Transmission Lines and Reflected Signals

Transmission lines are a very important circuit element in electrical engineering. Transmission lines are distributed elements, in contrast to lumped elements such as resistors (R), capacitors (C), and inductors (L). The electrical characteristics of a distributed element depend upon its physical geometry, and the electromagnetic fields which dictate its circuit behavior are distributed over a range of space. Unlike in a purely lumped element circuit, geometry matters and is a primary factor for how the circuit behaves. A transmission line cannot be described by a simple current-voltage (I-V) relationship like RCL elements can. Distributed elements, such as transmission lines, are more fundamentally described by the electromagnetic field distributions, which can be either static (DC), time harmonic (AC), or transient waves or pulses. Transmission lines, the subject of this laboratory, are conduits for the propagation of electromagnetic waves which carry both information and power. Travelling waves interact with inhomogeneities in their path, and these produce reflections. These reflected waves are an integral aspect of transmission line behavior which can be both useful and a challenge to manage.

A quick overview

The characteristic impedance of a transmission line Z_0 is the ratio of the voltage and current of a wave travelling along the line; that is, a wave travelling in one direction in the absence of reflections in the other direction. The characteristic impedance is determined by the geometry and materials of the transmission line. In a lumped-element model, Z_0 can be expressed in terms of RLGC parameters and the angular frequency ω of the electromagnetic wave:

$$Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \ .$$

The phase velocity, also called the propagation velocity, is determined by the material itself:

$$v = \frac{1}{\sqrt{\mu\varepsilon}} \ ,$$

where μ and ε are respectively the magnetic permeability and electrical permittivity of the dielectric material separating the conductors.

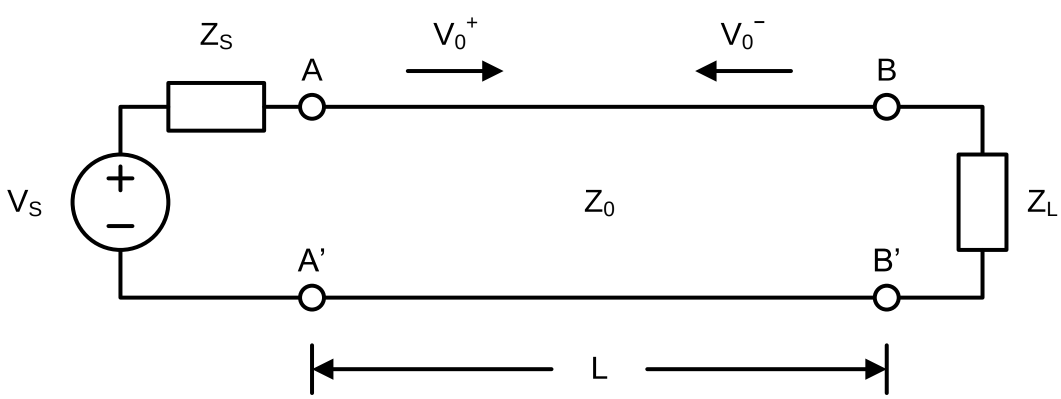

Figure 1. A transmission line of length L connected to a source and a load.

A signal travelling along an electrical transmission line will be partly, or wholly, reflected back in the opposite direction when the travelling signal encounters a discontinuity in the characteristic impedance of the line, or if the far end of the line is not terminated in its characteristic impedance. As shown in Fig. 1,

V_S is the source, Z_S is source resistance, AA′ and BB′ are ends of the transmission line, and Z_L is the load. The reflection coefficient Γ represents the ratio of the amplitude of the reflected voltage (or current) wave to the amplitude of the incident voltage (or current) at the load:

$$\Gamma = \frac{V_0^+}{V_0^-} = \frac{Z_L - Z_0}{Z_L + Z_0} \ .$$

For this lab, three types of loads will be considered first: an open circuit load, a short circuit load, and a properly matched load. An open circuit load ideally gives $Z_L = \infty$, although in practice a load for which $Z_L >> Z_0$ or simply the lack of any component on the end of the line are effectively open circuit loads. A short circuit load ideally gives $Z_L = 0$, and likewise $Z_L << Z_0$ is effectively a short circuit load in practice. A short circuit load and an open circuit load both represent the case of total reflection. For the open circuit load, $\Gamma = +1$; and for the short circuit load, $\Gamma = -1$. Note that the short circuit load produces a phase reversal of the reflected voltage wave. A matched load is a load whose impedance is equal to the characteristic impedance of the transmission line, $Z_L = Z_0$, at a certain frequency. A matched load produces no reflections, $\Gamma = 0$, and all of the incident power is absorbed by the load.

