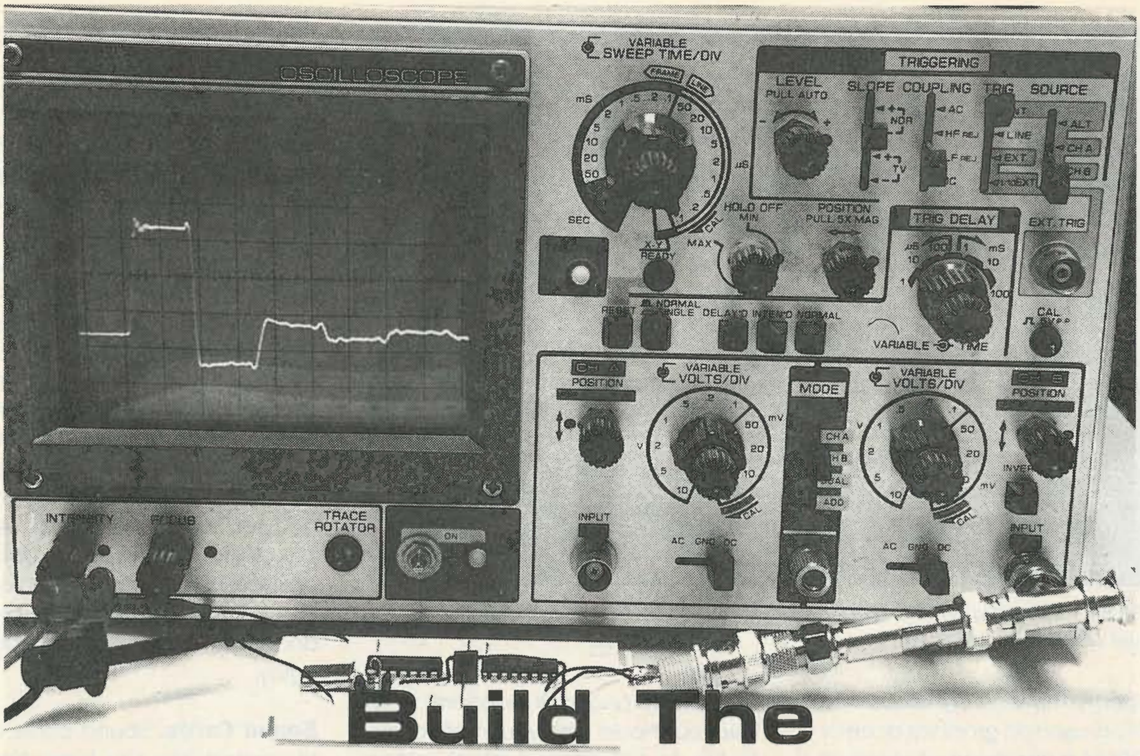


Build The CABLE REFLECTION TESTER

Need to test a damaged or suspect coaxial cable? This handy circuit will do the trick without sending you to the poorhouse for buying expensive equipment. If you supply the oscilloscope and about five bucks for parts, we'll supply the know-how.

JAMES E. CICON

You have a spool of coaxial or twin-lead cable and want to know how long it is. Unwinding the cable would be impractical.

After a rainstorm, you sometimes lose the picture on your television set. You figure that the satellite-TV antenna cable probably has a crack in the insulation somewhere along its length. The problem is that the cable is over 250 feet long. It snakes through your walls, across your roof, and then drops down underground for the run to the dish. It would be nice to know how far down the line the crack is.

Your local-area network at work goes down whenever a certain machine is brought on-line. The installation techs say that the LAN administrator has the software configuration fouled up. The LAN administrator says the installation techs had been working too much overtime when they hooked up that particular machine. Can you pinpoint who is right?

Televisions, computer networks, CBs, ham radios, cellular telephones—all of those devices send or receive information using electrical waves that might travel through a cable for at least some distance. If the cable is damaged, defective, or the wrong type for the job, the original signal traveling down the cable will become garbled. That will cause poor picture reception on a TV, data collisions on a LAN, and other problems. Wouldn't it be great if you could easily and quickly diagnose the cause of those types of cabling headaches?

