The Matching Question Redux

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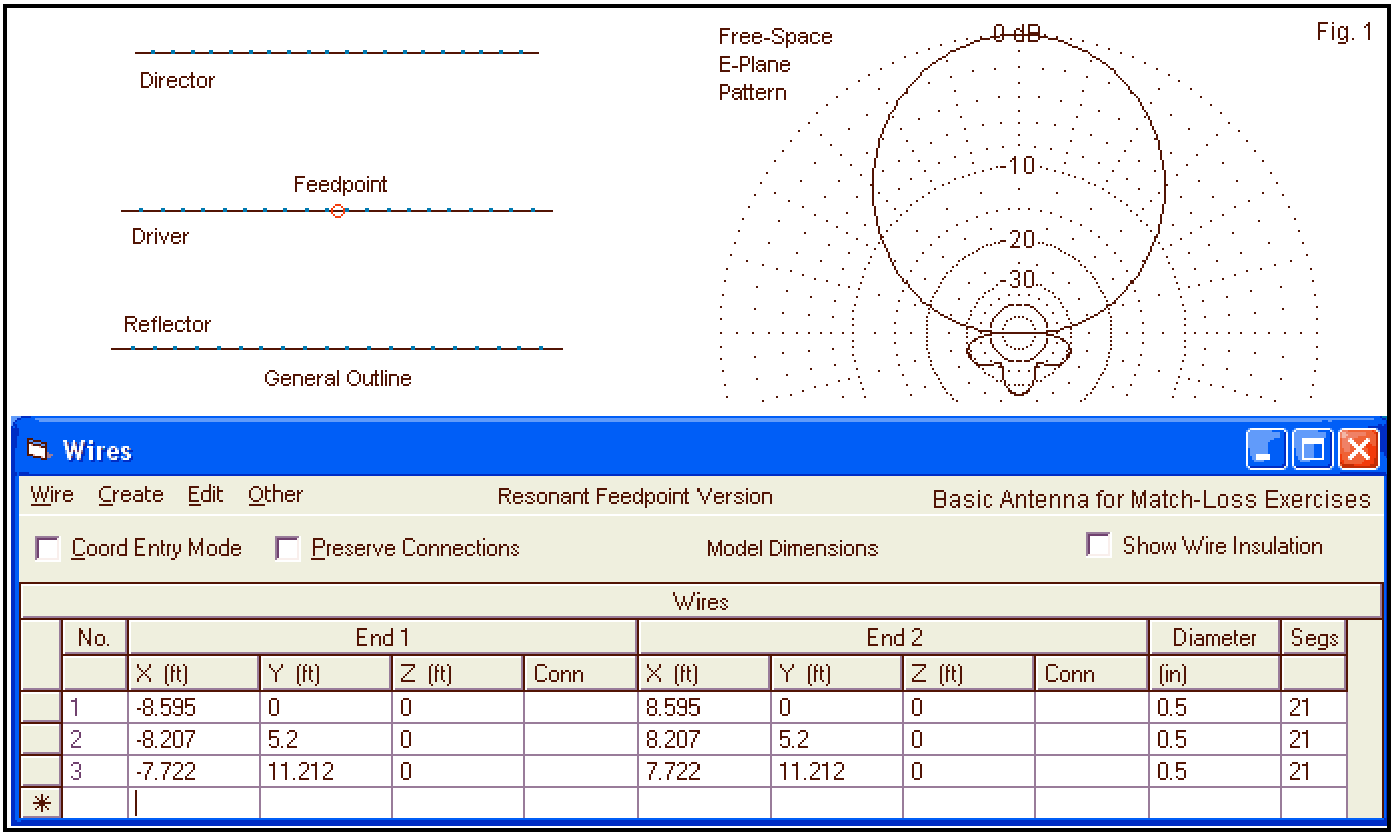
Back in 1998, I took a look at the matching question, especially as applied to the driver element of typical amateur beam antennas, such as the Yagi-Uda array of various sizes. See "Whose Afraid of a Little Matching?". In those notes, I used a set of external utility programs to calculation the components and the losses of some common types of matching systems applied normally to the feedpoint of antennas to change the natural impedance of the driver to the standard 50-Ohm coaxial cable. In virtually all cases, the losses turned out to be negligible.