The voltage standing wave ratio or VSWR is the ratio of the maximum voltage $|V|_{\max}$ to minimum voltage $|V|_{\min}$ along the transmission line:

$$\text{VSWR} = \frac{|V|_{\max}}{|V|_{\min}} = \frac{1+|\Gamma|}{1-|\Gamma|} \ .$$

The VSWR, sometimes called simply SWR when it is understood that voltage is being described, provides a measure of the mismatch between the load and the transmission line; for a matched load with $\Gamma = 0$, the VSWR = 1, and for a line with $|\Gamma| = 1$, the VSWR = ∞. VSWR or SWR is the most common method of specifying how well a transmission line is delivering its incident wave to the load, i.e. how well reflections are being minimized. Unity VSWR is the ideal that is desired. VSWR meters are very common on equipment that deals with sending RF power to loads, such as transmitters, tuners, and matching networks.

Some practice measurements of reflection coefficient

This exercise will give some practice using the FieldFox CAT application for making several types of cable measurements. Return Loss (RL) and Insertion Loss (IL) are purely scalar functions which measure the power lost to the cable as a function of frequency, and these have been examined previously. The measurement of VSWR and the very powerful Distance To Fault (DTF) function involve measurements of the signal reflected back from the cable, and lying at the heart of both of these is the reflection coefficient Γ. This lab will concentrate on the VSWR and DTF functions.

The FieldFox is fundamentally a swept frequency analyzer (SFA), and the CAT application operates in that manner. The Distance To Fault (DTF) function displays the fraction of power that is reflected from various distances out along the cable. It might at first seem a bit mysterious just how the instrument accomplishes this measurement. The FieldFox creates the DTF measurement by first taking a frequency sweep over a specified range and measuring the signal that is reflected back into Port 1 relative to the amplitude of the test signal that was sent out from Port 1. The FieldFox then performs a numerical Fourier transform to create a time domain representation of the reflected signal from the frequency sweep. By assuming a default propagation velocity for the waves, the speed of light c, the time delay for reflected components of the received signal can be related to distance down the cable, once a factor of 2 has been included to account for all such delays being round trip times. In other words, the instrument takes data in the frequency domain, converts it numerically to the time domain, and then converts time to distance by assuming a propagation velocity, the speed of light being the default.

The resulting DTF display is an exceeding powerful tool for locating the source of problems in cables. Suppose that a 1000 ft. long buried cable is found to have a short circuit. Where would one need to dig to repair the short? An ohmmeter or oscilloscope would be of no help; the actual location of the short circuit needs to be determined. This is precisely the situation in which a swept frequency analyzer can isolate the location of the problem, potentially saving a lot of time and money on excavation costs which might otherwise be required to dig up and replace the entire cable.

There are other types of instruments which perform similar cable test functions by launching a fast rise time pulse and recording the delay of the reflected signal in the time domain. These are known as time domain reflectometers or TDRs. The main difference between these and the CAT function of the FieldFox is that the time domain representation of the return signal is computed from the frequency sweep of the FieldFox rather than measured directly.

To get started, first turn on the FieldFox and allow the CAT application to load and launch. Refer to the prior labs on setting up the FieldFox if needed. Attach type N to type SMA coaxial adapters to Ports 1 and 2 of the FieldFox if they are not already present.