There is an instrument that can do just that. It's called a "Time Domain Reflectometer," or TDR. A TDR can tell you many things about the health of a cabling system. It can quickly and easily tell you the length of cable. It can also tell you if there is an impedance mismatch (such as two different types of cable spliced together) on a cable. It can help you locate a fault in a cable such as a break or a short circuit. A TDR has only one real drawback—its price tag. You can easily pay thousands of dollars for one.

But there is a less expensive alternative. In this article we're going to show you how to build and use the Cable Reflection Tester, or C.R.T. for short—a device that will let you see the effects of the various cable faults mentioned before. Not only does the C.R.T. demonstrate some very interesting properties of electrical waves from a purely academic standpoint, but the project has a very practical side. We'll take you through a few experiments to demonstrate how to use the C.R.T. to measure the length of a cable, and to determine the health of a cable.

Using the C.R.T. requires an oscilloscope, and a handful of inexpensive parts for the C.R.T. itself. If you don't already have most of the parts on hand, you can probably buy them for less than $5. The prototype was originally built and tested on a solderless breadboard. If you really like the C.R.T., there is no reason not to mount it permanently inside the oscilloscope. You could then tie it into the oscilloscope's power supply and be able to use it wherever and whenever you wish.

A fancy scope is not needed for the C.R.T. The scope used here is a beat-up 35-MHz model that is over ten years old. It has been through a flood and dropped several times. Despite the abuse, it works surprisingly well with the C.R.T.

Background Theory. The time-honored way to understand how electricity works is to think of electricity as water and wires as pipes. That mental image has helped many students to understand electrical phenomena, and is also one that is very useful in explaining how the C.R.T. works. The analogy is not perfect and breaks down if pushed too far, but for our needs, it still has a lot of value.

Imagine spilling a glass of water into a tray. The water will start to spread out over the bottom of the tray until it comes to a side. While it is spreading, the puddle will have some depth. That depth depends on how fast the water is being poured into the tray and how fast the water can spread out to fill the tray. Water clings better to some surfaces than to others. If you are pouring the water into a tray made of a material to which water clings, the water will spread more slowly, and the resulting depth of the puddle while it is spreading out will be deeper.

That "clinginess" is a feature of the material of which the tray is made. It "impedes," or restricts, the flow of the water. You could call the clinginess of a tray its *characteristic impedance*. How fast the water spreads across the tray (its *velocity factor*) largely depends on the tray's characteristic impedance. To compare the velocity factor of one tray to another, you could pick one tray as a standard. If water spreads half as fast in one tray than in the tray that is the standard, you could say that the velocity factor of the tray under test is 0.5 or 50%.

What happens when the water reaches the side of the tray? It will slosh back, of course. Ripples will travel back from the side to the center where the water is being poured into the tray. The level of the water in the tray will now start to rise. Remember that before the water reached the side of the tray, the level of the water was determined only by how fast the water could spread out. Now the level of the water is determined by how much water you pour in. Another way to think of it is that, at first, the water level is determined by the characteristic impedance of the tray. After all the waves and ripples have settled down, the level is determined by what the original potential of the water was to fill the tray.

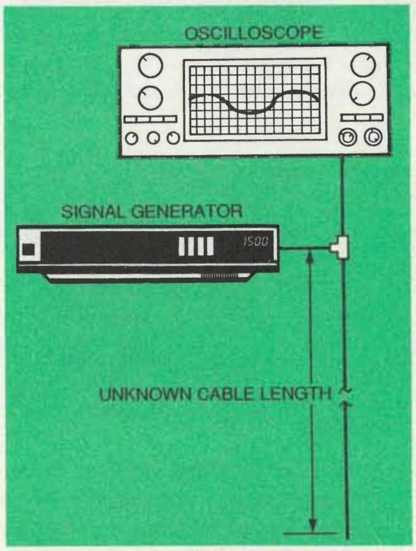


Fig. 1. This setup will let you easily measure the length of a cable without using a tape measure. Connect a signal generator to one end of the cable and measure the amount of time it takes to see the steps in the waveform on an oscilloscope.

Let's say that you want to know the distance from the center of the tray to the side of the tray. However, you are limited to two measurements: the height of the water in the center of the tray, and time. You also know the tray's velocity factor.

