Estimating T-network losses at 80 and 160 meters

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T-network tuners are popular for matching antennas for 160 through 10 meters. Recent articles by Frank Witt, AI1H[1] and Andrew Griffith, W4ULD,[2] addressed how to measure tuner loss for various resistive loads; gave some example calculations and measurements; and showed how to adjust the tuner for minimum loss. Measuring your tuner's loss is the only sure way to know, but by examining the worst case losses at various standing wave ratios, some useful simplifications and estimates of tuner losses can be made. Simple computer programs can accurately analyze your tuner once you know the component values and all the numerical results here can be obtained in this way, but often a "back of the envelope" calculation can give additional insight. You can, for example, look at a hamfest tuner, or read the advertised specifications of a tuner, and easily make an educated guess of the sort of power loss that you can expect on 80 and 160 meters.

Figure 1a gives the schematic diagram of a typical T-network tuner. Since most of the loss is in the coil, lossless capacitors are assumed, and coil loss is included by the equivalent parallel resistance QX_L. Figure 1b shows an equivalent circuit where the desired impedance $R_0 = 50$ ohms in series with the input capacitor C_1 is transformed into its equivalent parallel resistance and reactance. The output resistance R and reactance X in series with the output capacitor C_2 are also transformed into their parallel equivalents.

The input impedance will be 50 ohms if the tuner elements are selected so that the parallel equivalent output resistance in parallel with the coil loss resistance gives the parallel equivalent input resistance,

$$\frac{R_0}{R_0^2 + X_{C1}^2} = \frac{R}{R^2 + (X_{C2} + X)^2} + \frac{1}{QX_L}, \tag{1}$$

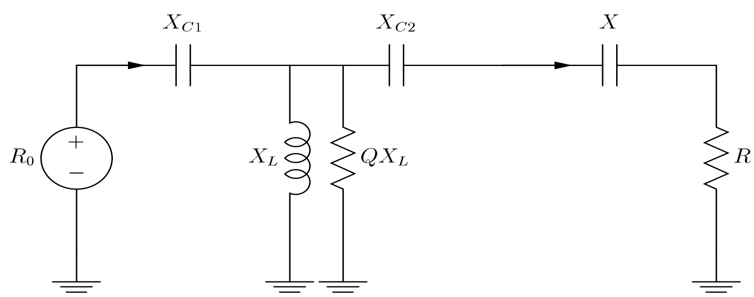
and if the parallel reactances are tuned to resonance,

$$0 = \frac{X_{C1}}{R_0^2 + X_{C1}^2} + \frac{X_{C2} + X}{R^2 + (X_{C2} + X)^2} + \frac{1}{X_L}. \tag{2}$$

The usual T-network has C_1, C_2, and L all variable. Since there are only two matching equations, many combinations will provide a match. The optimum combination is the one that minimizes power loss. The fractional power loss is the ratio of parallel equivalent input resistance to the the parallel coil resistance.

Notice that the parallel equivalent source and load resistances are larger than either of the original source or load resistances. In other words, any T-network will transform the load resistance to a higher value which must also be higher than 50 ohms. It then transforms this high value down to 50 ohms to produce a match. Typical examples at 80 meters would be a 10 ohm load resistance transformed to a 4000 ohm parallel equivalent which is transformed back to 50 ohms, while a 100 ohm load resistance might be transformed to 1000 ohms before being transformed back to 50 ohms. The loss mechanism is now easier to see. For these typical cases, the coil reactance will be around a few hundred ohms. The parallel equivalent coil resistance for a coil of Q=100 would be 10 or 20 thousand ohms. This resistance is enormous compared to 50 ohms and initially you might be tempted to ignore it, but it is placed across a point in the circuit where the impedance is transformed to a few thousand ohms. This means that the loss would be of order 10 percent, hardly negligible if a 1500 watt transmitter is used unless your coil is designed to dissipate 150 watts.

