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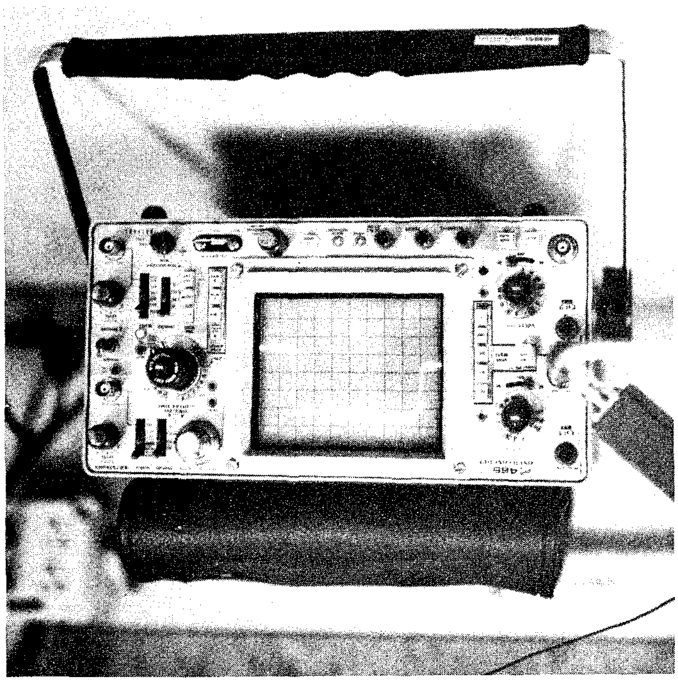
Find Fault with Your Coax

Is your cable really doing its job?
Find out with this elegant detective method.

Time Domain Reflectometry (TDR) is perhaps the most powerful method for wringing out a radio transmission line. Professional TDR instruments are expensive and therefore beyond the reach of amateurs. If you have access to an oscilloscope, however, you can build an *impromptu* TDR unit that will provide at least elementary capability.

TDR techniques can be used to locate faults on transmission lines, measure vswr, and determine the velocity factor of coaxial cable. The fault-finding capability is especially useful on systems containing very long transmission line, or, where the transmission line is hidden for much of its run.



The K4IPV home-brewed reflectometer.

Transmission Lines—Simplified and Revisited

Most amateurs have a rudimentary idea of the nature of a transmission line, especially as the term is used in radio-antenna contexts. On the naive level, we know that it is the cable which carries signals back and forth between the rig and the antenna. On a slightly more technical level, we find that the transmission line can be modeled as a complex circuit having both distributed inductance (L) and distributed capacitance (C). Fig. 1 shows an equivalent circuit. If dimension "A" in Fig. 1 is unit length, then L is the inductance per unit of length and C is the capacitance per unit of length. There is also a source impedance, R_S, which is the transmitter output impedance, and a load impedance, R_L, which is the antenna radiation resistance.

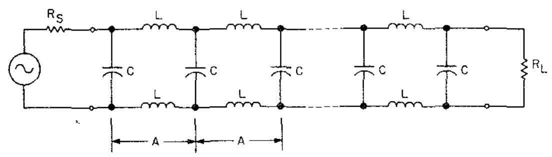


Fig. 1. Schematic representation of a transmission line.

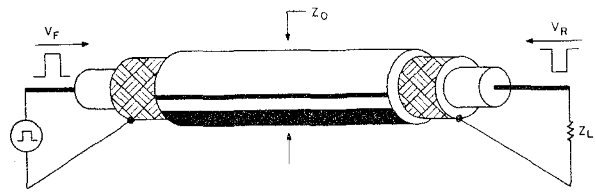


Fig. 2. Coax cable with surge impedance Z_0 and load impedance Z_L.

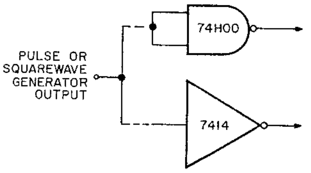


Fig. 3. Buffer to improve rise time of a signal.

