Getting the Most Out of Your T-Network Antenna Tuner

Here's how to adjust this popular tuning circuit so it transfers maximum power to your antenna without going snap, crackle and pop.

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Look into most of today's commercially manufactured antenna tuners, and you'll probably see a circuit that ultimately boils down to one coil and two capacitors. Whether the tuner is a stand-alone unit or one of the "automatic" types built into a current MF/HF transceiver, it probably consists of a **T** *network*, so named because of how it looks when we draw its schematic (Figure 1). The circuit consists of two variable capacitors, C_{IN} and C_{OUT}, and a variable inductance, L, connected between common and the junction of C_{IN} and C_{OUT}. For the purposes of the discussion to follow, we'll assume that C_{IN} and C_{OUT} can be adjusted from 20 to 240 pF, and that L is a 0.1 to 35-µH inductor.[1]

Especially in automatic tuners, C_{IN} and C_{OUT} may consist of a combination of variable and fixed-value capacitors. In built-in automatic and many manual outboard tuners, L is a fixed inductor with multiple, switch-selectable taps. In upscale stand-alone tuners, L may be a continuously variable *roller* inductor.

[1]Notes appear on page 47.

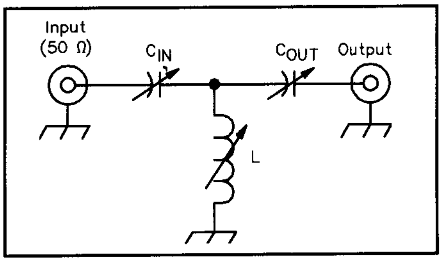

Figure 1— Today's built-in and outboard ham antenna tuners most commonly use this generic circuit, the *T network*. In many automatic tuners, motors adjust the circuit's tuning capacitors (C_{IN} and C_{OUT}), and relays ground various L taps to vary the network's inductance. (Relays may switch in additional inductance or capacitance to extend the network's tuning or matching range.) In manually adjusted tuners, front-panel controls (perhaps labeled **TRANSMITTER** [C_{IN}] and **ANTENNA** [C_{OUT}]) adjust the capacitors, and L may be a front-panel-adjustable roller inductor or a multiply tapped coil teamed with a rotary switch. In exploring the **T** net's performance, we'll assume that C_{IN} and C_{OUT} can be adjusted from 20 to 240 pF, and that L is adjustable from 0.1 to 35 µH.

Stand-alone outboard tuners often include a 4:1 balun transformer that extends the tuner's matching range and allows it to drive balanced feed lines. The balun's 4× (balanced) side connects to the load, and its 1× (unbalanced) side connects to the tuner output. Some tuners use a 1:1 balun instead.

It's usually possible to find more than one group of **T** network settings capable of transforming a given load to 50 Ω. Some of these values may work better than others; some may even be worth avoiding altogether! Sometimes a **T**-network's components overheat or arc over; sometimes, it seems hard to match a garden-variety load even with a wide-range tuner. Let's see if we can find out why.

T Network Basics

The **T** network is a versatile matching circuit. If its capacitors and inductor can be set to the necessary values, it can match practically any antenna impedance radio amateurs are likely to encounter. What makes this tricky is that, for a given matching problem, an infinite number of C_{IN}, C_{OUT} and L values can achieve a match! We need not endlessly seek a workable set of values, however. Once we set any one of the network's three components to some arbitrary fixed value, we can readily determine the other two values necessary for matching a given load.

For example, say we want to match a 50-Ω transmitter to a 200-Ω resistive load at 3.8 MHz. If we set C_{OUT} to midrange (about 130 pF), C_{IN} must be 233.7 pF, and the inductance must be 5.65 µH.[2] We could preset either of the network's other two variables, C_{IN} or L, instead, and as long as its value is one that allows the network to transform 200 Ω to 50 Ω at 3.8 MHz, we could determine the other two values by experimentation.

If the tuner's inductor is continuously variable, any of the network's variables can serve as the fixed one. If the tuner has a tapped inductor, the inductance is the logical choice for the fixed variable. More than one setting of the inductor switch may allow us to achieve a match within the range of C_{IN} and C_{OUT}.