Next, attach one of the male SMA connectors of an 18-inch long section of RG58C/U coaxial cable to Port 1 and connect the other end to a male short circuit cap using a female-female SMA barrel connector. Figure 2 shows the male shorting cap, and Fig. 3 shows the photo of the female-female SMA barrel connector. Figure 4 shows the final connection of the cable and the FieldFox.

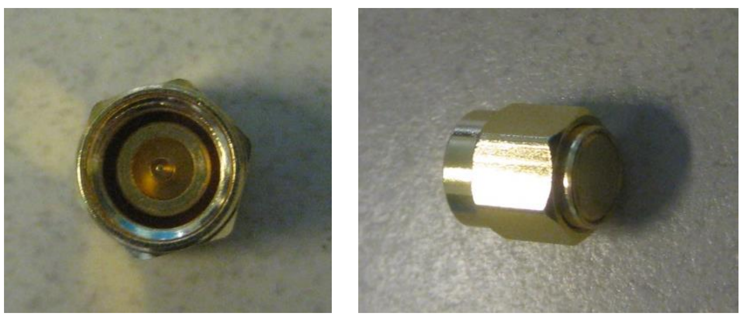

Figure 2. The male short circuit cap, top view and side view.

Figure 3. The female-female SMA barrel connector.

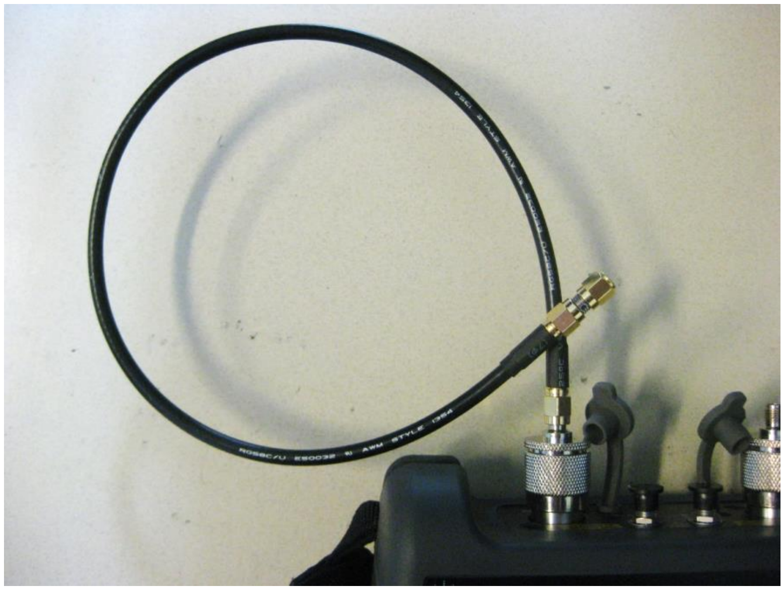

Figure 4. Connection of the FieldFox to the RG58C/U coaxial cable loaded with a short circuit cap.

Next, select the Distance To Fault (dB) measurement function. The DTF measurement function displays the reflected power along the y-axis as a function of distance along the x-axis. The default distance range is from 0 m to 100 m, so change the range from 0 m to 1 m. Press the Freq/Dist button and then press the Stop Distance soft key, followed by ‘1’ and the ‘m’ soft key for meters.

The reflected power is displayed as a function of distance. Observe the largest peak which indicates the reflection at the end of the cable. Record the distance at which the peak occurs, ℓ_0, which should theoretically be the length of the cable. This can be easily accomplished by using the marker function. Note that this measurement corresponds to a velocity factor of 1.000, which means that the FieldFox is assuming a propagation velocity equal to the speed of light. This is the default, because the FieldFox has not been supplied with any other information about the cable.

Now remove the shorting cap to convert the termination into an open circuit load. The DTF display should have only changed very slightly. Most of the reflected power is still coming from the reflection at the end of the cable. As far as the DTF function is concerned, a short circuit load and an open circuit load look electrically the same. Later on, the network analyzer application will show how these two situations are entirely different when phase information is included. For both the short circuit and open circuit loads, the level of the reflected signal should have been only 1 to 2 dB down from the level of the test signal that was sent out from Port 1.

