HOW TO

Locate Faults in Coaxial Cables

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Troubleshooting and determining the characteristics of coaxial cable can easily be done with the help of a time domain reflectometer. You can make your own using equipment you already have.

TRANSMISSION LINES ARE NOTORIOUSLY difficult to troubleshoot. Faults become even more gruesome to troubleshoot when they are located in coaxial cable that is buried either underground or inside a wall. Both TV master-antenna people and communications people occasionally have to troubleshoot coaxial cable transmission lines. How would you like to be the chief engineer of a broadcast station, and find that you have a bad transmission line 150 feet long buried underground? Would *you* like to dig a 150-foot trench between the transmitter building and the antenna tuning box? Not I!

But how do you go about locating the fault? You could use an ohmmeter, but that only (sometimes) tells you whether or not a fault exists. For the MATV or broadcast technician trying to locate the fault to within a foot or so, along a 100 – 150-foot hidden path, that is not much help. You could also try using an antenna impedance bridge—but that doesn't always help, either.

There is a system, though, that does work. How would you like an instrument that will tell you *whether* a fault exists, *where* it exists along the cable and allows you to measure a cable's approximate SWR (*S*tanding *W*ave *R*ation), its length—and lets you determine its velocity factor? Does that sound impossible? It isn't; that can all be done by a standard instrument called a *time domain reflectometer* (TDR).

Commercially available TDR's are very expensive; but you can make a simple TDR using only a pulse generator and a good oscilloscope. You will need a fast-risetime pulse generator, and an oscilloscope with a wide bandwidth. The wider the oscilloscope's bandwidth, the better, but usable results can be obtained on models with just a 10–15-MHz bandwidth. That TDR will not produce results as accurate as the commercial instrument, and it will only work properly with resistive loads, but it will suffice for most applications.

The equipment connections for the TDR are shown in Fig. 1. The output of the pulse generator is connected to both the vertical input of the oscilloscope and to the input end of the coaxial cable, using a "T"-connector. It is important to keep the length of cable between the T-connector and the oscilloscope as short as possible. In the pulse-generator circuit to be shown later, a T-connector is mounted to the cabinet housing the generator, so the pulse output is connected directly to the oscilloscope input.

The value of the load resistor (Z_L) should match the characteristic impedance of the coaxial cable (Z_O). Since we cannot easily understand the patterns of *reactive* loads, it is important that only *resistive* loads be used. If the coaxial cable is connected to an antenna, or MATV preamplifier, or to any other form of reactive load, then disconnect it and substitute a dummy load at the output end of the coaxial cable.

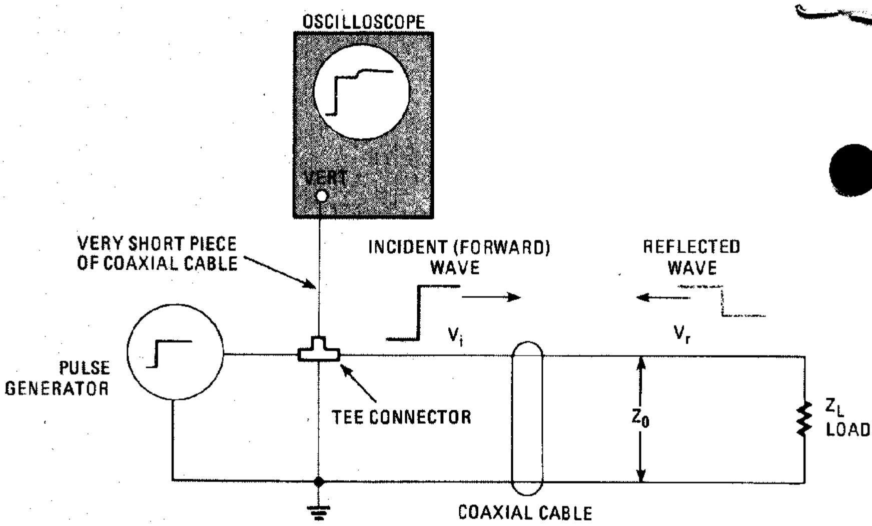

FIG. 1—TDR INTERCONNECTIONS. Pulse generator must be as close to scope as possible.