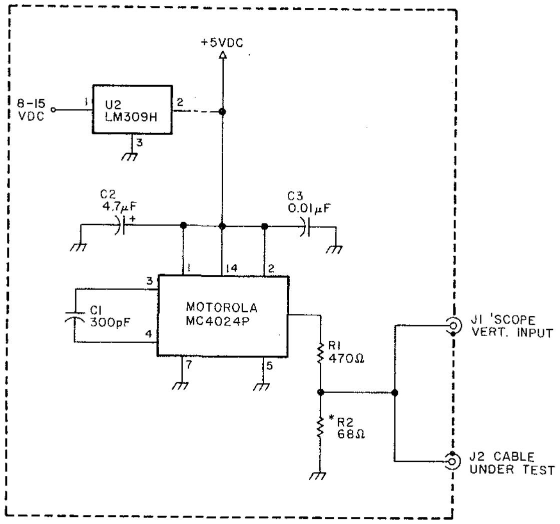


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Fig. 4(a). Square-wave signal generator.

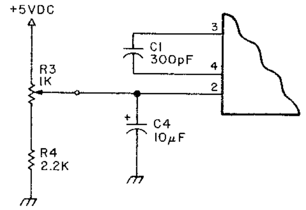

Fig. 4(b). Variable frequency modification.

Transmission lines have a property called either *surge impedance* or *characteristic impedance,* either of which is represented by the symbol Z_0. In the simplest definition, surge impedance is the square route of the ratio L to C: $Z_0=\sqrt{L/C}$.

Let's consider what happens on a transmission line; see Fig. 2. In this illustration, we have a length of coaxial cable with a surge impedance, Z_0, terminated with a load impedance, Z_L. At the input end of the transmission line is a pulse generator. So what normally happens?

We are told that the transmission line acts as if it were infinitely long when $Z_L=Z_0$. In that case, a pulse (V_F) applied to the input end will disappear into the coax and never return. In other words, the load will dissipate *all* of the pulse's energy when the load impedance (Z_L) matches the transmission line surge impedance (Z_0). This is why we put so much emphasis on a proper match between Z_L and Z_0, as indicated (hopefully) by a 1:1 vswr.

But what of the case where Z_L is not equal to Z_0? In that case, not all of the energy in the forward or incident pulse (V_F) is absorbed by the load. Some of the energy is reflected back down the line in the opposite direction. Pulse V_F in Fig. 2 is the forward pulse that is applied by the signal generator. When it hits the load end of the line, some of its energy is absorbed by Z_L and the remainder is reflected back towards the load in the form of pulse V_R. (Note that the *phase* of the V_R is reversed compared with V_F.)

Radio waves and pulses travel down a transmission line at a known velocity that is some fraction of the speed of light (c). The so-called *velocity factor* of a transmission line is that fraction. Thus, a velocity factor of 0.66 means that waves and pulses propagate in that line at 66% of the speed of light (i.e., 0.66c).

If the speed of propagation on a line is known or can be measured, and if we have a means of timing the interval between the application of the forward pulse and the return of the reflected pulse, then we can calculate the length of the line. If the line is either open or shorted, then the length computed is the distance from the input end and the fault. In a long system, such information can save a lot of hunt 'n' check work.

Signal Sources

There are two basic TDR techniques available to the amateur; one uses a real pulse and the other a square wave. Equipment needed for these techniques is rather simple, except for the 'scope.

The oscilloscope needs a bandwidth of 5 MHz or more (preferably more). In addition, it must have a horizontal sweep calibrated in units of time (e.g., μs/cm).

The signal source can be any pulse or square-wave generator, either commercial or home-brew. In researching this article, I used a Tektronix IM-500 series pulse generator, a Heath IF-18 square-wave generator, and several home-brew generators (discussed in text). It is highly desirable that the signal source have a fast rise time.

If your oscilloscope has a +GATE output, then you may already have a pulse generator. The +GATE outputs a short-duration pulse every time the sweep is triggered. In the auto-trigger (i.e., free run) mode, the sweep is constantly retriggered regardless of whether or not a signal is present in the vertical channel. Thus, we will see a constant pulse train at the +GATE output during auto-trigger operation.