To find out how far the side of the tray is from the center where you are pouring water in, you could start pouring water into the center. Keep an eye on the height of the water in the center of the tray. The water height will stay constant for a while and then start to rise. Time how long it took for the water to start rising from the moment you started pouring the water in. That is the time that it took the water to reach the side of the tray plus the time it took for the returning wave to bounce back to the center.

Divide the time in half, and then multiply that result by the tray's velocity factor. That gives the distance from the center of the tray to its nearest side. If you are wondering why you divided the time in half, it is because the water traveled out to the side of the tray and then back again, actually traveling twice the distance you want to measure.

We can take that procedure and express it as an equation:

$$L = t/2 \times V_f \times V_r$$

where L is the distance to the side of the tray, t is the time for the wave to travel to the side of the tray and back again, V_f is the tray's velocity factor, and V_r is the velocity of a wave traveling in the reference tray.

How the C.R.T. Works. The C.R.T. works in a very similar way to the example of pouring water into a tray. Substitute the pouring water with a signal generator and the tray with a cable. Instead of watching the water level with your eyes, use an oscilloscope to help you monitor the electrical voltage level on the cable. Figure 1 shows the basic block diagram of the C.R.T.

When a squarewave from the signal generator goes high, you will see that on the oscilloscope. Notice that the voltage level doesn't immediately rise to the level that the signal generator is producing. It initially steps to some intermediate value. After a short delay, the level changes to either a higher level or a lower level, depending on whether the far end of the cable is open- or short-circuited. That will show up as a stair-step waveform on the oscilloscope.

Let's think about why that happens. The first step in the waveform is equivalent to just starting to pour the water into the tray in our example. The voltage level is determined largely by the characteristic impedance of the cable. If the end of the cable is open, the voltage wave has nowhere to go when it reaches the end of the line. That is the electrical equivalent of hit-

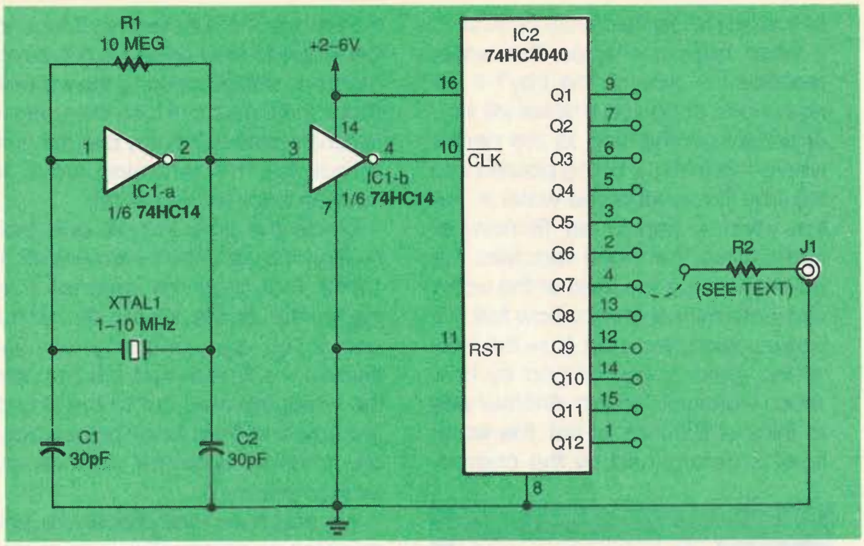


Fig. 2. Here's the schematic diagram for the Cable Reflection Tester. The components shouldn't cost more than $5, and it can be built up on a solderless breadboard in only a few minutes.

TABLE 1

Cable Type	Velocity Factor	Characteristic Impedance
RG-58/U	66%	52 ohms
RG-59/U	66%	75 ohms
RG-6/U	75%	75 ohms
RG-8/U	66%	52 ohms
RG-8/M	75%	52 ohms
RG-174	66%	50 ohms
RG-62A/U	84%	93 ohms

ting the wall of the tray and the voltage wave is reflected back, which is seen as a second step up as it reaches the scope. Eventually, after all the ripples settle down, the cable "fills" up, and the final voltage level is equal to the level being produced by the signal generator.