Matching Range

For purely resistive loads, a **T** network with Figure 1's C_{IN}, C_{OUT} and L values can match loads of about 10 Ω to 3 kΩ from 160 through 15 meters. At 10 and 12 meters, the range narrows to about 10 Ω to 1.5 kΩ because C_{IN} and C_{OUT} cannot be adjusted to less than 20 pF.

When the load impedance to be transformed is reactive, the matching range narrows. Even with reactance present, very few cases should occur in which the antenna cannot be matched with the proper tuning technique. (We'll discuss tuning technique shortly.)

Harmonic Attenuation

The C-L-C **T** shown in Figure 1 is basically a high-pass network. Thus, it can't attenuate harmonics very much. As Figure 2, Table 1 and Table 2 show, making the network tune more sharply somewhat increases its harmonic attenuation, but even at maximum tuning sharpness, the network's attenuation would likely contribute little to improve a transmitter's spectral purity.

This is why this form of **T** network was not used in Amateur Radio circles until recently. Because modern commercial transmitters and amplifiers must meet rigid spurious-emission standards, further harmonic suppression by outboard devices is usually not necessary. If we used variable inductances to replace C_{IN} and C_{OUT}, and replaced L with a variable capacitor, we'd have an L-C-L **T**—a *low*-pass network similar to the familiar pi networks often used in