The TDR works by passing a step-function (i.e., the leading edge of the pulse from the generator) down the line. The horizontal sweep of the oscilloscope is triggered by that pulse. The horizontal sweep controls are then adjusted to display only the top half of the output pulse. In most cases, a 1-MHz square-wave is used as the pulse. That pulse has a 500-nanosecond duration along the top edge (1000-nanosecond total duration). That frequency is chosen because it permits the testing of foam-filled cables up to 200 feet in length, and regular coaxial cable up to 160 feet in length (the difference is due to the difference in velocity factors between the two cables).

The pulse from the generator does not travel as rapidly down a coaxial cable as it does through space. Thus, a pulse of a given frequency will take longer to travel the same distance on an insulated line than it will through air. The amount by which the pulse signal is slowed is determined by the dielectric constant of the insulator and is called the *velocity of propagation* or *velocity factor*. Both are related to the velocity of light. Velocity factor V_F is expressed as a decimal value and velocity of propagation V_P is expressed as a percentage of the velocity of light. The speed at which the pulse travels down the coax line is the product of V_F and the speed of light (300,000,000 meters per second). Foam-filled coaxial line has a velocity factor of 0.8 so the velocity of a pulse down the cable is $(0.8) \times (30 \times 10^8)$ meters per second or 2.4×10^8 meters per second. Similarly, regular polyethylene-filled cable has a velocity factor of 0.66 so a wave travels at $(0.66 \times 3 \times 10^8)$ or 1.98×10^8 meters per second.

When the incident, or forward, pulse reaches the load, it will either be totally

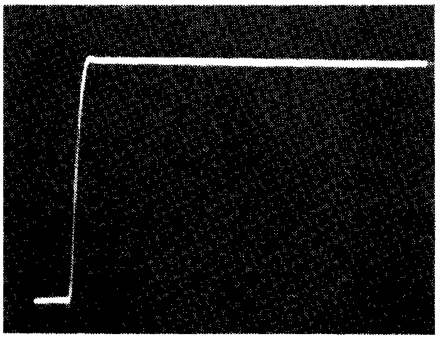

FIG. 2—IDEAL SCOPE DISPLAY indicating that input and output impedances are equal.

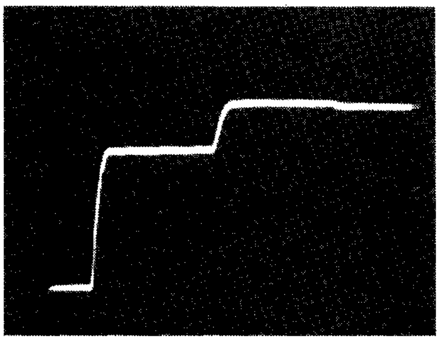

FIG. 3—LOAD IMPEDANCE GREATER than input impedance. Reflected pulse is added to incident pulse.

absorbed (if $Z_L = Z_O$), or will be partially absorbed, and partially reflected ($Z_L \neq Z_O$). In the case of a complete short circuit or complete open circuit in place of Z_L, *all* of the pulse will be reflected.

With a TDR, the reflected pulse combined with the incident pulse is displayed. That comparison allows us to make certain measurements. Figures 2—5 show four possible situations. The condition in Fig. 2 shows what happens when the load is matched to the characteristic, or surge, impedance of the coax. There is no reflection taking place, so the top edge of the waveform is flat. But look what happens in the case where Z_L is greater than Z_O (Fig. 3). In that case, the reflected pulse is added to the incident pulse, and produces the oscilloscope display shown. By determining the delay time between the two pulses and their relative amplitudes, the measurements described earlier can be determined.

A similar curve, shown in Fig. 4, is obtained for cases in which Z_L is less than Z_O. In that case, however, the reflected pulse is subtracted from the incident pulse, and produces a dip in the line.

The curve resulting from an open line will resemble Fig. 5. Note that the second hump is almost as large as first. In an ideal transmission line, two humps would have equal amplitudes. The difference noted here is due to the loss in the coaxial cable. A similar curve is obtained when the cable is

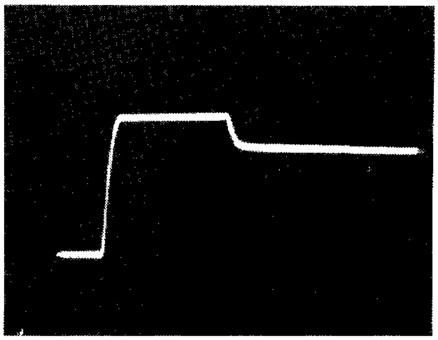

FIG. 4—LOAD IMPEDANCE LESS than input impedance. Reflected pulse subtracts from incident pulse in this case.