If, on the other hand, the end of the cable is shorted, something different happens. The water analogy does not work as well as when the cable is open. As the signal generator drives the line high, the initial step up will appear on the scope as the voltage wave starts to travel down the cable. When the wave gets to the end of the cable, it sees a short circuit. Electrically speaking, the short circuit acts like a reverse wall. The wave striking it is bounced back upside down, canceling out some or all of the forward-traveling wave. When that negative-traveling wave finally travels back to the scope, it will be seen as a step down.

Those stair-step waveforms can be used in many different ways. You can measure the width of the first stair step to determine the length of the cable. Remember that the width of the first stair step is the time it takes the initial wave to travel to the end of the line and back, just like measuring the length of the tray in the water analogy. The other thing you can determine is if the end of the line is open or shorted. We'll do those experiments later. First, we need to build the C.R.T. itself. Generating and viewing the waveforms on an actual cable is a lot better than just talking about them.

Designing and Building the C.R.T.

The C.R.T.'s design is so simple, building it is almost trivial. All we need is a squarewave signal generator that has a very short rise time. A crisp squarewave will result in nice, sharp stair-step display, making it easier to see the effects that we're looking for. The schematic in Fig. 2 shows how simple the design actually is.

Integrated circuit IC1-a is an inverter. It is the active component in an oscillator that generates the C.R.T.'s squarewave. The rest of the oscillator consists of R1, XTAL1, C1, and C2. Resistor R1 provides a DC feedback path for IC1-a. The value of R1 is not critical, but should not be too large. The suggested value of 10 megohms will work quite well. Capacitors C1 and C2 stabilize the oscillator, and their values are also not critical, but should be between 10 and 60 pF. The smaller their value is, the more quickly the oscillator will start, but the less stable it will be. XTAL1 sets the frequency of the oscillator. Its value is also not critical, but should be between 1 and 10 MHz for good results.

The output of IC1-a is buffered by IC1-b and fed to IC2, whose purpose is to divide the signal frequency down so that cables of various lengths can be measured. Without IC2, the reflected waves in very long cables may not return in one complete oscillator cycle. By slowing the clock frequency down with IC2, it is easier to measure longer cables. If you are only working with short cable runs, it might be possible to omit IC2.

The oscillator is matched to the cable being tested with R2. Its value should be equal to the characteristic

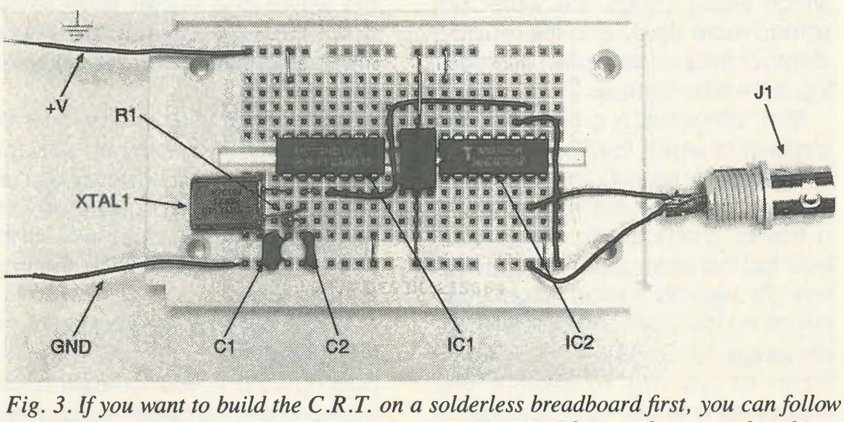


Fig. 3. If you want to build the C.R.T. on a solderless breadboard first, you can follow this photo as one way to locate the components. Resistor R2 is not being used in this version of the C.R.T., and an additional .01–0.1-µF capacitor has been added between IC1 and IC2 to smooth out the power supply from ripples caused by the integrated circuits.

impedance of the cable being tested. That match helps prevent multiple reflections, and helps make the stair-step response easier to see. Resistor R2 is not absolutely needed, especially if you are concerned with only the first step of the stair-step waveform.

