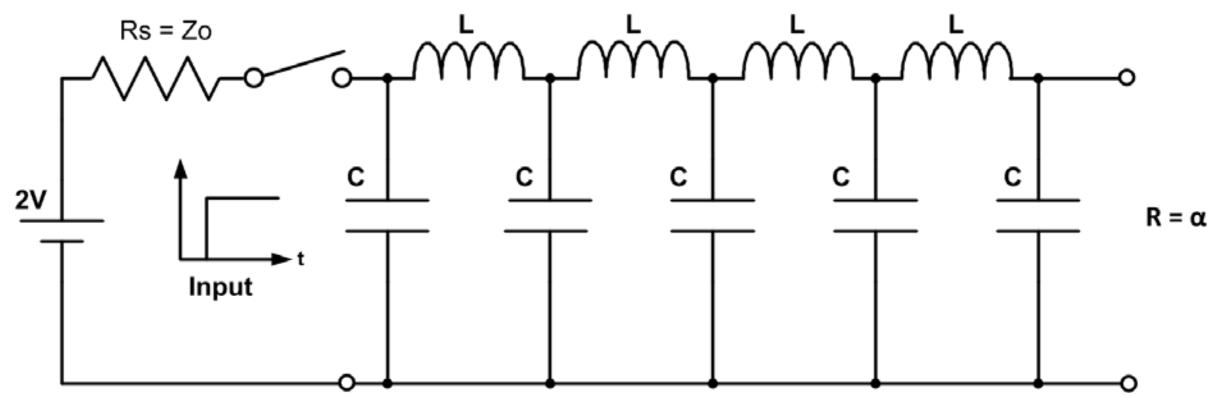
Fig. 6.7b. If Tr ≥ 10TD the output resembles the input and we have little distortion. It is not necessary to have the correct termination resistance.

In practice any short (ns) rise time signals and/or long cables (more than a few meters) should be examined with a scope for reflections, and if necessary termination applied (sending or receiving end).