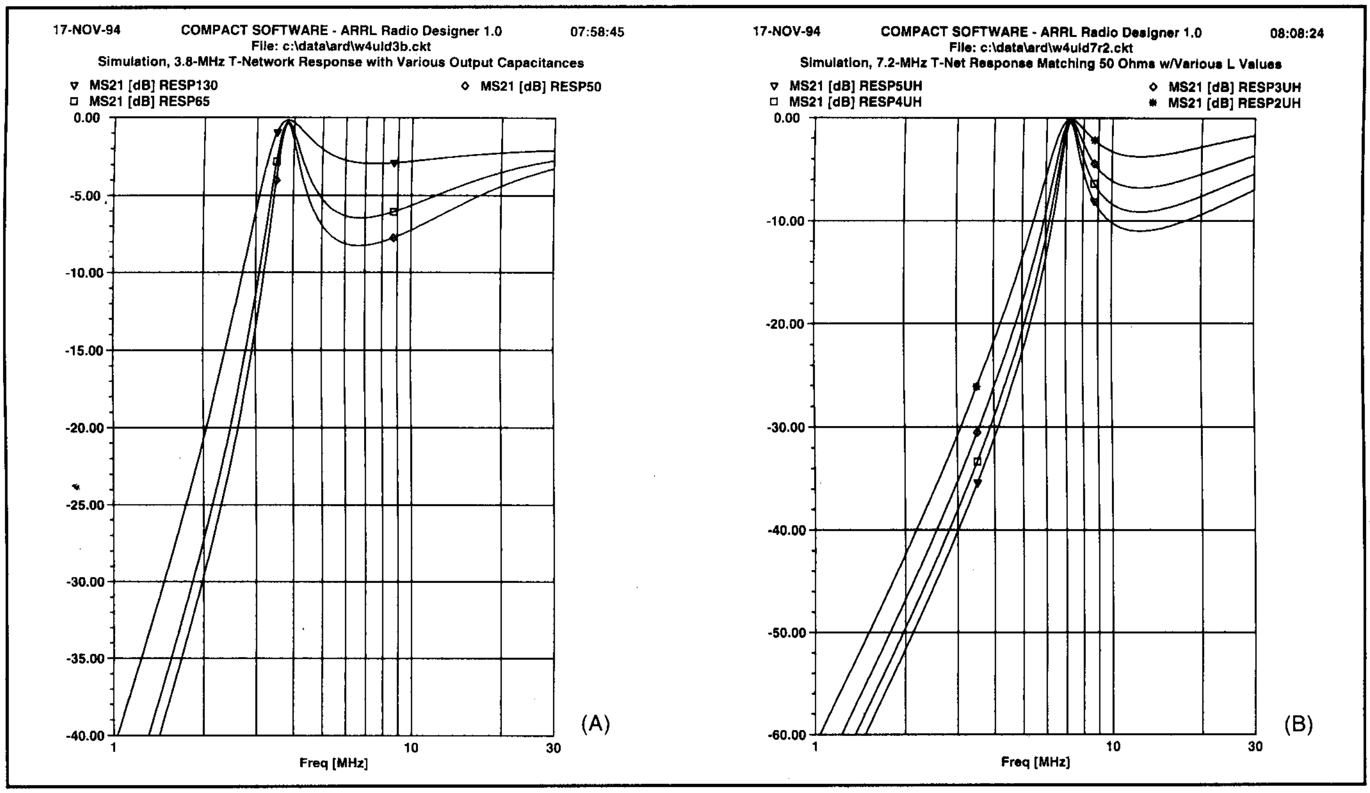

Figure 2—How different sets of T-network C_{IN}, C_{OUT} and L values can vary the network's tuning sharpness for a given impedance transformation. Graph A shows three 200 to 50-Ω transformations at 3.8 MHz, with C_{OUT} as the fixed variable; Graph B shows four 50 to 50-Ω transformations at 7.2 MHz, with L as the fixed variable. (A T network left in line to "flatten" an antenna's modest impedance shifts above and below resonance must be able to "transform" 50+*j*0 Ω to 50+*j*0 Ω as well as transform divergent impedances to 50+*j*0 Ω.) Tables 1 and 2 show the network values and minimum losses associated with these graphs. (*Network simulated, optimized and graphed by WJ1Z with* ARRL Radio Designer 1.0)

Table 1

Simulation, 3.8-MHz T-Network Response with Various Fixed C_{OUT} Values, 200+*j*0 Ω to 50+*j*0 Ω Transformation (Figure 2A)

Curve	RESP130	RESP65	RESP50
C_{IN} (pF)*	233.7	130	103
C_{OUT} (pF)*	130	65	50
L (μH)†	5.65	9.4	11.8
Loss (dB)	0.16	0.31	0.39

*Q=1000
†Q (skin-effect model)=200 at 7.9 MHz

Table 2

Simulation, 7.2-MHz T-Network Response with Various Fixed L Values, 50+*j*0 Ω to 50+*j*0 Ω Transformation (Figure 2B)

Curve	RESP5UH	RESP4UH	RESP3UH	RESP2UH
C_{IN} (pF)*	50.7	63.5	85.7	133.3
C_{OUT} (pF)*	48.2	61	83.1	133.3
L (μH)†	5	4	3	2
Loss (dB)	0.43	0.34	0.25	0.16

*Q=1000
†Q (skin-effect model)=200 at 7.9 MHz.

vacuum-tube RF power amplifiers. However, doing so would add considerably to the cost of a tuner, and its tuning would be more awkward.

Tuner Losses and Power Limitations

Because tuner components are not 100% efficient, some of the RF power applied to a tuner's input turns into heat instead of showing up at the tuner's output. It's often said that these power losses are "not worth worrying about." The truth of this statement depends on how much power your tuner can safely dissipate, and how much loss you *want* to worry about. Power loss in a tuner occurs mostly in the inductor, and is inversely proportional to the inductor's quality factor (Q)—the higher an inductor's Q, the lower its loss. Losses can also occur in a tuner's connectors and balun, but let's neglect these additional losses and assume that the tuner's inductor is good quality, with a Q of 200. A typical tuner task is to extend the range of a dipole over an entire band. Curve C of Figure 3 shows the tuner loss for this situation. At 40 through 10 meters, the loss is less than 0.1 dB—that is, 2.3%. At 160 meters, the loss rises to about 0.32 dB, or about 7%. Even a purist might agree that a loss this low is "not worth worrying about"—but in saying so, we'd be assuming that the tuner components doing the "lossing" can safely dissipate 7% of the power applied. Seven percent of 100 W is 7 W; 7% of 1.5 kW is *105* W. Depending on your transmitter power, and your tuner's loss and dissipation capability, *any* decibel value of tuner loss may be worth worrying about!