All of the components for the C.R.T. can be mounted on a small breadboard. The photograph in Fig. 3 shows both the completed prototype and placement of the parts. Assembly can be finished in 5 minutes or less. The power supply for the circuit can be anywhere between 2 and 6 volts, so the C.R.T. can be powered with your choice of either batteries or a bench-top power supply.

Experiments. We've already seen (from the water-tray example) a method that allows us to measure the distance the water travels to the side of the tray. That method can be applied to electrical waves traveling in cables as well. An oscilloscope can be used to measure both the time that a wave takes to travel the length of a cable, and what the voltage level of that wave is. Some common types of coaxial cable are listed in Table 1 along with their velocity factors and characteristic impedances.

An electrical wave's velocity factor (how fast the water spreads across the tray in our analogy from before) is related to the speed of light in a vacuum. For example, according to the information in Table 1, a wave in RG-58/U cable travels at 66% of the speed of light. We can use the characteristic impedance of the cable to tell us what value we should use for R2.

PARTS LIST FOR THE CABLE REFLECTION TESTER

SEMICONDUCTORS

IC1—74HC14 hex HCMOS inverting Schmitt trigger, integrated circuit
IC2—74HC4040 HCMOS 12-stage binary counter, integrated circuit (optional, see text)

RESISTORS

(All resistors are ¼-watt, 5% units.)
R1—10-megohm
R2—optional, see text

ADDITIONAL PARTS AND MATERIALS

C1, C2—30-pF ceramic-disc capacitor
J1—BNC female connector (Digi-Key ARFX1063-ND or similar)
XTAL1—1-10 MHz crystal, see text
Printed-circuit board or breadboard, wire, battery, etc.

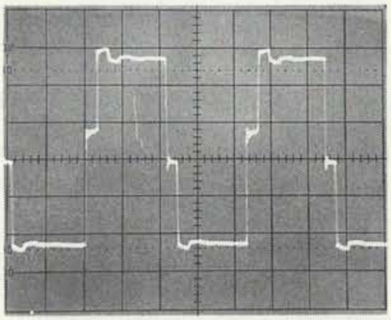


Fig. 4. Here's the C.R.T. hooked up to 50 feet of RG-59/U coaxial cable. The plateau halfway up the pulse is the effect of the signal bouncing back from the end of the cable. The length of time of that plateau measures how long it took for the signal to travel to the end of the cable and back.

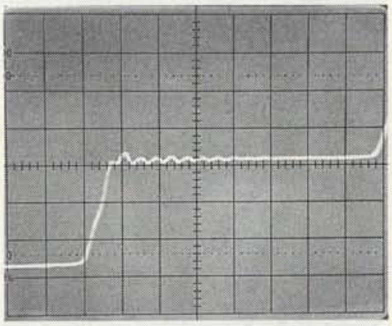


Fig. 5. In this photo, the scope is magnifying the plateau mentioned in Fig. 4. Since we know how fast electricity travels in this particular cable, half the distance shown here is how long it takes for the signal to go from one end of the cable to the other. It's now a simple matter to apply Distance = Time × Speed to figure out the length of the cable.

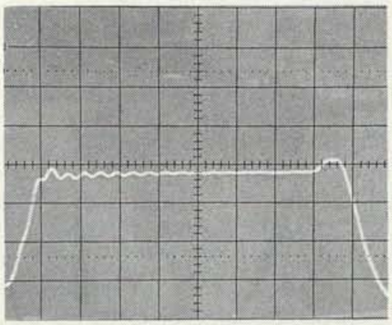


Fig. 6. Now we've shorted the far end of the cable. Instead of going higher, the reflected signal makes the display drop down. Not only does that tell us that the cable is shorted, it also can tell us the distance to the short.

Now for some experiments. Connect the C.R.T. to an oscilloscope as shown in Fig. 1 using a 50-foot length of RG-59/U coaxial cable. Leave the long end of the cable unconnected. The waveform on the scope should be similar to that shown in Fig. 4.

You can easily see the very obvious stair-step effect in both the leading and trailing edges of the squarewave. Figure 4 is interesting because it shows several complete cycles of the squarewave and the overall effect of the reflected wave upon it.

