On the Quest for an Ideal Antenna Tuner

This discussion of optimum antenna tuners for feeding antennas through balanced lines will clear up some common misconceptions.

Introduction

The function of an antenna system tuning unit (ASTU) is to transform the impedance at the input end of the transmission line to the 50 Ω impedance required by the transmitter, and so establish a conjugate match for maximum power transfer to the antenna system. Over the years, radio amateurs have devised many circuits for doing this. At one time, when open wire transmission lines were in common use, transmitters had link coupled tuned circuits to provide the balanced output needed to feed a balanced antenna system such as a ladder line-fed multiband dipole.

Coaxial cable feed lines are now more commonly used, and most commercial and homebrew antenna tuners use unbalanced networks. Thus, to feed an antenna system, such as a multiband dipole, a balun is required at the point where the coaxial cable connects to the balanced antenna system. If open wire transmission line is used, the balun is usually placed between the ASTU and the balanced line, where the VSWR can be high. This stresses the balun, and could lead to balun failure. In addition, power loss can be considerable.

Most commercial ASTUs used by amateurs employ a high-pass T network. Dean Straw, N6BV (and others) have developed computer simulation programs that make it possible to estimate matching range, internal losses and peak RF voltages for T, π and L section networks. This program is provided with recent editions of The ARRL Antenna Book, and example calculations are given, in aid of selecting the most practical tuner. The high power tuner designed and built by N6BV is a T section matching network. James Garland, W8ZHR, using the ARRL program, describes a very professional looking automatic T network-based tuner in his QST article series.

The principal differences between N6BV's tuner and W8ZHR's tuner are as follows:

- N6BV has constructed his tuner so that the "ground" terminal of the unbalanced T network can be isolated from chassis ground. That is, the chassis is not hot but the unbalanced RF network can be floated with respect to the chassis and transceiver ground. Hence, a balun can be inserted at the input to the ASTU (between the transmitter and the tuner), and the output terminals are in effect balanced with respect to ground. W8ZHR's tuner is the more usual unbalanced network arrangement, and so to feed a balanced transmission line a balun is inserted between the tuner and the transmission line (where the VSWR can be high); and
- W8ZHR has automated his tuner, which is certainly an accomplishment that I could not do. The inductor in his circuit will certainly have a Q factor that is high compared with the compact commercial automatic tuners, which are less efficient when used to tune antenna systems that have a large capacitive input impedance.

Simplifying the Network

W8ZHR's three part article begins with a brief review of antenna system tuning units and follows with a description of versions of the T network. He decides in his quest for the "ideal tuner" to base his design on the popular T network. A consideration of the L network is provided in the following comment in a footnote:

"For tuners dedicated to specific antennas, many amateurs swear by the simple L network. However, the L network cannot match both low and high impedance loads without changing the configuration, and this shortcoming makes it unsuitable for a general purpose antenna tuner."

I have used L networks for 50 years to match antenna systems, for ease of matching and to allow visualizing what I am doing. The procedure that I use is to resonate the antenna by a series reactance, and then use an L network to match the resistive component of the antenna's impedance to the required 50 Ω impedance. If the antenna's resistance is less than 50 Ω, a two element L-C network will do the trick. If the antenna's impedance is greater than 50 Ω, a reversed L network must be used, and so the two element L network then becomes a three element network, or a T network. A rearrangement of the circuit elements can usually provide a match using a two element L network for almost any antenna system impedance (see below).

With the L network or the reversed L network referred to by W8ZHR, the so-called "shortcoming" is not really a problem. A single pole double throw switch can be used to change the configuration, as shown in Figure 1. When impedance matching, the user of the T has to tune three knobs to match while an L matching network requires only two (and one less variable RF component). In the words of my Newfoundland colleague Joe Craig, VO1NA, "the user of a T wastes..."
time mucking about with a 'useless knob,' since an L network is just as useful for getting a low VSWR.

To tune balanced loads, the "ground" connection for the network (normally connected to chassis ground) needs to be isolated from chassis ground. See Figure 1. The tuner input terminals could be a standard female coaxial connector, mounted on a small square piece of Plexiglas so it can be isolated from chassis ground. The jumper connections provide the necessary connections at the input and output terminals to chassis ground, as required for tuning unbalanced antenna systems. A 1:1 W2DU-type current balun, ferrite beads over the coaxial cable, is shown in the figure. This balun is in fact an integral part of the coaxial line connecting the tuner to the transmitter.