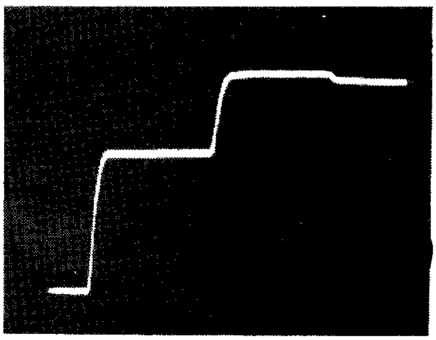

FIG. 5—OPEN-LOAD curve. In theory, incident and reflected pulses are equal.

shorted. In both cases, the entire incident pulse is reflected. The standing-wave curves for those two cases differ only in *phase* (i.e., the location of the nodes and antinodes).

Equipment

The only expensive piece of equipment required for this TDR is a wide-band oscilloscope. Most laboratories, service shops, and even many hobbyists, now own such scopes. The scope must have a vertical bandwidth of at least 10 MHz, but a greater bandwidth would be better.

If you own a fast-risetime pulse generator, then you are ready to make some of those tests. Many squarewave generators or function generators will have a fast enough risetime, but beware: some will not. In the laboratory where I ran my experiments, the pulse-and-function generators were moderately expensive and from a well-known manufacturer. They did not, though, have a risetime that was sufficiently fast for TDR work. Interestingly enough, a simple TTL squarewave generator that can be built for a few dollars will produce a pulse having the required risetime. The circuit is shown in Fig. 6. The generator is constructed using a Motorola TTL VCO IC, according to instructions given in the MC4024 spec sheet and Don Lancaster's *TTL Cookbook*. Note that the MC4024 is TTL—not CMOS, as it might seem. The value of C1 is hand-picked to yield a precise 1-MHz output. In my case, the value was 560 pF, but the exact value will vary from circuit to circuit.

The generator was built inside a small cabinet that was fitted with a BNC connector at one end and a grommet through which the two leads from the +5 volt DC power supply could pass. Capacitor C2 can be anything in the 1-to-10 μF range, and should be tantalum. It should be mounted where the +5 volt lead comes into the cabinet. Capacitor C3 is mounted as close to the V+ and ground pins of IC1 as possible. When the pulse generator is constructed in that manner,

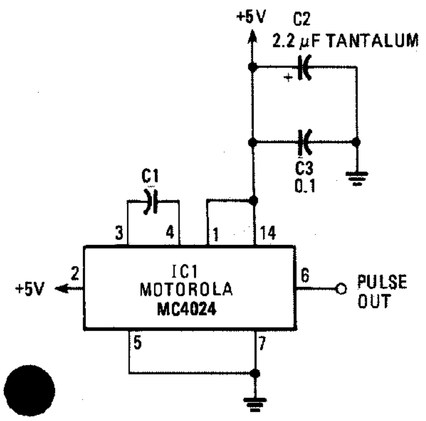

FIG. 6—SCHEMATIC of pulse generator using Motorola MC4024. Despite nomenclature, this IC is TTL, not CMOS.

it can be connected directly to the BNC vertical-input connector of the oscilloscope.

The circuit shown in Fig. 6 should produce pulses with an adequate risetime. It was used without problem by this author. But if you want to improve that risetime, then try connecting a high-speed TTL gate as an output buffer (see Fig. 7), or drive the input of a high-speed TTL flip-flop. Of course, in the latter case the frequency of the oscilloscope must be twice the required frequency; i.e., 2 MHz instead of 1 MHz.

Another possible variation on that circuit, also derived from the MC4024 applications notes, is shown in Fig. 8. The MC4024 is a VCO (*V*oltage *C*ontrolled *O*scillator). In the original circuit of Fig. 6 we tied the voltage input to V+, and allowed the device to oscillate at a fixed frequency. But in Fig. 8 we use a voltage divider to produce a variable voltage. Potentiometer R1 can be adjusted to bring the oscillator frequency exactly to 1 MHz.