If you plan to use a square-wave generator as the signal source, then it may be advisable to improve the rise time of the signal. Fig. 3 shows two buffers that can be used. The 74H00 is a high-speed version of the 7400 two-input NAND gate. This device is shown connected as an inverter (i.e., both inputs tied together). The 7400 is recommended for TTL-compatible outputs.

The 7414 used in Fig. 3 is a Schmitt trigger. As such, it will produce a fast rise-time output pulse. Like all TTL devices, there are limits to the allowable input-voltage swings. Note that the Schmitt trigger can be used to make square waves out of sine waves. The Schmitt output is binary, i.e., only two states are allowed, HIGH and LOW. The output will snap HIGH when the input passes a certain threshold voltage in a positive-going direction and will drop LOW only when the signal crosses another threshold in the negative-going direction.

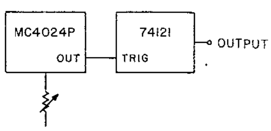

Fig. 5(a). Pulse-generator circuit (block diagram).

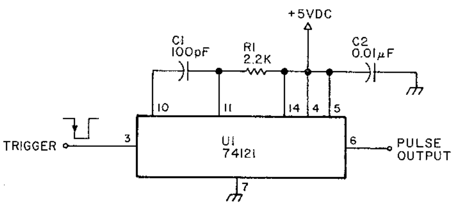

Fig. 5(b). Pulse-generator schematic.

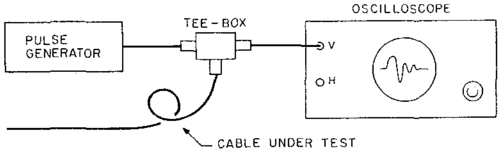

Fig. 6(a). Test setup.

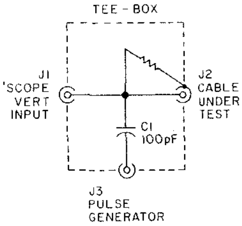

Fig. 6(b). Tee-box detail.

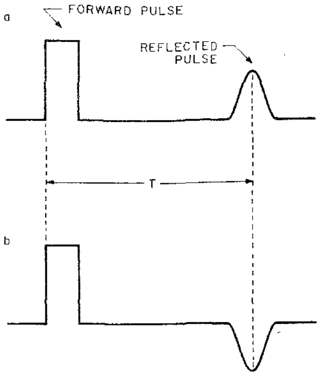

Fig. 7. TDR with a pulse-train signal source.

Fig. 4(a) shows a homebrew square-wave signal generator based on the Motorola MC4024P voltage-controlled oscillator (vco) chip. *Note*: this is not the CMOS 4024 device.

The MC4024P contains two vco's, but this project uses only one. The frequency is controlled by capacitor C1 and is set to approximately the range needed for our application. In some cases we will want to vary the frequency, so we can use the circuit modification of Fig. 4(b). Potentiometer R3 changes the voltage applied to the vco-control input (pin 2). A 3:1 frequency ratio is possible. One use for this capability is optimization of one of the TDR techniques given below.

The output from the MC4024P device is a TTL-compatible square wave. For TDR, however, we can use almost any level within the ability of the 'scope, but the source must have an output impedance that is matched to the transmission line. Impedance matching is the function of R2 in Fig. 4(a). If only one style of coax is being tested, then set R2 equal to its Z_0 (e.g., 50 Ohms, 75 Ohms, etc.); the value of 68 Ohms allows testing in 50- *and* 75-Ohm systems with only a small effect on the system.

The photo shows the version that I built. In this case only one BNC jack is used, and an external BNC "tee" separates the signals to the oscilloscope and the cable under test. Note that the entire system, including the Pomona box, represents only a $15 accessory to a standard oscilloscope.

A pulse-generator circuit is shown in Figs. 5(a) and 5(b). Here we see a monostable multivibrator (one-shot) driven by a square-wave source such as the one in Figs. 4(a) and 4(b). The detailed circuit for the one-shot stage is given in Fig. 5(b).