In order to get a useful measurement however, you must zoom in on just the first step on either the leading or trailing edge. Figure 5 shows the waveform of Fig. 4 with the scope's magnifier turned on. That will, unfortunately, decrease the accuracy of the measurement. Count the divisions on the scope's screen. The example in Fig. 5 has a stair-step about 8 divisions wide. Make sure that you don't just measure the width of the step itself (which is only 7 divisions wide). Include time it took to rise up to that step (another division). The scope in Fig. 5 is set to .02 μs/division. The velocity factor from Table 1 for the cable (type RG-59/U) is 66%.

Now we can pull out our equation and plug in the numbers. A stair-step of 8 divisions at .02 μs/division is .16 μs long. Dividing that by 2 gives us .08 μs. We then multiply by both the cable's velocity factor (66%, or .66) and the speed of light, which is 186,284 miles/second. Since our time measurement is in μs, we need to change the speed-of-light constant to μs, also. That conversion alone would be fine if we needed the length in miles, but the cable being tested is only 50 feet long, so multiply the speed-of-light constant by 5280. The final speed-of-light constant we will use in the length formula is now how many feet light travels in 1 μs, which is about 983 feet.

Let's substitute into the formula:

$$L = t/2 \times V_f \times V_l$$
$$= {}^{0.16}\!/_{2} \times 0.66 \times 983$$
$$= 51.9$$

The distance of the cable works out to be 51.9 feet. Considering the second-rate accuracy of the scope being

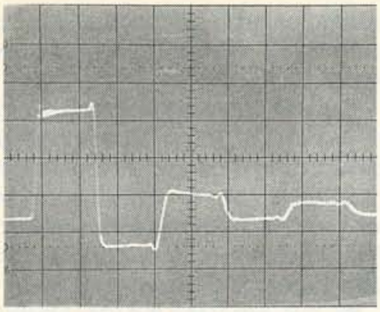


Fig. 7. If you don't use the proper value for R2, the reflected signal will keep echoing back and forth in the cable.

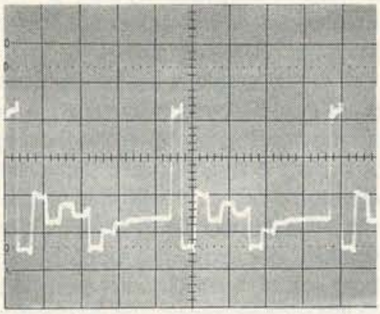


Fig. 8. Multiple echoes and reflections caused by bypassing R2 will mix with the original signal, distorting it badly.

used and the simple carpenter's tape measure used to check the actual length of the cable, the results are suprisingly accurate.

What happens if the end of the cable is shorted instead of left open? The results of that are shown in Fig. 6. Notice that instead of a stair-stepping-up waveform, the waveform steps up, then down. The down step is the result of the wave being reflected off of the shorted end of the cable. An additional change to the setup used for Fig. 6 is that R2 has been bypassed. That means that the signal generator is not matched to the cable, so when the reflected wave comes back it is once more reflected out. That back and forth reflection continues on and on like a pendulum with the waveform getting smaller each time. Additional views showing the reflected waves can be seen in Figs. 7 and 8.

Practical Applications. While digging in your yard, you accidentally severed a length of your satellite-TV cable. You had a repairman come out to replace it, but your reception has been terrible since then. The cable in your system is RG-58/U. You suspect that the repairman may have put in RG-59/U by mistake. How would you use the C.R.T. to diagnose that problem?

To simulate that situation, make up a cable from two 25-foot lengths of RG-58/U cable with a 25-foot length of RG-59/U cable spliced in between them. The overall cable length is 75 feet. Attach the C.R.T. to one end of the cable assembly and watch what

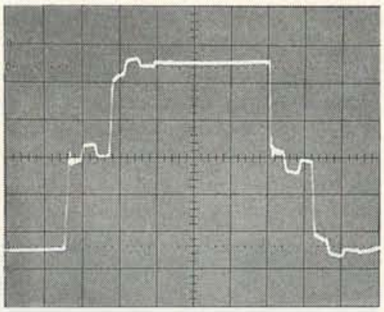


Fig. 9. If there is an impedance mismatch in the cable, the plateau will have an odd "hiccup" as the signal changes speed.