**A Case Study**

I have for many years been making the case that the best method to feed a multiband dipole is to use a balanced transmission line having the necessary length to reach from antenna terminals to receiver, not as Louis Varney, GSRV, did (see the Appendix). To illustrate the usefulness of the simple L network, using component values given in Figure 1, I have used the **EZNEC pro** antenna modeling program **NEC 4D** provided by Roy Lewallen, W7EL, combined with the **ARRL TLA Transmission Line Matching program**. I have shown that indeed this network (with the switch in Position B) can be used to match a 102-foot (30.1 meter) dipole, popularly called an GSRV dipole, fed with 450 ohm windowed twin lead, on all amateur bands 3.5 MHz to 29.7 MHz. The dipole height is 40 feet (12.2 meters) and for my numerical model this is the length of the transmission line [Editor’s note: The 19th and later editions of The **ARRL Antenna Book** bundled a Windows version called **TLW** (Transmission Line for Windows). **TLW** gives a more sophisticated set of values for nominal 450 ohm line compared with **TLA**].

The results of this case study are tabulated in Table 1. Note that for 3.75 MHz the maximum capacitance of the 135-503-1 capacitor is perhaps just enough (including distributed capacitance), and clearly a low minimum capacitance is also required for the higher frequencies.

The computed tuner losses (including the loss in the transmission line) using the default values of the **ARRL** program are a dB or less.

**A More Versatile Tuner**

One can certainly find impedances that this simple circuit will not match. This difficulty can usually be overcome by interchanging L and C. For optimum performance the circuit shown in Figure 2 could be used, since this arrangement permits by switch selection the full range of versatility available with the L network. Switch S1 is used (as in Figure 1) to switch the shunt element from the input to the output terminals. Switch S2 is a four pole, three position switch that interchanges C and L or bypasses the tuner. Switch S3 selects either a single section of a dual section capacitor, or parallels the two sections. This arrangement is used to maximize the minimum capacity setting for the capacitor C. If C were a vacuum variable this switch would not be needed. This switch should be a multi-position switch to connect fixed capacitors across C (or external fixed capacitors could be added by means of connection to banana plugs mounted on a Plexiglas strip), which may be needed for the lower bands (40 meters and up).

The ground circuit arrangement should be as indicated in Figure 1. To make the tuner even more versatile, a 4:1 balun could be used as an aid in matching some impedances. This is because, in effect, the balun is an integral part of the coaxial cable connecting the receiver to the **ASTU**. Thus, the tuner will then match to 200 ohms, instead of 50 ohms (see below).

**Some Aspects of the Balun Problem**

I have, see above, and in published articles, said that the place to put a balun is on the tuned side of an **ASTU** where the VSWR is 1:1. I have experimented with two versions of tuners feeding a system of off center fed dipoles—an antenna system that presents an unbalanced load to the balanced transmission line—because the arms of the dipole are different lengths. Each conductor of the transmission line sees a different impedance with respect to virtual ground. This antenna system makes an interesting load for an **ASTU**. I used (1) a balanced network with a voltage balun on the input "tuned side," and (2) an unbalanced network with a current balun on the output side (high VSWR).

Feeder currents I_1 and I_2 were monitored (by means of current transformers) at the input terminals of the balanced transmission line. The balanced transmission line was, in fact, two coaxial lines; we in effect had a center tap to measure