The appearance of the latest version of EZNEC Pro/4 (version 5) has provided an interesting opportunity to revisit the question and to make reasonably fair comparisons among most of the matching system candidates. Author Roy Lewallen has included in the user interface of the program a special set of facilities. In addition to the standard transmission line facility, upgraded to include line losses, Roy has added new facilities to create ideal transformers and L-networks. In fact, we can place back-to-back L-networks together to obtain 3-component networks such as PIs and Ts. Roy's system allows the user to specify resistance, inductance, and capacitance to the legs of the networks, so we can explore the effects of the components with any level of component loss (or low-Q) that we wish. Those who know how to handle the NT command can already do this, but on a single-frequency basis. In Roy's interface, for each change of frequency in a sweep, the interface calculates the correct NT commands for the specified component values before executing the core run for each frequency step. The result is a unique ability for the user to evaluate a total antenna system within any model, including matching networks and coaxial cables.

The new version of EZNEC gives a chance to look at most (but not all) of the common matching systems that we apply to beams using a common set of antenna elements and changing only the matching system and its components. For example, let's begin with a common 3-element Yagi that uses 0.5"-diameter aluminum elements for 28.5 MHz. Initially, we shall set the driver to resonance at the design frequency, even though the impedance will be about 25 Ohms. **Fig. 1** shows the Yagi dimensions, along with its outline and its free-space E-plane pattern.



No.	End 1				End 2				Diameter	Segs
	X (ft)	Y (ft)	Z (ft)	Conn	X (ft)	Y (ft)	Z (ft)	Conn	(in)	
1	-8.595	0	0		8.595	0	0		0.5	21
2	-8.207	5.2	0		8.207	5.2	0		0.5	21
3	-7.722	11.212	0		7.722	11.212	0		0.5	21
*										

In our exercises, we may use the free-space environment, since we are only examining the effects of matching systems applied at the feedpoint. In actual installations above a real and lossy ground, there will be other losses. However, these will vary with the antenna height and the quality of ground. Moreover, they will be constant for a given installation. Therefore, the differences that we are seeking will not change and show up most vividly by comparing them in free space.

Table 1 provides the basic performance information that we shall glean from each model. In this case, with no matching system, we obtain a certain forward gain and a 180-degree front-to-back value. As well, we obtain the feedpoint impedance. The next two figures show the SWR at 28 MHz and at 29 MHz. For the basic antenna, we used a reference impedance that equaled the resonant impedance of the driver at the design frequency. When we add matching systems to the antenna, we shall use 50 Ohms as the reference value. The two SWR values give us a rough estimate of the operating bandwidth of the antenna. Significant increases in the SWR values at either end of the 1-MHz span indicate a shrinking 2:1 SWR bandwidth. The final value is the radiation efficiency as calculated by NEC based on the sum of all losses, whether from the material losses (aluminum) of the elements or any losses in the components that we shall eventually add to the antenna system. Since our basic antenna has only material losses, the 99.2% efficiency is the highest value that we may obtain in this exercise. We shall encounter the value many times, since for each matching system, we shall begin with an idealized matching system with lossless components.

Basic antenna performance: 3-element Yagi with a resonant driver — Table 1
Design Frequency = 28.5 MHz

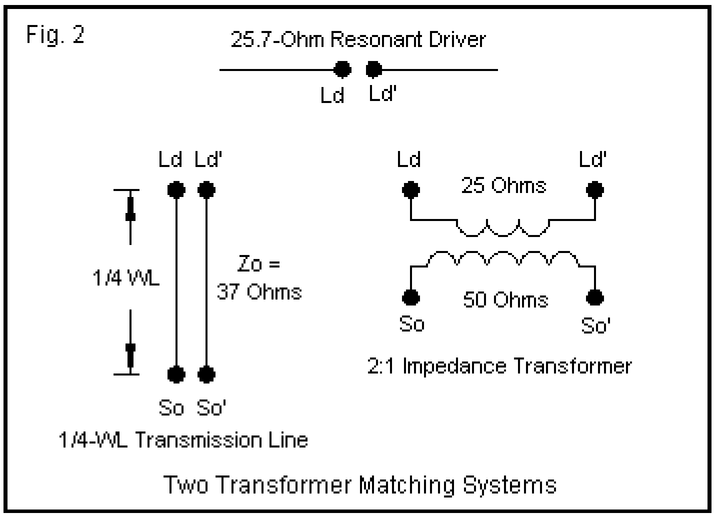
Gain dBi	F-B Ratio dB	Feed Impedance R +/- jX Ω	SWR @ 28 MHz	SWR @ 29 MHz	Efficiency %
8.11	27.11	25.7 – j0.8	1.96	2.30	99.2