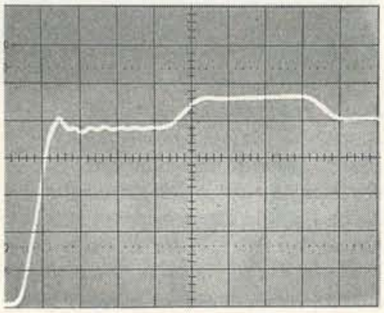


Fig. 10. This magnified view of a mismatched impedance can easily tell us not only how far up the cable the mismatch is, but the length of the offending portion of the cable.

happens on the scope when a squarewave is sent down the cable. The scope in Fig. 9 is set to display one complete cycle of the squarewave that was driving the cable.

The squarewave will initially step up as it travels down the RG-58/U. However, 25-feet later, it hits the RG-59/U. Since RG-59/U has a higher characteristic impedance than RG-58/U, a small positive reflection occurs. That causes the waveform to step up higher. The waveform travels another 25 feet when it hits RG-58/U again. The impedance mismatch (a mirror image of the first mismatch) causes a small negative reflection, which results in the step back down to the value appropriate for RG-58/U. The waveform continues on to the end of the line, and is then reflected back.

The scope has been set in Fig. 10 to zoom in on the leading edge of the stair-step waveform. If you don't know where the RG-59/U was spliced in, you can easily calculate the location using the length calculations from before. The first part of the waveform is about 4 divisions long. That is the initial length of cable before the splice, which works out to be about 25.9 feet.

The length of the spliced cable causes the short step up, which is also

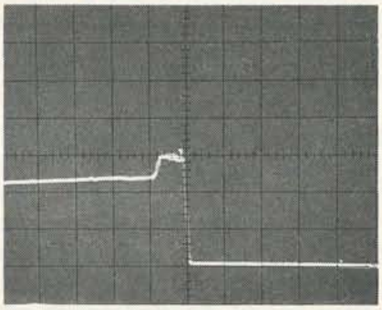


Fig. 11. A step down usually means an impedance mismatch, but the mismatch shown here is a problem of extreme proportions: using the wrong impedance cable! In this test of a computer-network cable, using the wrong type of cable results in garbled data that the interface card cannot read.

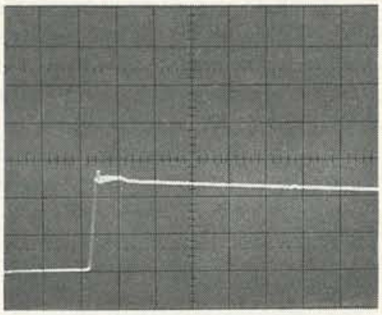


Fig. 12. After the computer-network cable in Fig. 11 is replaced with the proper type, the signal becomes much cleaner. The slow droop in the signal is caused by the capacitor-like quality of the cable: two conductors separated by an insulator.

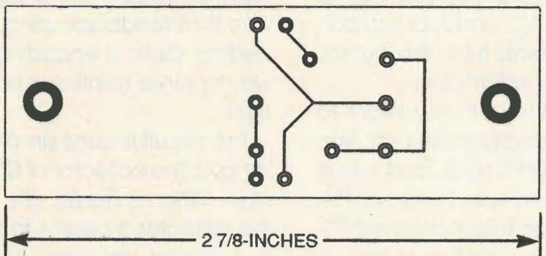
about 4 divisions long. Since RG-58/U has the same velocity factor as RG-59/U, the same calculations as before can be used, so the length of the spliced cable is also about 25.9 feet.

Don't lose sight, however, of the most important part of that measure-

(Continued on page 68)

You can make an encoder disc from poster paper or other stiff, thin material, as shown in Fig. 5. The diameter of the center hole should be slightly smaller than the shaft of the stepper motor. To mount the disc, remove the coupler on the stepper motor and loop a small rubber band around the shaft several times.