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**Table 1**

**Case Study by Simulation**

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Dipole Impedance (Ω)</th>
<th>Input Impedance of Antenna System (Ω)</th>
<th>Network Values</th>
<th>Transmission Line Loss (Tuner Loss)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.75</td>
<td>29 - 334.6</td>
<td>28.75 + j17.94</td>
<td>1.7 μH, 98.9 pF</td>
<td>0.9 dB (0.15 dB)</td>
</tr>
<tr>
<td>7.15</td>
<td>5393 + j1244</td>
<td>56.23 + j22.47</td>
<td>0.6 μH, 326.6 pF</td>
<td>0.18 dB (0.02 dB)</td>
</tr>
<tr>
<td>14.15</td>
<td>1148 + j54.5</td>
<td>154.13 + j243.56</td>
<td>1.7 μH, 98.9 pF</td>
<td>0.15 dB (0.09 dB)</td>
</tr>
<tr>
<td>18.1</td>
<td>2066 + j1573</td>
<td>65 + j21.5</td>
<td>0.3 μH, 122 pF</td>
<td>0.25 dB (0.02 dB)</td>
</tr>
<tr>
<td>21.15</td>
<td>2893 + j1048</td>
<td>863.1 + j1681.2</td>
<td>3.3 μH, 20.5 pF</td>
<td>0.41 dB (0.24 dB)</td>
</tr>
<tr>
<td>24.925</td>
<td>201.1 + j83.9</td>
<td>477.9 + j600</td>
<td>1.5 μH, 53.9 pF</td>
<td>0.14 dB (0.13 dB)</td>
</tr>
<tr>
<td>29.0</td>
<td>2108 + j502</td>
<td>67.4 + j21.35</td>
<td>0.2 μH, 75.1 pF</td>
<td>0.29 dB (0.02 dB)</td>
</tr>
</tbody>
</table>
current in the center tap lead to ground, \( I_{\text{gnd}} \). That is, the shields of the coaxial cables are connected at the transmitter end and at the antenna end and, at the transmitter end, the shields connect to chassis ground. The results of this experiment are shown in Figure 3. This experiment tells us that even though a balanced tuner was used, it is necessary to use a current balun to force almost equal currents into the two conductors of the balanced line. For our transmission line, if the currents are not exactly equal, there will be a difference current flowing in the ground lead that connects the braids of the two coaxial cables to the tuner ground. Peak \( I_{\text{gnd}} \) currents are less (except for one value) for the case where the balun is on the output side of the tuner (high VSWR) and, although the balun is certainly doing its job (equal currents into an unbalanced two conductor load), the balun losses are increased.

In other experiments with baluns placed at the output terminals of an unbalanced tuner, in cases where the VSWR can be high, we can have problems with baluns. The W2DU type balun (ferrite beads over coax) gets very hot at kW power levels. Increasing the number of beads from 100 to 300 helped the heat problem, but we still had excessive balun power loss. Various versions of the bifilar wound choke type balun\(^{19}\) on a ferrite toroid failed (blue flame and smoke) during testing (carbon burns damaged the insulation because of arcing between turns), and I even cracked the ferrite core of a so-called commercial kW balun.

Providing the VSWR is not too high, it does not matter where the balun is located (input or output end), but power loss will be smaller if the balun is on the input side.

Finally, I will comment on using a tuner with an unbalanced network, but with a “floating ground,” compared with using a balanced tuner. In my view there is no circuit performance difference, excepting that the balanced network component values are different, and at least three components are needed rather than two. The current balun insures equal transmission line conductor currents in both cases. Stray capacitance will also be slightly different.\(^{11}\)

Finally, looking again at Web discussions, it should be noted that an unbalanced network with a “floating ground” means the so-called “ground end” of the network is not connected to chassis ground. The chassis is not “hot,” the chassis is grounded, but the network is floating.

**Concluding Remarks**

The L matching network that I describe, using a switch arrangement to provide different circuit arrangements, is indeed a very versatile tuner. It is not, however, an...
innovative design that can provide performance better than any homebrew ASTU ever created. It can be designed to handle antenna systems having a high reactance. It has so far proven to be just as useful for getting a 1:1 VSWR as other tuners I have used, for example T matching networks made by Ventionics and by MFJ; and a π matching network made by R. L. Drake (I still have and use the performance proven Drake MN-1000).

A final comment on power loss in the ASTUs. From the point of view of resistance match, the L network can be used to provide a low loss (typically less than a dB) resistance match to almost any load resistance (from a few ohms to thousands of ohms). Tuner loss when using the T network increases with decrease in load resistance, and tuner loss becomes significant for load resistances less than the desired match load resistance (50 Ω). See, for example, Figure 3 in Part 1 of the article by W6ZR. Both types of tuners (T or L) suffer increasing loss when the decrease in the resistive component of the load impedance is associated with an increase in the capacitive reactance of the load (for example, tuning electrostatically small antennas). But this loss is unavoidable, since the capacitive reactance of the load has to be canceled by a conjugate inductive reactance provided by the tuner.