Figure 5. A 50 Ω load resistor.

Now terminate the cable with a 50 Ω load resistor, similar to that shown in Fig. 5, and observe how the power from the cable end reflection has been greatly reduced. The level of the peak reflected signal should now be more than 15 dB down from the level of the test signal. If the cable was terminated in a perfectly matched load of $Z_L = Z_0$, then $\Gamma = 0$ and the DTF function would ideally show no reflected signals at all.

Figure 6. The variable 500 Ω potentiometer load.

Next replace the 50 Ω load with a variable 500 Ω potentiometer load, as shown in Fig. 6. By adjusting the potentiometer, this load can be varied from a 0 Ω (a short circuit), to 50 Ω (a matched load), to 500 Ω (not quite an open circuit, but approaching one). Examine the potentiometer and determine which direction the wheel must be turned to produce the short circuit 0 Ω case. The DTF display should gain resemble that for the previous short or open. Slowly rotate the wheel of the potentiometer to increase the load resistance and observe the changes in the cable end reflection. The reflected power should drop to a minimum around where $Z_L = Z_0 = 50\ \Omega$, and then increase again as the potentiometer is dialed up to its full value of 500 Ω.

It might be observed that the cable end reflection has become double-peaked with the adjustable potentiometer load. By examining the geometry of this load, speculate on why there may now be two closely spaced peaks instead of one. Indeed, the round trip distances associated with the two peaks are different.

The DTF (dB) function is a logarithmic vertical axis which allows it to show a very wide dynamic range of reflected signals. To reduce the clutter and focus more on the strongest reflected signals, the DTF (VSWR) function provides better clarity. From the Measure menu, press the DTF (VSWR) soft key and the display should simplify to showing only the strongest reflections. It may be necessary to rescale the display. If this is needed, press the Scale/Amptd button, and then either adjust the Scale and/or Ref Level to a better choice of axes, or alternatively press the Autoscale soft key. Recall that a VSWR of unity corresponds to a zero reflection coefficient. The larger the VSWR, the greater the reflections.

The raw VSWR frequency sweep data can be displayed by pressing the VSWR soft key from the Measure menu. This will show a fairly complicated, oscillatory trace. Computing the Fourier Transform of the VSWR trace will produce the DTF (VSWR) data once the time axis has been scaled over to distance.

If it has not already been done, use the marker to find the distance of the cable end reflection, ℓ_0.

Some further analysis

The measured distance of the cable end reflection should have been found to be quite a bit larger than the nominal physical length of the coaxial cable, $\ell_0 > \ell_1 = 18$ in $= 0.457$ m. The electromagnetic wave propagates through the dielectric material of the coaxial cable which has a relative dielectric constant greater than unity. As a result of $\varepsilon > \varepsilon_0$, the wave propagates slower than the speed of light, $v < c = 2.99 \times 10^8$ m/s. Because of the smaller propagation velocity, a wavelength inside the cable is shorter than the wavelength of the same frequency electromagnetic wave propagating in vacuum, $\lambda < \lambda_0$. Note that the frequency is invariant to the media of propagation,

$$f = \frac{c}{\lambda_0} = \frac{v}{\lambda} \ .$$

Propagation time can analogously be phrased as

$$t = \frac{\ell_0}{c} = \frac{\ell_1}{v} \ ,$$

where ℓ_1 is the physical length of the cable, and ℓ_0 is known as the electrical length of the cable. The electrical length of a cable is most often phrased as a dimensionless equivalent number of wavelengths. The electrical length can therefore be computed as either ℓ_1/λ or ℓ_0/λ_0.

The velocity factor (VF) is the ratio of the actual propagation velocity *v* to the speed to light *c*, and this ratio becomes a scaling factor for each of the above proportions,

$$\mathrm{VF} = \frac{v}{c} = \frac{\lambda}{\lambda_0} = \frac{\ell_1}{\ell_0} \ .$$

Compute the velocity factor for the cable, based upon the measured electrical length and physical length.