Note: SWR relative to 25.7-Ω reference

We may note in passing that this antenna design is a very good monoband performer for the number of elements and the length of the boom. In addition to this basic antenna, we shall eventually introduce a variant to test beta-match systems. However, our initial matching efforts will use a resonant driver.

Impedance Transformers

Our first methods of transforming the natural driver impedance to 50 Ohms will involve two types of transformers, as suggested in **Fig. 2**. The first is a 1/4-wavelength section of transmission line whose characteristic impedance (Zo) is the geometric mean between the antenna terminal load impedance (at Ld and Ld') to the cable or source impedance (at So and So'). Since the ratio of the load and the source impedance values is 1:2, we may also employ a low-loss or nearly ideal transformer of any desired construction.



Two Transformer Matching Systems

The 1/4-wavelength matching section requires a 37-Ohm Zo, which we may obtain by parallel to pieces of 70-75-Ohm cable. The cables that we choose for the job are generally either RG-59 or RG-11, which have different loss values. The new version of EZNEC let's us introduce losses from any cable chart by entering the loss per 100' (or meters, if we choose that unit of measure for the model) at the nearest listed frequency. For 10 meters, the 10 MHz value is the useful one. The program then scales the losses to the selected model frequency. This technique is very effective except at very low frequencies and ultra high frequencies, and our sample cases will not press either limit. **Table 2** provides the results of our modeling.

Performance with ¼-λ 37-Ω matching section (5.78' @ 0.67 VF) — Table 2

Gain dBi	F-B Ratio dB	Feed Impedance R +/- jX Ω	SWR @ 28 MHz	SWR @ 29 MHz	Efficiency %
1. 0-loss transmission line					
8.11	27.11	53.2 + j1.5	1.95	2.32	99.2
2. Parallel RG-11 (loss = 0.7 dB/100' @ 10 MHz)					
8.03	27.12	52.9 + j1.0	1.91	2.32	97.5
3. Parallel RG-59 (loss = 1.3 dB/100' @ 10 MHz)					
7.97	27.12	52.7 + j0.5	1.87	2.32	96.1

Note: SWR relative to 50 reference

As we progress from the zero-loss case to RG-59, we discover a descending gain curve. The lossiest of the cables yields a forward gain that is down by 0.14 dB, an amount that we would have a very difficult time measuring in a range test, let alone detecting on normal operation. The front-to-back ratio is (and will be for all our models) virtually unchanged. The design frequency impedance values are well within acceptable limits relative to the ideal 50-Ohm value. As we add cable losses to the matching system, we note that the SWR at 28 MHz decreases very slightly, indicating that the cable losses broaden the SWR bandwidth--although we likely would not be able to measure the difference using the equipment generally available to radio amateurs. We also discover that the total antenna system efficiency has dropped from a maximum of 99.2% down to 96.1% for the RG-59 implementation. The 3% drop (or about 3-watts added loss for a supplied power of 100 watts) shows up in the gain and the bandwidth numbers, which made no detectable dent in anticipated performance.