1a



1b

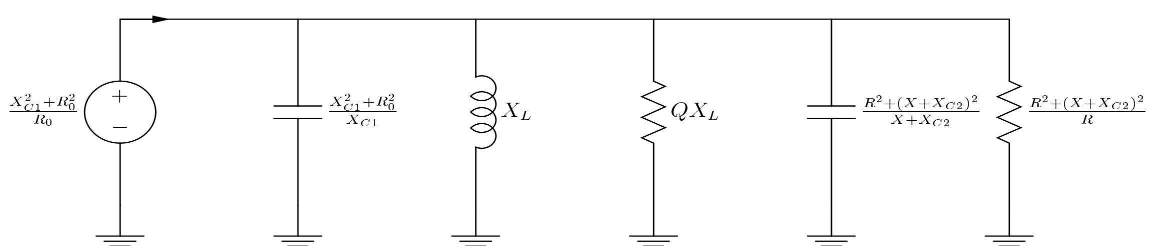


Figure 1: A Typical T-network connected between a source designed for a termination of R_0, and a load impedance consisting of a resistance R and a reactance X. The coil loss is shown as a parallel equivalent resistance (a). An equivalent circuit for the T-network where all elements have been transformed into parallel equivalents (b). Matching requires the load and source parallel equivalent resistances to be equal, and for all the parallel equivalent reactors to resonate.

As discussed by Griffith, a typical T-network designed for 160 through 10 meters has compromises. One of these is that the capacitors typically have a maximum value of 200 to 300 pF. Another is that L is usually a roller inductor. Tom Rauch, W8JI, who has investigated the Q of some roller inductors tells me that a rough estimate of the Q of high quality, off the shelf, commercial roller inductors would range from a low of around 20 at low values of inductance, up to a maximum Q around 100. Custom roller inductors can have a higher Q. Since 80 and 160 meters are the lower frequency limits of these tuners, and the antennas to be tuned there are often relatively short or far from resonance, losses for these bands are important concerns. Problems also occur at the high frequency limit of these tuners with large stray reactances, component minimum values, and low coil Q. Here I will concentrate only on performance at lower frequencies.

Maximum loss occurs for low impedance loads. In figure 2, I show a smith chart where I have plotted points joined by straight lines to approximate contours of constant loss. The inner group of points corresponds to a loss of 0.3 dB, the middle group 0.5 dB, and the outer group 1.0 dB loss. Because the contours are centered toward the right hand side of the chart which corresponds to higher impedances, lower losses tend to occur at higher impedances and higher losses at lower impedances for a given SWR. The contours are shifted toward the top of the chart which indicates somewhat lower losses for inductive rather than capacitive loads. In table 1, I show the loss at 3.7MHz for a tuner with capacitors with a maximum value of 250 pF, coil Qs of 50, 100, and 200, and purely resistive loads. The tuner is adjusted to give the least loss.

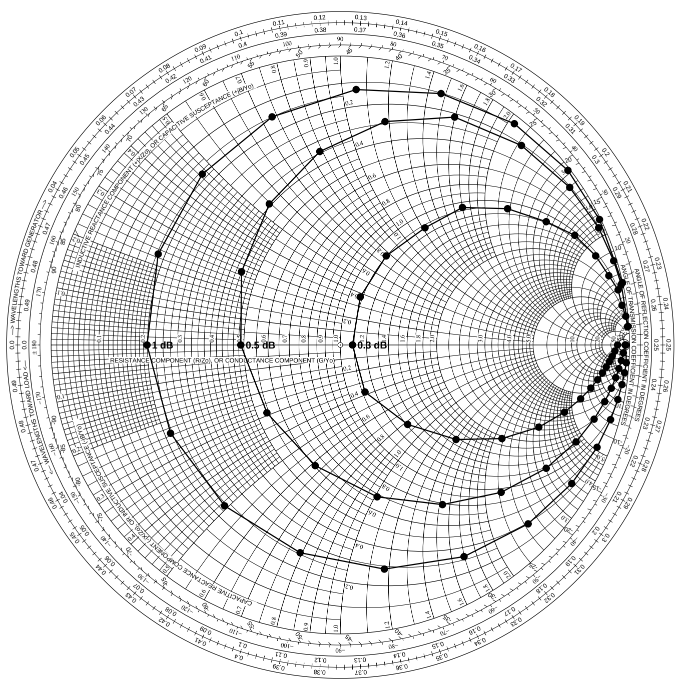
Loads with significant reactance also can be matched with a T-network. In table 2, I show the worst case loss and the load that causes the maximum loss in the network for an SWR of s, calculated by a straightforward numerical search on a computer.