At any frequency, **T**-network loss goes up as the load impedance goes down. As Figure 4 shows, the worst case (for a **T** network with the L and C values shown for Figure 1) is 160 meters, where power losses of *over 20%* can occur *even though the tuner is adjusted for maximum efficiency.* Figure 3's A and B curves show minimum and maximum loss versus frequency with a load impedance of 10 Ω.

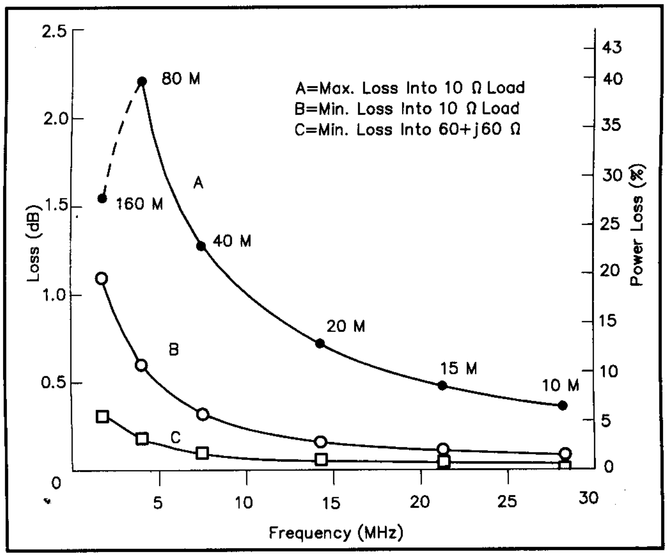

Figure 3—How lossy can a T network be? Curves A and B show the Figure 1 network's maximum and minimum losses when transforming a 10+*j*0-Ω load to 50+*j*0 Ω. Curve C shows the network's minimum loss when matching an 50-Ω antenna slightly off resonance (60+*j*60 Ω). Depending on the transmitter power and tuner type involved, even a network loss on the order of 0.3 dB can cause tuner components to overheat or fail. (*Graph by W4ULD*)

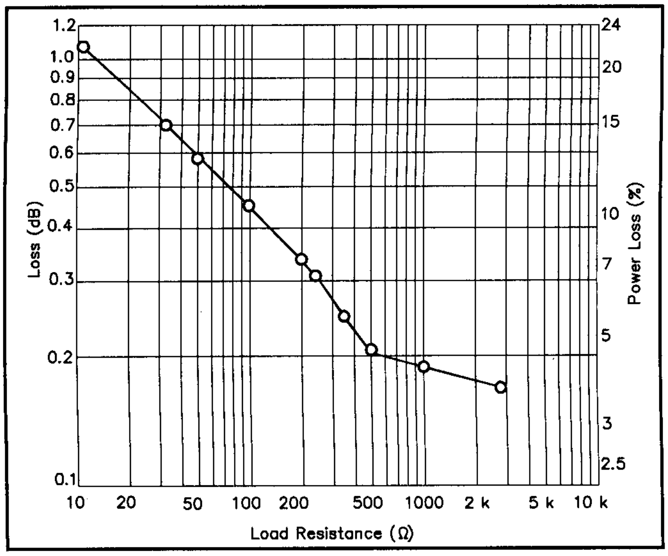

Figure 4—A T network with Figure 1's values can transform a wide range of impedances to 50+*j*0 Ω at 160 meters, but its loss is significant for lower-impedance loads. Using a 500-pF variable at C_{IN} and a 1000-pF variable at C_{OUT} would allow network losses of less than 0.3 dB even when matching 10 Ω, but these capacitors' high minimum capacitances would then restrict the network's high-Z matching ability on higher-frequency bands.

In the T network, loss is also proportional to tuning sharpness (the sharper the tuning, the higher the loss). Tuning sharpness is inversely proportional to output capacitance (the lower the value of C_{OUT}, the higher the loss). Figure 3's A curve shows loss versus frequency with the minimum output capacity that allows a match at the desired frequency. We are now talking about losses between *10% and 40%*! The highest losses occur from 40 to 160 meters.