The FieldFox provides automatic velocity factor conversions, and the actual velocity factor can be either entered as a numerical value or pulled from a preloaded cable table. To set the velocity factor, first press the Meas Setup key, and then the DTF Cable Specifications soft key. From here, there are two options. The velocity factor and cable loss can be manually entered as numerical values by choosing Velocity Factor and Cable Loss and entering the proper values. Alternatively, if the cable type is known, it can be selected from the cable table which contains the velocity factor and cable loss for different type of cables. To use the cable table, first press Edit/Save/Recall Cables soft key, and then press Recall Cables. Rotate the dial to highlight the entry RG58C, which will be on the second page, and then press Enter. The FieldFox will then display the distance axis taking into account this velocity factor. Go back to the DTF Cable Specifications, and it should now show a velocity factor of 0.667 and a cable loss of 0.00 dB/m.

Observe the rescaled DTF display, discuss the changes introduced by the velocity factor scaling, and now compare the distance to fault for the cable end reflection as compared to the nominal physical length of the cable. Are these two values now in better agreement?

As a side note, the vast majority of all low-cost coaxial cable uses polyethylene (LDPE or HDPE) plastic as the dielectric material. This happens to have some rather convenient values for DTF calculations. The dielectric constant of polyethylene, as used in most cable applications, is $\varepsilon_r = 2.25$. The velocity factor is then

$$\mathrm{VF} = \frac{1}{\sqrt{\varepsilon_r}} = \frac{1}{\sqrt{2.25}} = \frac{1}{1.500} = 0.667 \ .$$

A wavelength inside the cable is therefore 2/3 of a free space wavelength, and the physical length of the cable is 50% greater than the electrical length. When the data points to a velocity factor of 0.667, it is a pretty safe bet that the cable has polyethylene dielectric material. Most other plastics used as dielectric materials will have significantly higher dielectric constants, for example polyvinylchloride (PVC) has $\varepsilon_r = 3.0$ and silicone rubber has $\varepsilon_r = 3.5$. Teflon (PTFE or TFE) is one of the few materials with a lower dielectric constant of $\varepsilon_r = 2.05$. The electrical properties of a transmission line or cable reveal quite a bit about the materials it is made from, and vice-versa.

Measurement assignment

Now experiment with the CAT application and examine the effects of some common situations that occur in cable testing. For most of these measurements, the DTF (VSWR) function will prove the most convenient. If additional sensitivity is needed, switch to the DTF (dB) function to obtain greater dynamic range. Feel free to rescale either of the display axes to zoom in or out of the measurement trace features.

First, double the coaxial cable length by connecting another 18 inch long cable to the end of the first using a female-female SMA barrel connector. Test this overall 36 inch long cable with the open circuit, short circuit, and matched loads. Adjust the x-axis and y-axis of the DTF display as necessary, and explain the differences between the doubled cable from the single cable. A smaller peak may be observed in the location where the two cables are joined by the barrel connector. This is a minor reflection that arises from the imperfections of the connector itself. Likewise, there may also be observed a smaller peak at a distance very close to the FieldFox Port 1. This similarly arises from the imperfections of the first connection point and the N to SMA adapter.

Slowly unscrew one side of the barrel connector that is between the two 18 inch cable sections. Examine the DTF trace as the connection becomes looser and looser. There will be a sharp point where the reflection from this connection point will jump upwards and the reflection at the far end of the cable will fall. This is a fairly clear indication of an open circuit problem with the cable which is restricting signal transmission.

Replace the female-female barrel connector with a 3-port T-connector, leaving the third port simply unconnected and the far end of the second section terminated in an open circuit. Again, observe the DTF trace and interpret the results. Note that the 3-port T-connector simply connects the three ports together in parallel with no special attention to impedance matching or wave reflections from those ports. As a consequence, it can function as a 2-port union connector, but a poorer one than the simpler barrel connector. Explain why this is so based upon the geometry of the T-connector. As a side note, there are specific 3-port devices such as power splitters or power combiners which do pay a great deal of attention to proper matching of the port impedances so as to minimize reflections. Power splitters and combiners are completely different from the simple 3-port T-connector used here.