Referring to Fig. 6, push the encoder disc onto the shaft. The disc should have a firm press-fit, without bending or distorting. Reinstall the coupler and adjust the disc and the rubber band so that the disc rests directly against the bottom of the coupler and is held tight by the rubber band. Position the encoder PC board against the short ends of the blocks holding the stepper motor (shown last time), and adjust the positions of the IR emitter and detector so that they are close to the encoder disc and centered along the aperture in the disc. Secure the encoder PC board to the short ends of the blocks.



Since parts alignment is fairly critical, use this PC board when building the optical encoder.

To test the circuit and align the disc, use the program shown in Listing 4. Connect the APT to your power supply and parallel port, but leave the tray off for now. Run the program and note that the encoder disc rotates. The disc should stop with the aperture directly between, or at least near, the IR devices. If it's directly under, you're done. Otherwise, rotate the disc slightly, as instructed by the program. In either case, press <Enter> to end the program. Move the shaft (not the disc) so the aperture is not under the diode and run the program again. Now, the disc should stop with its aperture directly under the diode. After completing the alignment, reinstall the tray.

Let's take a quick look at the alignment program. Lines 7–16 form a loop that continually looks for the aperture. Within that loop, lines 8–13 constitute our old stepper-motor movement routine. Line 10 senses when pin 11 of J1 goes low (input = 1), indicating that IR energy from the diode is passing through the aperture and pulling the detector's output low. Since the aperture could be detected during any of the four motion steps, line 16 repositions the stepper motor at the start of the sequence (ainit). The program then lets you align the aperture beneath the diode. Last, line 22 de-energizes the motor.

What's Next? There are several directions you could take if you wanted to continue experimenting with stepper motors. For example, you could modify the program to include encoder-disc sensing. You could also modify the encoder disc to incorporate twelve apertures, one for each bin position.

A more ambitious project would be to use stepper motors to provide accurate X-Y positioning. In that way you could create an automated system for drilling PC boards with ease and precision. That will be our next project; look for it soon! Ω

REFLECTION TESTER

(Continued from page 62)

ment. You have positively found an impedance mismatch in the cable. You also know exactly where it is, and how long it is.

The TV-antenna-cable problem worked out great. Can the C.R.T. help you figure out why your LAN isn't working? Let's imagine a really bad scenario. You have just installed a LAN for a small business. You are using Ethernet technology in a 10Base2 configuration. You have finished hooking up all of the hardware and installed all the necessary software, but nothing works. What do you do?

After you sit and stare for a while thinking how nice it would be camping in the middle of a stand of eastern white pine, a thought crosses your mind. Could the problem be in the cabling? You take out your C.R.T. and put it in-line with one of the workstations. The waveform on the scope looks like the display in Fig. 11. The measurement of the initial step up accounts for the 25 foot length of cable between the C.R.T. and the workstation, but at the end there is a strange step down.

A step down in the display, as we just learned in the TV antenna cable example before, indicates an impedance mismatch. But where is that step down coming from? The workstation is properly terminated with a 50-ohm terminator. But then you notice that you have wired the system with RG-59/U instead of RG-58/U. The cable is not properly matched to the Ethernet cards and terminators. The Ethernet is interpreting that mismatch as data collisions. Obviously, new cable will have to be ordered, but hopefully the cable has not yet been run under the floor tiles or through the ceiling joists.

Now that we've seen several cases of impedance mismatches, what does a healthy cable look like? Figure 12 shows a cable that is in good condition and is properly terminated with a resistor that is equal to the characteristic impedance of the line. It is a length of RG-58/U terminated with a 50-ohm resistor. If the proper cable was chosen for the LAN problem, the scope display would have looked like Fig. 12 instead of Fig. 11.

If the world were an ideal place, Fig. 12 would show a straight line after the initial ringing, but you can see that it doesn't. There is still a slight hump where the terminator connects to the cable, but it is very small and there are no multiple reflections. Also notice one other curious thing: the waveform is slowly curving down over time. That is due to the capacitive component of the line.

There you have it—a poor man's TDR. Suprising accuracy is practicable with even a crude setup. If you find the C.R.T. very useful, lay it out on printed-circuit board and mount it either in a box or in your oscilloscope. If you have any questions or problems, you can reach the author via e-mail at 75104.3104@compuserve.com. Ω