Let me consider, for point of illustration, a case study—the matching an impedance of 5+j400 Ω at a frequency 3.75 MHz. Tuner loss (using default values for the ARRL program) for the L section network is 2 dB (according to TLA). Tuning the same load with a T matching network yields a loss of 4.1 dB to 2.1 dB, depending on the setting of the output series capacitor (100 pF to 5000 pF, respectively). This example illustrates that for the T there can be a range of settings that lead to a 1:1 VSWR and that some settings are better than others.

In other words, a low resistance high capacitive reactance is not good for anybody's tuner. That is why electrically short antennas should be tuned by a high Q (low loss) base loading coil.

Dean Straw, N6BV, noted, on reading an earlier version of this article, that if I had used a longer transmission line (62 feet instead of 40 feet) for my G5RV dipole, I would have to match a different impedance at 3.75 MHz, 50+j600 Ω (instead of 26+j173 8Ω). He noted that a high-pass T network with the maximum output series capacity of 400 pF will match this impedance, and the loss will be 0.9 dB. My L network will match this impedance (series L on the output side, shunt C) but the loss is 0.33 dB. The T network is better.

The question mark—is it? If instead of asking the ASTU to match to 50 Ω, suppose we match to 200 Ω. An L network (shunt L, series C on the output side) will tune and match this antenna impedance, and the loss will be 0.04 dB.

Finally, I noted above that most commercial tuners use a T network, with the balun on the output side of the tuner. At least two tuners (but I have seen and used only one) employ an L network. One is a tuner made a number of years ago by UPC (Unique Wire Products), their “Unique Wire Tuner” (I have one). The other is the Ten-Tec Model 243B, a high power tuner in current production that utilizes an L network. This L network has a series inductance with a switching arrangement to move the combination fixed and variable capacitors between input and output to match high and low impedances.

Professional (Laboratory type) L matching networks that I have used for high-power work-related projects all used quality components: Jennings vacuum variable capacitors and silver plated edge wound inductors made by Gates (Q factor 500 compared with 200, the default value for the ARRL program). In my experience, antenna engineers usually employ the L matching network to tune antenna systems. The T and π matching networks are used (on the tuned side) for phased array antenna systems, since a resistance match (to control current) can be realized for the required phase lag needed for the direction of signal propagation. The phase lag for the L matching network is what turns out to be, depending on the impedances to be matched.

I will be interested to hear from anyone who might construct my versatile L matching network shown in Figure 2. A comment for those who do: matching some impedances on some bands may appear (at first) to be a bit tricky, since the knobs may initially have no observable effect on VSWR. This may be because you are using the wrong network configuration. There are four configurations. Sometimes more than one configuration will tune the antenna, sometimes only one. With the correct network configuration tuning will be very precise, and a VSWR of 1:1 will be achievable. Each time you tune to a new band, log the switch positions, and the output impedance and inductor dial settings, for convenience when returning to the same frequency or band.

Notes


11. To use TLA to analyze a balanced network, change the delay for the input impedance to 25° (instead of 50°). We want to match half the antenna’s impedance to the half the desired input impedance. TLA tells us that this for the network is the same as for the unbalanced network, but do not get confused. This loss in dB is a power loss for half the transmitter power, so the total loss is identical.


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Appendix

The initial design[13] of the antenna designed by Louis Varney, G5RV (SK), still popularly used, employed a two part transmission line between the dipole and the transceiver. The first part is a 34 foot (10.34 meter) length of open wire transmission or window transmission line, referred to as a “matching section.” The second part is a coaxial cable “feeder transmission line” with a recommended length of 50 to 60 feet. Varney recognized that “under certain conditions” a current may flow on the outside surface of the coaxial cable, and that a balun should be used at the place where the coaxial cable connects to the matching section. His recommendation was not to use a balun, because “later experiments and a better understanding of the theory of operation of the balun indicate that such a device was unsuitable because of the highly reactive load it would see at the base of the matching section or make up section on most HF bands.” Let me look at the effect feeding the antenna with this transmission line arrangement and no balun.