Two kinds of termination: sending end and receiving end

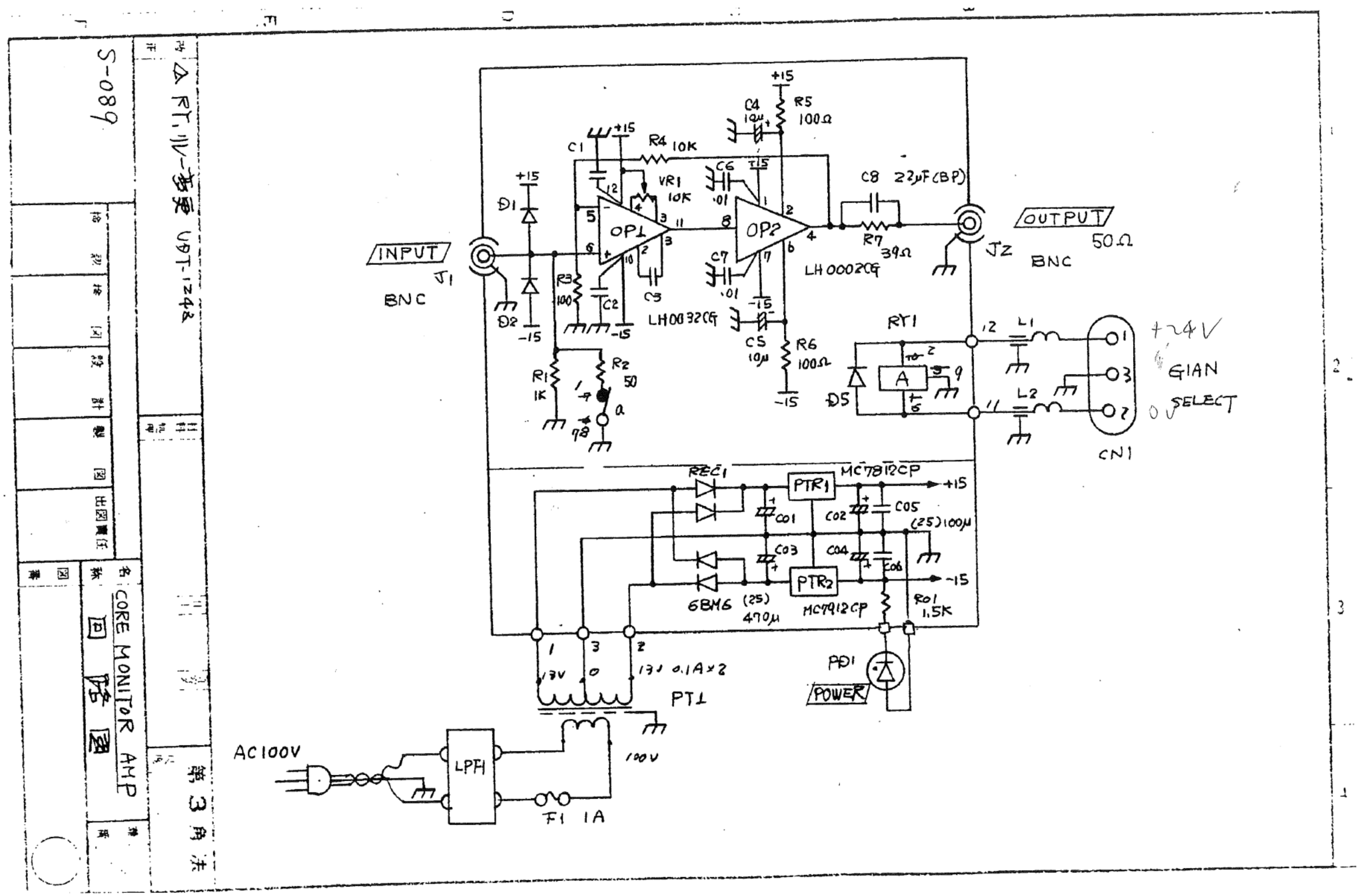


- Either kind can stop distortion due to multiple reflections.
- You can use both to remove multiple reflections if the termination is not perfect.
- Sending end is best as it requires less current from the signal source and can gives twice the signal voltage (2V) at the cable output due to the one reflection that doubles the output.