A typical test setup is shown in Fig. 6(a). The interconnections between instruments is accomplished by a special tee-box—see Fig. 6(b). The circuitry is housed in a Pomona box fitted with three BNC or (if older test equipment is used) SO-239 UHF connectors. When building the tee-box, keep leads as short as possible; use "good VHF layout practices." Note that the tee-box is not needed if you build your own pulse/square-wave signal source that incorporates similar elements.

TDR Methods

There are two methods by which we can use TDR on simple systems. If a pulse-train signal source is used, we will get indications such as Fig. 7. The forward pulse, as applied by the signal source, will have a higher amplitude and sharper features than the reflected pulse. Coaxial code normally attenuates signal, so one would expect the amplitude to decrease. The waveshape also will change since this attenuation is different for different frequencies.

Notice that the reflected wave is different in (a) and (b) in Fig. 7. In (a) we see the situation existing when the transmission line is unterminated, i.e., open-circuited. Here the reflected pulse has the same polarity as the forward pulse. If there is a break in the coax line, then we will see this waveform. The situation for a terminated or shorted line is shown in (b); here the reflected wave has a reverse polarity.

The length of the line can be found from the time T required for the reflected pulse to return to the point of origin. The following factors affect T: length of the line, velocity factor of the line, and constant representing the speed of light. Our basic equation is:

$$L = 983.5VT/2$$

where L is the line length in feet, V is the velocity factor (0–1), T is the round-trip time in microseconds, as measured on the oscilloscope, 983.5 is the speed of light in feet per microseconds (ft/μs), and 2 represents the fact that T is a round-trip time.

We can rearrange the basic equation to also find T or V, as needed:

$$V = 2L/983.5T$$
$$T = 2L/983.5V$$

Let's work an example of each. Let's say we have a long piece of 75-Ohm coaxial cable used as a data line between the computer and a CRT video terminal. Your boss knows you catch bullets in your teeth and dabble in ham radio. *You*, therefore, are the resident expert and have to find out where the signal went. Being smart enough to subscribe to this magazine, you remember this article and pull it out. You obtain a pulse waveform similar to (b) in Fig. 7 and measure T as 0.63 microseconds. How far down the line is the short? First, we must determine the velocity factor. Since most TV-type coax is foam, we

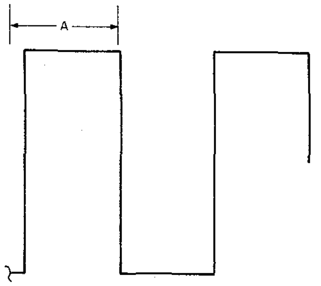

Fig. 8. Adjust square wave to match "A."

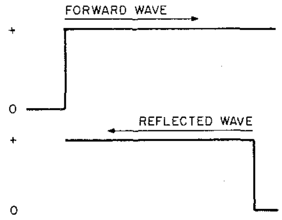

Fig. 9(a). The adjusted waveform.

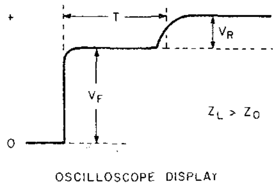

Fig. 9(b). Sum of the forward and reverse voltages.

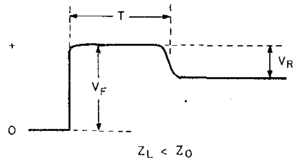

Fig. 9(c). Load impedance less than surge impedance.

can assume V=0.8. Therefore:

$$L = 983.5VT/2$$

$$L = (983.5)(0.8)(0.63)/2$$

$$L = 495.7/2 = 248 \text{ feet}$$

Tracing the line on the building plans, you find the area where the short should be found. Going to that area, you find a carpenter at work subdividing a room—and find the nail he drove through your coax! You hold off busting his chops when you notice the hammer in his hand.

You can use the same equation to find the length of coax needed to accomplish a specified delay. Coax delay lines are used often and are a lot cheaper than lumped-constant delay lines.