I have numerically modeled a sloping G5RV, sloping since a single tower is used for support. The dipole arm lengths are 51 feet (15.5 meters) with an angle between arms of the dipole of 120°. It is fed by a 34 foot (10.36 meters) length of open wire line, and 28 feet 5 inches (8.66 meters) of coaxial cable. My dipole is supported by a 62 foot tower and thus is at a height of 62 feet (19 meters).

To feed the G5RV with open wire transmission line, I place a jumper across the input end of the transmission line (Varney’s “matching section”) and placed my source in the center of that jumper wire.

Now add the coax feeder, no balun. The coax is grounded at the transmitter end (transceiver ground). The shield of the coax at the antenna end connects to one conductor of the open wire line, the center conductor of the coax to other conductor. In effect, this places the source at the junction between coax and open wire line (see Figure 4A). Certainly currents flowing on the inside surface of the coax and on the center conductor of the coaxial cable do not radiate. My model for the shield of the coax is a ½ inch (12.7 mm) thick conductor, with the source moved to the antenna end.

The tower and the shield of the coaxial cable are grounded to 10 foot (3 meter) stake grounds. Figure 4A shows my wire model and the currents on all wires of the model (green traces) for a frequency of 7.2 MHz. Notice:

- the currents on the two arms of the dipole are certainly not equal;
- this is because the currents on the two conductors of the open wire line are not equal (these currents are approximately 180° out of phase); and
- current is induced to flow on the outer surface of the coaxial cable, and on the support tower.

The impedance at the effective feed point, at the junction between the coaxial cable and the open wire line is 111 – J231 Ω, which indicates the problem of installing a balun there.

Clearly current everywhere is undesirable.

If the dipole is fed by open wire line all the way, the currents on the two arms of the dipole will be equal (not shown), and there will be no induced current on the support tower.

ALPHA 4510 COMPUTING WATTMETER

The Alpha/Powerr 4510 is a computing wattmeter for the 1.8-30 MHz 60 mW to 3000 W range. It features both an analog and a digital display. The LED digital display can be used for a quick on-the-air glance to ensure the transmitter is working, as well as for power readout. Either forward power or delivered power can be displayed on the digital meter. The analog meter is said to be useful for peaking or nulling and has nine full-scale power ranges from 300 mW to 3000 W. Either forward power, reflected power or SWR can be displayed on the analog meter. The 4510 features a fast-sampling mode for tune-up, and a PEP mode for normal operation. The computer-based PEP estimation algorithm is said to be more accurate than traditional diode/capacitor approaches. The unit measures its internal temperature and estimates the frequency of the power applied to it, and uses these to improve the measurement accuracy. All measurements are available at full accuracy through a serial interface, using a simple ASCII protocol. Power accuracy is specified at 5% of reading max, 3% typical.

The unit is supplied with an 80-260 V power cube that supplies the 12 V at 0.5 A required for operation. All illumination is by LED. A CD-ROM is included with a Windows application to display the serial data on a PC. For more information, see www.alphamps.com or call 303-473-9232.

FEEDBACK

A couple of errors crept into the K2AOP oscillator schematic in Technical Correspondence [Figure 1, “A Simple, Well-Behaved Crystal Oscillator,” Sep 2004, p 67]. R1, shown as 22 MΩ, should be 2.2 MΩ. R5, shown as 100 Ω, should be 1000 Ω. The variable trimmer capacitor (shown as C4) should be C3 (18 pF). C4 should be a fixed capacitor.

The ferrite core referred to in the caption of Figure 2 in “The Doctor is IN” [Aug 2004, p 54], should be a type FT50-75 rather than the FT37-75 shown. The schematic reference is correct.

In “About FM” [Jul 2004, p 39], the definition of m is incorrect in stating that there are 180/π radians in a circle. That is the conversion factor from radians to degrees. There are actually 2π radians in a circle. One radian does equal 57.3°.

The article entitled “A High Quality Speaker System” appears in this issue; it was inadvertently included in the list of articles on the cover of last month’s issue.