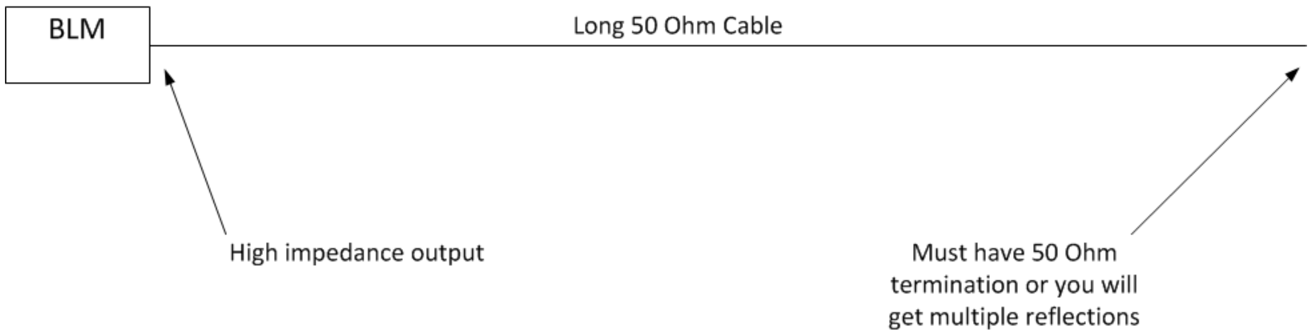
Examples at SLRI of Termination Schemes

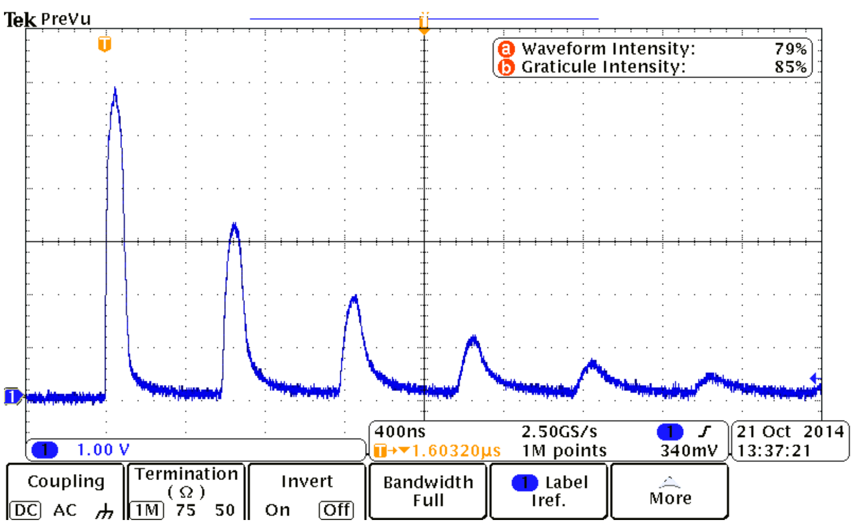
Linac current monitor signals: sending end terminated 50 ohm



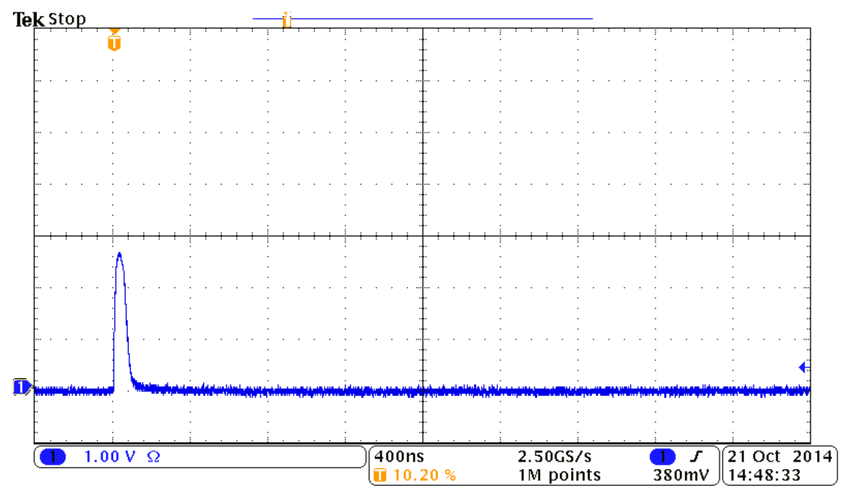
Examples at SLRI of Termination Schemes

Beam Loss Monitor (BLM) signals





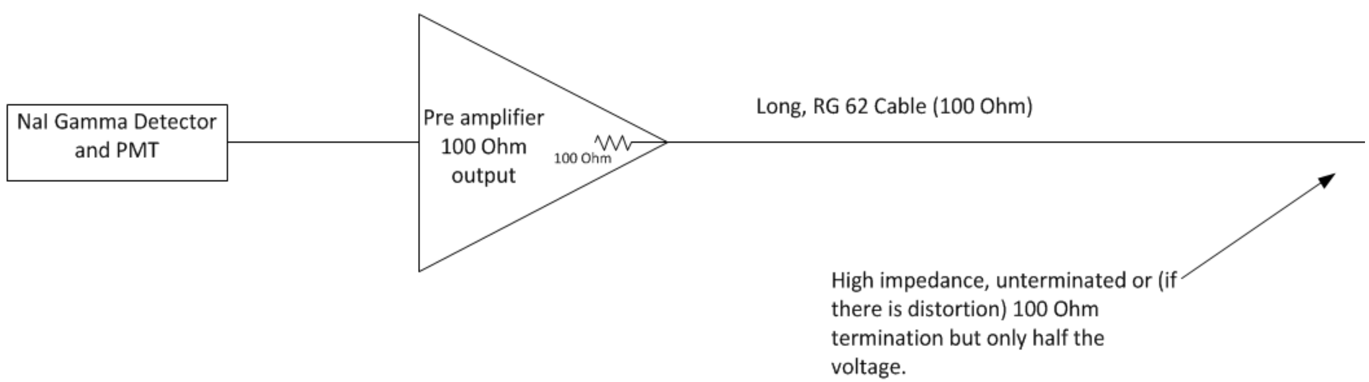
Unterminated, multiple reflections.