Low load impedances don't just cause high losses; they also cause relatively high voltages to appear across the network's capacitors. When a short circuit occurred in my 75-meter antenna's coaxial feed line, my T-network tuner could successfully load the shorted coax at 100 W output. At about 750 W, one of the network's air-dielectric capacitors arced over.

Some tuners switch in solid-dielectric fixed capacitors for more efficient matching on lower-frequency bands. Like air capacitors, these can flash over in response to overvoltage. Unlike air capacitors, however, they can also overheat and fail if subjected to the high RF currents that may occur in some extreme matching situations.

Practical T-Network Tips

What I've covered so far about loss and capacitor flashover suggests two practical hints for T networks with C and L values like those of Figure 1:

- To achieve the highest possible efficiency at a given impedance transformation, tune the network with the highest output capacitance that allows a match.
- When matching loads of less than 25 Ω on 80 meters and 160 meters, you may have to reduce your output power to reduce tuner heating or to keep it from arcing. With loads like this, you may not be able to use a legal-limit amplifier even with a tuner specified to handle 1.5 kW.

When operating with high power, take the following precautions:

- Don't feed short (less than 0.3 λ), loaded dipoles with a feed line that's a multiple of ½-λ (electrical) long. Such antennas may have feedpoint impedances of 5 to 9 Ω, and since the input impedance of a ½-λ line section closely mirrors the impedance of its output load, the tuner will also see a very low load impedance.
- Don't operate a 160-meter ½-λ dipole on 80 meters, or an 80-meter ½-λ dipole on 40 meters, with a coax feed line that's an odd multiple of ¼-λ (electrical) long. In this situation, the antenna's high feedpoint impedance will be transformed to 1.5 to 2 Ω at the tuner. To add insult to injury, the feed line loss will be excessive—over 6 dB. *A 6-dB loss wastes ¾ of your transmitter power as heat.*
- Don't use a tuner's 4:1 balun to feed a ½-λ dipole via a ladder line that's a multiple of ½-λ (electrical) long. The tuner may see a load impedance of 12 to 15 Ω. A 1:1 balun would be a better choice in this situation.

A Tried and True T Tuning Technique

I find that a T network built with the component values shown for Figure 1 can match most antennas to 50 Ω. Problems in tuning usually result from improper technique.

We commonly adjust roller-inductor tuners by adjusting each control in sequence to achieve a minimum SWR. The problem with this approach is that the minimum SWR combination may be passed each time a single control is adjusted, making the true minimum hard to find. Confronted with this situation, we may think that the best we can do is an SWR of 1.5 or more. With a little practice, the T-network tuning technique I'm about to describe should work almost every time.

Practice with low power and a dummy antenna fed via coaxial cable. If a large variable capacitor of about 100 pF is available, connect it in series with the center conductor of the coax at the dummy antenna. By setting this capacitor to various values, you can practice matching reactive loads that produce high SWRs. Instead of driving the tuner with a transceiver, you can use an antenna analyzer.

Remember, if one of a T network's three variables is fixed, only one setting of each of the other two variables can provide a match. You can't adjust the tuner's tuning sharpness with a knob, of course; the settings you ultimately arrive at will determine it. Generally, less C_{OUT} translates to sharper tuning. But because efficient tuner operation is more important than a tuner's harmonic reduction, it's more important to remember that more C_{OUT} translates to less loss.

For Roller-Inductor Tuners:

1. Set C_{OUT} at maximum capacitance and leave it there.
2. Set C_{IN} to about half scale.
3. Adjust the roller inductor for an SWR dip. (The dip may be barely noticeable.)
4. Slightly increase or decrease the C_{IN},

and readjust the inductor for a dip.

5A. If the SWR is lower than it was in Step 3, slightly vary C_{IN} in the same direction as in Step 4.