Change the displayed distance range to cover 0.00 to 2.00 meters. With open circuits on the T-connector and on the far end of the second section of cable, more than just two significant reflections should be observed. Explain the origin of the reflections which are associated with distances of 18 inches, 36 inches, 54 inches, and 72 inches. How can these happen if the total cable length is only 36 inches?

For an additional twist, literally, connect the far end of the second cable to the third port of the T-connector. This will produce a re-entrant loop using the second cable. New reflection peaks should now appear at distances halfway in between those that were showing previously. Explain the origin of these additional peaks. As a hint, remember that the Field Fox assumes a full round trip transit for each reflected signal. Later on, this configuration will be shown to be a simple form of resonator, somewhat analogous to a Fabry-Perot cavity in optics. The loop can then be disconnected at the T-connector.

Next, attach a matched 50 Ω load to the far end of the second cable and observe the effect on the DTF trace. Now attach a shorting cap to the third port of the T-connector. Although a short has been introduced into the middle of the transmission line, it only interrupts the signal transmission by a small amount. There still exists a significant reflection from the 50 Ω load, indicating that a good deal of power is passing through the T-connector in spite of its third port being shorted. In low frequency systems, shorting a pair of wires in the middle of their length would normally kill the possibility of transmitting any power past that point. Not so for high frequency RF and microwave systems. The propagation is due to travelling waves, not static voltages.

It is of interest to see how other types of transmission lines behave. Locate an 18 inch long section of twisted pair line which has female SMA connectors soldered on to both ends, as shown in Fig. 7.

Connect the twisted pair line to Port 1 using an SMA male-male adapter, as shown in Fig. 8. Leave the far end of the twisted pair line open circuited. Compare the DTF traces for the twisted pair line to that of the previous coaxial cable.

Figure 7. An 18 inch section of twisted pair line with female SMA connectors.

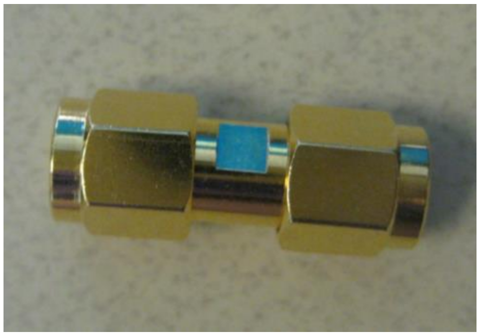

Figure 8. A male-male SMA connector.

One important feature is that the characteristic impedance of the twisted pair line is no longer 50 Ω. Most twisted pair line has a characteristic impedance closer to ~75 Ω. This means that the FieldFox will measure a strong reflection from a location very close to Port 1. Because of the closeness of this reflection to the N to SMA adapter, it can be difficult to distinguish its effects from those of the adapter. To move the junction to the twisted pair line farther away from Port 1, replace the male-male SMA connector with an 18 inch section of coaxial cable. The strongest reflection should still come from the transition from 50 Ω to 75 Ω line, but this should now occur at a distance of 18 inches out from Port 1.

With a clearly distinguishable peak associated with each end of the twisted pair line, its electrical length can also be measured. Note that the velocity factor is still set to 0.667 for the coaxial cable. Use the Marker Delta function to measure the distance between the reflection peaks from the two ends of the twisted pair line. Then measure the distance between the reflection peaks from the two ends of the coaxial cable. Both types of transmission lines are nominally 18.0 in = 0.457 m long. Use these measurements to compute the velocity factor for the twisted pair line, and from that, estimate what the effective dielectric constant for the twisted pair line would be. The twisted pair line does not use a polyethylene dielectric material. Instead, the insulation on the wires is polyvinylchloride (PVC) with ε_r = 3.0. Is this consistent with the velocity factor measurements? Explain what may be the cause of the discrepancy.

Experiment further with different combinations of coaxial cable and twisted pair line, and with the different open, short, matched, and variable terminations. Try to develop an eye for what the DTF traces are revealing about the transmission line. This will prove valuable in properly interpreting future results.

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