50 Ohm terminated, half the amplitude.

Examples at SLRI of Termination Schemes

- Radiation detector (NaI Gamma Safety Monitors) preamp outputs (100 ohm)
- Any others ?



Some Practical Considerations

Using scopes to measure reflections:

- You need to be able to properly trigger and use a scope to correctly see reflections. Set to ‘Normal’ trigger (not ‘Auto’) and correctly adjust the trigger level. If necessary get a scope tutorial.
- The bandwidth of the scope must be enough to be able to correctly see the rise time of your signal. Use the formula, f = 0.35/tr, to calculate the required bandwidth f for any rise time tr. So a 1ns rise time requires, at least, a 0.35GHz (350MHz) scope. A 100MHz scope can correctly see 3.5ns rise times - no less.
- Don’t make the mistake of looking at a signal on a scope input set to 50 Ohm and seeing no distortion, then moving the cable to some other equipment and thinking it is still terminated. It might not be! Use a T piece and a scope probe to check. See demonstration.
- Calculate how much delay is in your cable (5ns/m x length) and set the timescale of your scope screen width to more than twice that or you may miss the reflection – it might be off screen.

Some Practical Considerations (continued)

- T’s and split cables connections: Be careful when connecting the end of a long cable to two inputs. Only ONE of them should be terminated. The other should be high impedance with a very short extra cable.

  If you split the end of a long 50 ohm cable with a T piece and terminate both outputs with 50 ohms the total load impedance on the long cable will be only 25 ohms and you will get reflections.

Table 2.1 Properties of common coaxial cables.

Cable Type	V MAX (v)	Impedance (ohms)	Capacitance /foot (pF)	Outside Diam. (in.)	Matching Plug
RG-58C/U	1,900	50	29.5	0.199	UG 88C/U(BNC)
RG-213	3,000	50	29.5	0.405	UG 959(BNC)
RG-59B/U	2,300	75	20.5	0.242	UG 260(BNC) or MHV or SHV
RG-62A/U	750	93	13.5	0.249	UG 260
RG-174/U	1,500	50	30.0	0.1	Lemo FOO.250
Micro-dot 93 -3913		100	13.0	0.132	Micro-dot 32 - 75

- Note that cables of the same impedance always have the same capacitance no matter what the physical size.
- Lower capacitance cables (100 ohm) are often used in critical, low noise applications such as the short (less capacitance) cable from semiconductor radiation detectors to preamplifier’s inputs. Or if a long cable needs to be connected to an amplifier output that cannot drive a large capacitance as is the case with some amplifiers.

Some Practical Considerations (continued)

- Learn to 'feel' the difference in size between 50 ohm RG58 and 75 ohm RG59 or '100ohm' RG62. If necessary read the cable printing to make sure. Don't normally mix different impedance cables in any connections – that will cause reflections. 75 ohm cables are used in TV video applications – don't accidentally pick one up and use it in a 50 ohm application.

- Check the current capability of pulse amplifier outputs when terminating at the receiving end with high count rates. Amplifiers can become non-linear (reduced amplitude for large signals) if overloaded.

e.g. 10 V pulses at very high count rates can give an average DC voltage close to 10V. 10 V across 50 ohms produces a current of 10/0.05 = 200mA. This current must be supplied by the output so check that the output is capable of supplying this much current.

This is another reason why sending end termination is better than receiving end.

- Final Note: you only really learn this stuff when you play around with different cables, terminators and a scope, and see what happens and try to figure it out. That’s when it sinks in.

Thank You for Your Attention