The load shown is that for Q of 100. Detailed analytic calculations show that the worst case loss for SWRs greater than about 2 occurs at an impedance that is slightly capacitive, and is given approximately by

$$\begin{aligned} R &= \frac{R_0}{s}, \\ X &= \frac{R_0^2}{2X_{C2}}, \end{aligned} \tag{3}$$

which agrees with the load calculated numerically and shown in table 2.

Figure 2: A Smith chart, normalized to 50 ohms, showing points of constant loss for a T network with 250 pF capacitors and coil Q of 100. The inner set of dots are at points with 0.3 dB loss. The points have been joined by lines to guide the eye. The outer set of points correspond to 1 dB loss, and middle set correspond to 0.5 dB loss.



R	SWR	Loss(dB) Q=50	Loss(dB) Q=100	Loss(dB) Q=200
1	50:1	7.47	4.99	3.08
2.5	20:1	4.62	2.79	1.57
5	10:1	3.00	1.69	0.91
10	5:1	1.85	1.00	0.52
25	2:1	0.95	0.49	0.25
50	1:1	0.62	0.31	0.15
100	2:1	0.53	0.26	0.13
250	5:1	0.43	0.21	0.10
500	10:1	0.37	0.18	0.08
1000	20:1	0.39	0.20	0.10
2500	50:1	0.61	0.31	0.15

Table 1: Calculated Loss in dB for a T-network tuner at 3.7 MHz using the full equivalent circuit of figure 1b with input and output capacitances of 250 pF, with resistive loads, R, and coil Q shown.

R	X	SWR	Loss(dB) Q=50	Loss(dB) Q=100	Loss(dB) Q=200
50	0	1:1	0.62	0.31	0.15
26	-7	2:1	0.97	0.50	0.25
10	-8	5:1	1.89	1.02	0.53
5	-8	10:1	3.05	1.72	0.93
2.5	-8	20:1	4.69	2.84	1.60
1	-8	50:1	7.56	5.06	3.13

Table 2: Calculated worst case loss and corresponding load for a T-network tuner at 3.7 MHz using the full equivalent circuit of figure reff1b with input and output capacitances of 250 pF. The R and X values shown are for Q=100.

A comparison of tables 1 and 2 shows that while the maximum loss for a given SWR is at a slightly capacitive load, an excellent approximation to the worst case loss at a given SWR is given by calculating with a purely resistive load with

$$R = \frac{R_0}{s}. \tag{4}$$

This numerical result is verified by analytical calculations which show that the additional loss for the reactive load over the purely resistive is given roughly by an additional factor of $R_0^2/(4X_{C2}^2)$ which changes the calculated loss by only a few percent.

The usefulness of these results is that the worst case loss can be approximated simply. For typical capacitor values used and these low resistance loads, the magnitude of the capacitive reactances of C_1 and C_2 at 80 and 160 meters is significantly larger than either R_0 or the load resistance R; a 250 pF capacitance corresponds to roughly 175 ohms at 80 meters and 350 ohms at 160 meters. If the loss is assumed small, Eqs. 1 and 2 can be approximated by

$$X_{C1}^2 = \frac{R_0}{R} X_{C2}^2 = s X_{C2}^2, \tag{5}$$

and

$$\frac{1}{X_L} = -\frac{1}{X_{C1}} - \frac{1}{X_{C2}}. \tag{6}$$

The ratio of the power dissipated in the coil $P_{\rm loss}$ to the power input P is approximately

$$\frac{P_{\rm loss}}{P} = \frac{X_{C1}^2}{R_0 Q X_L}. \tag{7}$$

Using Eqs. 5 and 6, this becomes,

$$\frac{P_{\rm loss}}{P} = \frac{(s + \sqrt{s})|X_{C2}|}{R_0 Q}. \tag{8}$$

This equation shows that the value of $|X_{C2}|$ should be minimized to minimize the loss. Therefore the capacitors should be adjusted to have the largest value they can while achieving a match. For this low impedance case, C_2 should be set to its maximum value. The loss in the T network in dB is

$$L_{dB}^T = -10 \log_{10}(1 - \frac{P_{\rm loss}}{P}). \tag{9}$$

Table 3: Worst case loss for a T-network tuner at 3.7 MHz with input and output capacitances of 250 pF, using Eq. 11.