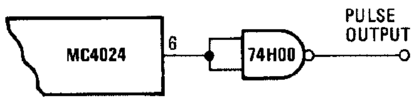

FIG. 7—RISETIME can be improved by using high-speed 74H00 IC after pulse generator.

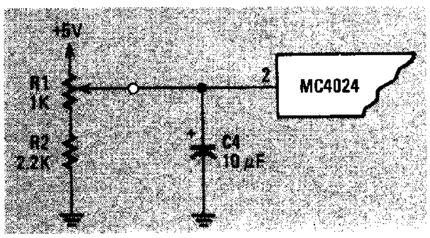

FIG. 8—FREQUENCY of pulse generator can be altered using voltage-divider circuit.

Making measurements

We can measure the time between the start of the incident pulse and the return of the reflected pulse along the horizontal axis of the oscilloscope. We can also measure the relative amplitudes of the reflected and incident pulses on the vertical axis. Keep in mind, however, that the value of the reflected pulse is only approximate since there is some loss during propagation along the line.

Figures 9-a and 9-b show the values needed to make most measurements with our simple TDR. Time T is the difference between the start of the incident pulse and the return of the reflected pulse. It therefore represents *twice* the time needed for a wave to propagate down the line (i.e., down and back). We could measure T between any two similar points on the incident and reflected pulses, but we find that there is some loss of sharpness at the bottom and top of the pulses (as might be expected). We can be more precise if we measure the time interval, T, using the

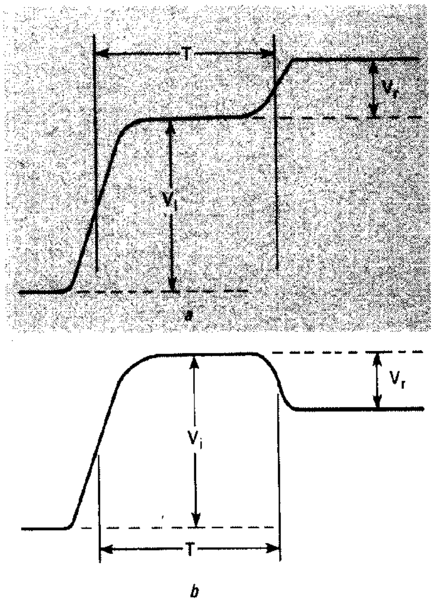

FIG. 9—VALUES USED in making TDR computations. Refer to text for full explanation.

midpoints of the two pulse edges.

The incident voltage V_i is measured from the baseline to the first horizontal section of the curve. The reflected voltage V_R is measured from the first horizontal section of the curve to the second.

In an actual laboratory experiment, 65 feet of 75-ohm, foam-filled, coaxial cable (the type normally used in MATV work) was used. Measuring T on the oscilloscope showed 3.4 divisions between the pulse-edge midpoints, when the horizontal control was set to 0.05 μs/div. The value of T, then, is:

$$3.4 \times 0.05\ \mu s = 0.17\ \mu s$$

This time, 0.17 μs, is the same as 1.7×10^{-7} seconds, and we will use *seconds* in the following calculations. The formula we'll use for many of our measurements is:

$$T = 2L/V_P$$

Where:

T is the time, measured as in Figure 9, expressed in *seconds* (s).

L is the length of the coaxial cable being tested.

V_P is the velocity of propagation of the pulse along the cable (V_P is 2.4×10^8 meters-per-second for foam cables with a velocity factor of 0.8, and 1.98×10^8 meters-per-second for regular coax with a velocity factor of 0.66).

Finding cable length, or length to fault

We may use the above equation to find the length of the coaxial cable or the distance to a fault on the cable. Since it is rare for a cable to reflect all of the energy fed into it, even when the fault is a short, there will be two humps in most defective cables. One, the larger, will indicate the point where the fault is located, while the smaller will be at the load end. Multiple faults show up as multiple humps.