5B. If the SWR is higher than before, adjust C_{IN} in the direction opposite to that taken in Step 4. Alternatively, inch C_{IN} in the Step 4 direction and redip the SWR with the inductor until you obtain an SWR near 1:1.

6. When you've almost reached the match point, the SWR may start to go up as you adjust C_{IN}, but make the change anyway and redip with the inductance.

7. Continue to adjust C_{IN} in the same direction until adjusting the inductor produces a higher SWR than before. Inch the capacitor back to the previous setting.

8. If you cannot obtain a 1:1 SWR, reduce C_{OUT} and repeat the process, beginning at Step 2. If you cannot acceptably minimize the SWR at some setting of C_{OUT}, the antenna impedance is out of range of the tuner.

For Tapped-Inductor Tuners:

The only disadvantage of a tapped-inductor **T** network tuner is that its limited inductance resolution may not let you set C_{OUT} to its maximum possible value at match. With the tapped-inductor tuner, the inductance becomes the fixed variable.

1. Set C_{IN} and C_{OUT} to midscale. Select an inductance switch position, and rotate the C_{OUT} through its range to look for an SWR dip. As before, the dip may be very slight.

2. If you don't find a dip, set the inductance switch to another position and adjust C_{OUT} for an SWR dip.

3. When you find a dip, adjust C_{IN} for minimum SWR.

4. Inch C_{OUT} in one direction or the other, and redip with C_{IN}.

5. If the SWR is lower now than it was with the previous C_{OUT} setting, continue to inch C_{OUT} in the same direction and redip the SWR with C_{IN} until you obtain a 1:1 SWR.

In some cases, an SWR dip can be obtained with two inductance settings. Choose the setting with the lower inductance to get the larger output capacitance.

Summary

Properly configured, a **T** network tuner can match practically any antenna the radio amateur is likely to encounter. Using Figure 1's C and L values, it can transform purely resistive 10 Ω to 3 kΩ loads to 50 Ω, resistive, in the amateur bands from 1.8 through 21 MHz, and it can transform 10 Ω to 1.5 kΩ loads to 50 Ω, resistive, from 24 to 29 MHz.

Because the **T** network is a peaked high-pass network, you should not expect it to provide significant harmonic reduction. Since FCC's Amateur Radio Rules require that acceptable levels of harmonic reduction be built into modern transmitters, we need not expect an antenna tuner to improve it. This lets us design and adjust our tuners for maximum transformation efficiency instead of wasting power in sharply tuned matching networks.

Loss in a **T** network tuner is often less than 0.3 dB, but may be considerably higher. For a given impedance transformation, minimum loss occurs when C_{OUT} is as high as possible when a match has been achieved. The loss in a **T** network that uses Figure 1's L and C values can approach 2 dB when matching load impedances lower than 20 Ω at 40, 80 and 160 meters. Under these conditions, component heating and/or arcing may occur, and the tuner's power-handling capability may have to be derated. With the proper tuning techniques, however, an acceptable impedance transformation—as indicated by a 1:1 SWR—should be obtainable under most circumstances.

Notes

[1]This capacitor-inductor-capacitor (C-L-C) **T** arrangement forms only one of many possible **T** combinations of coils and capacitors. In this article, "**T** network" means the C-L-C circuit, which is the most widely used **T** configuration in Amateur Radio antenna tuners today.—*Ed.*

[2]I determined these values with a GW-BASIC computer program I wrote (and we confirmed and refined them with *ARRL Radio Designer 1.0—Ed.*). This article is about finding **T**-network values by experiment, so it doesn't included the formulas I used to achieve this 80-meter match. If you're interested in experimenting with my program, you can download the file TNETWORK.BAS from the ARRL BBS at 203-666-0578.

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You can also download the *HAMCALC* ver 8.7 from the ARRL HQ BBS at 203-666-0578, or via Internet, by anonymous FTP from several sites, including oak.oakland.edu. The files on this site include a mirror of ARRL HQ's e-mail information server (info@arrl.org) in the directory pub/hamradio/arrl/infoserver and a number of programs and binary files that accompany *QST* articles in the directory pub/hamradio/arrl/qst-binaries.