SWR	Loss(dB) Q=50	Loss(dB) Q=100	Loss(dB) Q=200
1:1	0.61	0.30	0.15
2:1	1.03	0.52	0.26
5:1	2.19	1.10	0.55
10:1	3.98	1.99	1.00
20:1	7.41	3.70	1.85
50:1	17.28	8.64	4.32

Since the approximate formula is only good at small values of loss, I can expand the logarithm without making the approximation worse, using

$$\log_{10}(1-x) \approx -\frac{x}{\ln(10)}. \tag{10}$$

If the frequency f is given in MHz, the maximum capacitance of the capacitors is written as C_{max} and given in pF, then using $R_0 = 50$ ohms,

$$L^T_{dB} \approx 14,000 \frac{s+\sqrt{s}}{C_{max} f Q}. \tag{11}$$

The results of Eq. 11 are shown in table 3, and can be compared with those of table 2. For losses less than a dB or two, the agreement is good.

Eq. 11 allows us to estimate the worst possible loss that can occur with an output swr of s. The loss can be a lot smaller; for example if the swr is 5, but corresponds to a purely resistive load of 250 ohms, Eq. 11 greatly overestimates the loss. However if the swr of 5 corresponds to a purely resistive load of 10 ohms, Eq. 11 should fairly accurately predict the loss

Analytic calculations show that the least loss with a purely resistive load will occur approximately when both capacitors are set to the maximum value, and the load resistance is R $= X_C^2/R_0$ where X_C is the reactance of one of the capacitors. The minimum loss with a resistive load is approximately half that of the loss for a matched load of $R_0 = 50$ ohms if the coil Q remains the same. This result and Eq. 11 give reasonable upper and lower bounds to the loss.

Only the product of the Q value of the coil and the maximum value of the output capacitor needs to be measured or estimated to use Eq. 11. The maximum value of the capacitor is often given in the tuner specifications; if not, it can be easily measured or estimated from handbook formulas from the size, spacing, and number of plates. The coil Q can be guessed, or, for a more accurate estimate, measured using an r.f. bridge or Q meter. Alternatively, measuring the loss for a 50 ohm load and then applying Eq. 11 will give a value of QC_{max} at the measurement frequency. This matched loss can be measured by matching a 50 ohm dummy load with your tuner and using a power meter to measure the input and output powers. Once QC_{max} is known, it can be used to calculate the worst case loss at other SWR values.

Another popular tuner uses a differential T-network. In this network the capacitors C_1 and C_2 are ganged together so that their values sum to approximately C_{max}. The worst case loss can be calculated as before and is

$$L_{dB}^{diffT} \approx 14,000 \frac{(1+\sqrt{s})^2}{C_{max} f Q}. \tag{12}$$

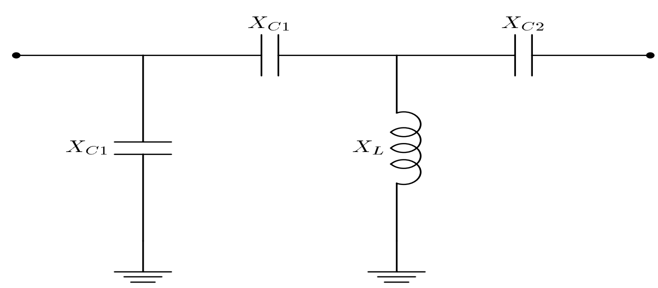
The worst case loss of the differential T network is a factor of 2 worse at an SWR of 1, but becomes the same as the standard T for large values of SWR. This disadvantage is offset by the convenience of having only 2 components to adjust, and by the fact that one source of operator error is eliminated since a really bad set of component values cannot be chosen. This is unlike the standard network where the operator can set the components to values that produce a match but greatly increase losses.