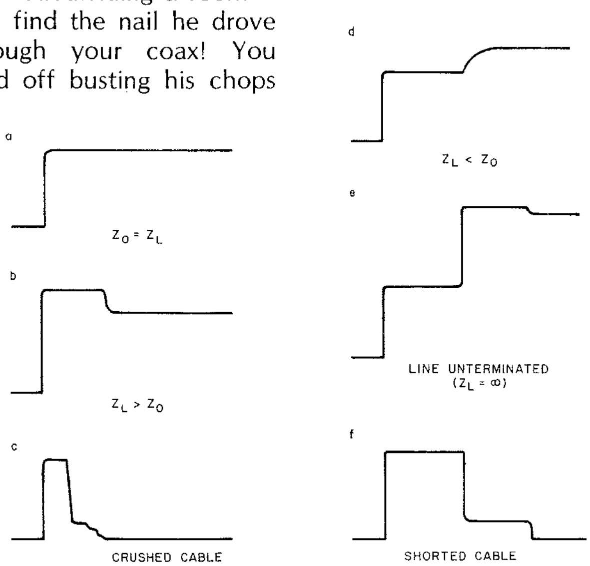

Fig. 10. A variety of traces.

It is necessary to know the actual velocity factor (V) of a piece of coax. If you are trying to make a quarter- or half-wavelength stub, then the velocity factor must be known. For noncritical applications, we can accept the common wisdom factors of 0.66 for regular cable, 0.7 for Teflon® and 0.8 for foam. But *actual* velocity factors often differ from these values, so they must be measured.

Make the measurement of T using about 50 feet of cable. The precise length must be known, and the load end should either be left unterminated or terminated in a severe mismatched impedance. This latter stipulation is needed to enhance the reflected pulse. If L and T are known, then V can be computed. If you make enough measurements on coax, you will find that published velocity factors are quite nominal and that the range of V for supposedly identical samples of cable is quite large. In fact, you may well come to doubt much of the "standard wisdom" published about transmission lines popular in amateur radio.

The alternate method used for amateur TDR uses a square wave rather than a pulse. Adjust the square-wave frequency and the oscilloscope timebase to display the top portion of the square wave as shown by dimension "A" in Fig. 8. For a perfectly symmetrical square wave, the period will be approximately 2A, so the frequency will be 1/2A.

In Fig. 9(a), the upper waveform represents the applied square wave as viewed on an oscilloscope adjusted per above instructions. The lower trace is the reflected wave.

The display on the oscilloscope will be the *sum* of forward (V_F) and reverse (V_R) voltages, such as Fig. 9(b). In the case where the load impedance is equal to the coax surge impedance (i.e, $Z_L = Z_0$), the trace will be similar to the upper trace in (a). The trace in (b) represents the case where the load impedance is greater than the surge impedance ($Z_L > Z_0$), while 9(c) is that obtained for Z_L less than Z_0 (i.e., $Z_L < Z_0$).

These traces not only tell us the direction of mismatch but also the approximate magnitude (in the form of a vswr). Using the designations of Figs. 9, we can compute the approximate vswr from:

$$\text{vswr} = V_F + V_R / V_F - V_R$$

The vswr measurement thus obtained is only approximate because transmission line attenuation reduces the reflected power returning to the transmitter end. This method, like all other methods, produces valid results only when the measurement is corrected for normal attenuation effects and the line is a multiple of half wavelength.

Fig. 10 shows the results of square-wave TDR for various situations. Fig. 10(a) shows the situation where $Z_L = Z_0$. If the system is perfect (rare!), then the upper horizontal line in (a) will be perfectly flat. If there are glitches in that portion, then it may indicate anomalies on the line. I have seen both minor crushes or bends and in-line connectors splicing sections of line cause anomalies in an otherwise perfect trace. For connectors, the glitch may be slight (especially if BNC connectors are used), but it *will* be present.

The traces shown in Fig. 10 demonstrate the wide degree of change of the trace caused by line problems. Although Time Domain Reflectometers are complex instruments compared with our simple system, our system is capable of giving us a great deal of data about transmission lines that would otherwise be difficult to obtain. ■