In the example above we noted that the value of T was 1.7×10^{-7} seconds. If we solve the equation above for L, then we can determine the length of the cable:

$$L = T V_P / 2$$

So, by plugging in the time (T), and the velocity (remember, foam coax is being used, so V_P is 2.4×10^8 meters-per-second), and solving the above equation for L:

$$L = ½ (1.7 \times 10^{-7}) (2.4 \times 10^8)$$

or 20.4 meters

Let's see. The cable is supposed to be 65 feet long. Let's find out how long it actually is. One meter equals 3.27 feet, so:

$$L = \frac{3.27 \text{ ft}}{\text{meter}} \times 20.4 \text{ meters}$$

or 66.7 feet

Finding the velocity factor

Suppose that we go to a hamfest, auction, or surplus store and buy some coaxial cable of unknown type. How can we determine the velocity factor? Easy ... we cut off a known length, and solve the first equation for V_P. Since V_P is a fraction of the speed of light, we can then calculate the velocity factor of the cable. Let us say that we have a 50-foot (15.3 meter) length. Measuring T, i.e., the time to the first hump on the CRT screen, we find that it is 0.15 μs, or 1.5×10^{-7} seconds.

$$V_P = \frac{2 \times L}{T}$$

$$\text{or } \frac{(2)(15.3 \text{ m})}{(1.5 \times 10^{-5}s)}$$

or 2.04×10^8 meters-per-second

To find the actual velocity factor (V_F), use the following equation:

$$V_F = \frac{V_P}{C}$$

$$\text{or } \frac{2.04 \times 10^8 \text{ meters-per-second}}{3.00 \times 10^8 \text{ meters-per-second}}$$

or 0.68

Measuring surge impedance (Z_O)

The surge impedance, also called characteristic impedance, (Z_O), is a very important factor in planning systems that include transmission lines. That value must be known, or an impedance mismatch, with its attendent SWR, will result. The measurement is made by taking a length of the cable—say 30 to 80 feet—and connecting a 100-ohm potentiometer across the load end (be careful not to use a wirewound pot; only carbon will do the trick). Carefully adjust the potentiometer, while applying a pulse to the source end of the line, until you obtain the trace of Fig. 2, or something similar to it, which indicates that the surge impedance equals the load impedance for resistance. The trace in Fig. 10 was the best that I could do using a single-turn potentiometer. The potentiometer is then disconnected from the cable, and an ohmmeter is used to measure its resistance. That is the surge impedance of the cable being tested. In the case shown, the value of the pot, as read on a quality DPM, was 73.5 ohms.

Measuring SWR

An approximate measurement of the SWR of the system can be obtained by comparing the voltage of the incident wave (V_i) with the voltage of the reflected wave (V_r). That measurement is only approximate because V_r is reduced by cable losses, and those losses are difficult to predict, especially on a pulse waveform. They can be computed by comparing pulse amplitudes at both ends of the cable, and adding a correction factor to the amplitude obtained in the measurement of V_r on the TDR.

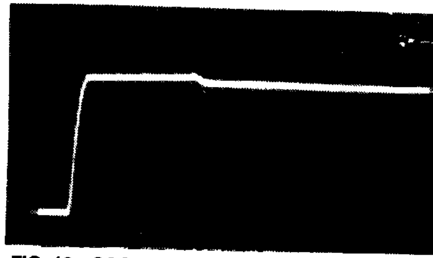

FIG. 10—SCOPE TRACE obtained in determining characteristic impedance of cable.

One possible means for determining the correction factor is to compare the V_r and V_i values with the line open-circuited. They *should* be equal; i.e., $V_r = V_i$. In our case (Fig. 5), the incident wave had an amplitude of 3.6, while the reflected wave had an amplitude of 3.2—only 89% of the correct amplitude. We can, then, multiply measured values of V_r by 3.6/3.2, or 1.125, to obtain the correct value. The actual VSWR is found from the formula:

$$VSWR = \frac{V_i + V_r}{V_i - V_r}$$

In the laboratory, we found that using a 150-ohm load on 75-ohm cable, produced the following values: $V_i = 3.6$ divisions, and $V_r = 1$ division (both vertical). Applying the correction factor, $V_r = 1.125$ divisions. We may substitute these values in the VSWR equation as follows:

$$VSWR = \frac{3.6 + 1.125}{3.6 - 1.125}$$

$$\text{or } \frac{4.725}{2.475}$$

or 1.91:1

TDR's have proven themselves to be very valuable in transmission-line measurements. The technique we've described allows small-budget users to gain some of the benefits of time-domain reflectometry. **R-E**