Other T type configurations can be examined. The ultimate[3] and SPC[4] transmatches are shown in figures 3a and 3b respectively. In these, one of the capacitors in the network is replaced with a two-section variable. For the ultimate transmatch, at 80 or 160 meters, the reactance of the capacitor across the input is significantly larger than 50 ohms, so it has little effect. You can simply ignore it in the loss analysis here; the extra section just increases the cost of the transmatch without improving it. The SPC transmatch has the second section of the output capacitor connected across the coil. The worst case loss of this circuit is always greater than the standard T network. The analysis above is easily extended by adding this additional capacitance across the coil. For the SPC network, the loss, when matching load resistances smaller than R_0, is given by

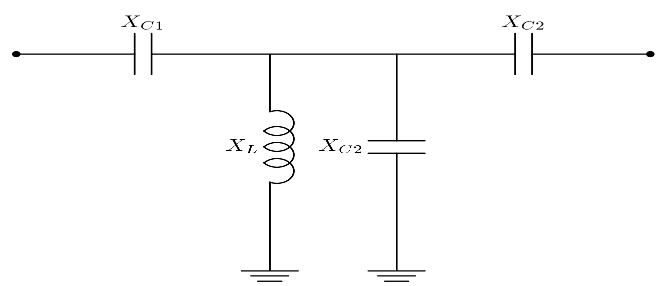
$$L_{dB}^{SPC} \approx 14,000 \frac{2s+\sqrt{s}}{C_{max} f Q}. \tag{13}$$

Figure 3: The ultimate transmatch circuit (a). The SPC transmatch circuit (b). An L-network for matching low resistance loads (c).

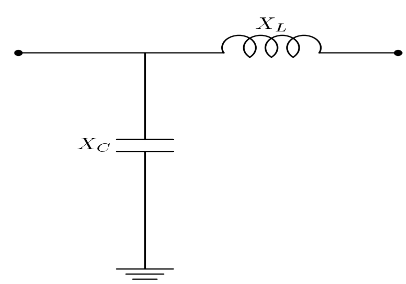
3a



3b



3c



where C_{max} is the maximum capacitance of one section of the output capacitor for the SPC circuit. The loss is 50 percent more than a standard T-network for an SWR of 1, increasing to double the loss as the output resistance drops. Unlike the differential T-network, there does not appear to me to be any benefits from this circuit that offset this additional loss.

It is amusing to compare the T-network results with those of a simple L-network designed to match a resistive low impedance load as shown in figure 3c. The result is

$$L_{dB}^{L} = \frac{10}{\ln(10)} \frac{\sqrt{s-1}}{Q}. \tag{14}$$

For this resistive load, the simple L network is better by an overall factor of $|X_{C2}|/R_0$ which is about a factor of 7 for C_{max} of 250 pF at 160 meters. In addition, the loss for a load of 50 ohms is zero (where the L and C values are both zero) and it increases slower with SWR than for the T networks. The penalty is the limited matching range. An L network tuner needs to be reconfigured to match a wide range of loads; this switching of components can get complicated.

The peak voltage across the output capacitor of a T-network for these loads can also be calculated within these same approximations. Since the series capacitors' reactance is significantly larger than 50 ohms, the voltage across the source can be ignored to get an estimate of the peak voltage. The peak input current is $I = \sqrt{2P/R_0}$. The peak voltage across the input capacitor is therefore,

$$V = I|X_{C1}| = \sqrt{\frac{2P}{R_0}}|X_{C1}|. \tag{15}$$

Substituting as above for the value of X_{C1} in terms of C_{max} in pF, the frequency f in MHz, and the swr s gives the approximate peak voltage across the capacitors for the standard T-network with $R_0 = 50$ ohms,

$$V = \frac{100,000}{\pi} \frac{\sqrt{P}}{fC_{max}} \sqrt{s}. \tag{16}$$

This equation also works for both the ultimate transmatch and SPC tuner circuits. For the differential T network, the relationship between C_1 and C_2 changes the result to,

$$V = \frac{100,000}{\pi} \frac{\sqrt{P}}{fC_{max}} (1 + \sqrt{s}). \tag{17}$$

SWR	Measured Loss (dB)	Calculated Loss (dB)
1:1	0.6	0.6
2:1	0.8	0.8
4:1	1.2	1.3
8:1	2.6	2.4
16:1	4.1	4.5

Table 4: Worst case loss on 80 meters calculated from Eq. 11, and compared to the loss measured in ref. 1 for the Heathkit SA-2040 tuner.

The power loss equations can be compared to some measurements given in Frank Witt's article[1]. The only T-network that he measured was a Heath SA-2040 which has the ultimate transmatch configuration. This tuner does not cover 160 meters. The input capacitor has a maximum value of 125 pF, and the output capacitor has a maximum value of 170 pF. Because these values are not equal, a little care is needed. For a 50 ohm input and output impedance, the capacitor values must be equal. This means that the output capacitor can have a maximum value of 125 pF for a match. However, when the output resistance is reduced, Eq. 5 can be applied to show that for loads below about $(125/170)^2 50$ ohms or about 27 ohms, the full 170 pF value of the output capacitor can be used. The measured loss with a 50 ohm load at 80 meters was 13 percent which corresponds to 0.6 dB. Converting this into a Q value using C_{max} of 125 pF, gives a Q of approximately 100, a reasonable value. Using this Q value and a C_{max} value of 170 pF in Eq. 11, gives the calculated values at other loads shown in table 4 along with the measured values. The values agree within about 10 percent. This level of agreement is partially fortuitous, but these results show that the simple "back of the envelope" calculations work.

For convenience, I have gathered the approximate loss and peak voltage formulas in table 5.

These results point out some fundamental problems in using a 160 through 10 meter T-network tuner at 80 and especially 160 meters. Even feeding a resistive 50 ohm load with a tuner with 250 pF capacitors and a coil Q of 100 gives a loss of about 0.6 dB. With a 1500 watt transmitter, the coil will have to dissipate about 180 watts. I doubt if many tuners can stand up to that. Increasing the SWR to 3, increases the worst case loss to 1.3 dB, and the dissipation could increase to almost 400 watts. Clearly a real 1500 watt 160 meter T-network tuner needs to have significantly larger capacitors and

Table 5: The "back of the envelope" formulas for the worst case loss and maximum peak voltage as a function of the swr s derived in the text. f is the frequency in MHz, C_{max} is the maximum value of the output capacitor in pF, Q is the coil Q, and P is the power. The formulas for the ultimate transmatch are the same as for the Standard T network.

Network	Loss in dB	Peak Voltage
Standard T	$14,000\frac{s+\sqrt{s}}{C_{max}fQ}$	$\frac{100{,}000}{\pi}\frac{\sqrt{P}}{fC_{max}}\sqrt{s}$
Differential T	$14,000\frac{(1+\sqrt{s})^2}{C_{max}fQ}$	$\frac{100{,}000}{\pi}\frac{\sqrt{P}}{fC_{max}}(1+\sqrt{s})$
SPC	$14,000\frac{2s+\sqrt{s}}{C_{max}fQ}$	$\frac{100{,}000}{\pi}\frac{\sqrt{P}}{fC_{max}}\sqrt{s}$

a high quality coil in a large cabinet to minimize loss.

I would like to thank Tom Rauch, W8JI, for reading a preliminary version of this work, for many helpful comments, and for providing me with reasonable estimates of the Q of the coils in these networks.

References

[1] Frank Witt, AI1H, "How to Evaluate Your Antenna Tuner," parts 1 and 2, QST, April and May 1995.

[2] Andrew Griffith, W4ULD, "Getting the Most Out of Your T-Network Antenna Tuner," QST, January 1995, p.44.

[3] Lewis G. McCoy, W1ICP,"The Ultimate Transmatch", QST, July 1970, p. 24.

[4] "A Transmatch for Balanced or Unbalanced Lines," page 25-8 in *The ARRL Antenna Book*, 17th Edition, edited by R.D. Straw, (ARRL,Newington,1994).