Performance with a 25-50-Ω low-loss transformer — Table 3

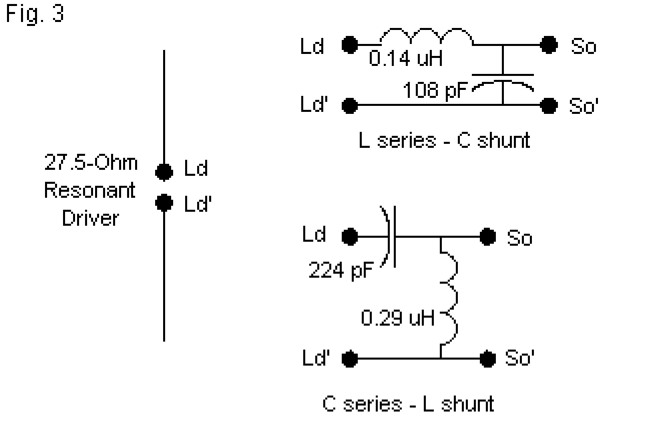
Gain dBi	F-B Ratio dB	Feed Impedance R +/- jX Ω	SWR @ 28 MHz	SWR @ 29 MHz	Efficiency %
8.10	27.12	51.5 - j1.6	1.98	2.31	99.0

Table 3 shows the result of employing a 1:2 impedance transformer in place of the 1/4-wavelength matching section. The transformer implementation in EZNEC is an idealization with a fixed very small loss. It might represent a very high-efficiency 2:1 balun and likely has less loss than a wide-band conventional transformer using a powdered iron toroidal form. Well-constructed conventional transformers may show a 2-3% loss, placing them in the general range of results obtained from the two types of real ("lossy") cables used in the 1/4-wavelength transformer exercise.

L-Networks

An alternative to using either transformer method to raise the natural 25-Ohm driver impedance to a 50-Ohm cable value is to place an L-network at the feedpoint of the antenna. Normally, we would use fixed components and calculate their values from an external utility program. When looking from the source to the load, we are down converting, which mean placing the shunt or parallel component of the L-network on the source side of the arrangement. As shown in **Fig. 3**, we have two main options for the required L-network.

Fig. 3



Two-Element L-Network Matching Systems

The sketch shows the approximate component values required by each version of the L-network. For each case, we may begin by using lossless components. Although we might assign Qs to the capacitors, the value would by over 1000 and more typically 5000. Such values will show no changes in the output. For practical cases, we can limit losses to the inductor. As a sample, I selected a Q of 200. This value is somewhat low for very carefully constructed coils, but may be typical of coils as we normally construct them and then house them for weather protection. **Table 4** provides the results of our models using both lossless and lossy inductors.

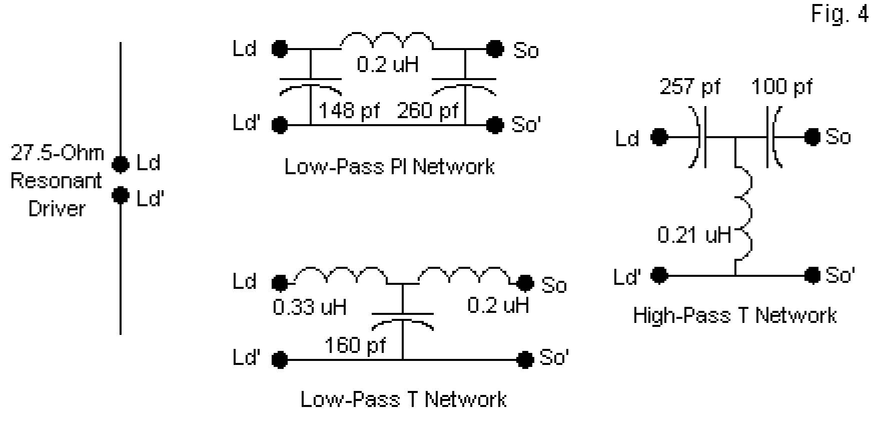
Performance with 2-element L-networks					Table 4
A. Series L (0.14 µH), parallel (shunt) C (109 pF)					
Gain	F-B Ratio	Feed Impedance	SWR	SWR	Efficiency
dBi	dB	R +/- jX Ω	@ 28 MHz	@ 29 MHz	%
1. 0-loss inductor					
8.11	27.11	48.7 – j0.1	1.97	2.36	99.2
2. Inductor Q = 200					
8.09	27.12	48.7 – j0.4	1.97	2.35	98.7
B. Series C (224 pF), parallel (shunt) L (0.29 µH)					
Gain	F-B Ratio	Feed Impedance	SWR	SWR	Efficiency
dBi	dB	R +/- jX Ω	@ 28 MHz	@ 29 MHz	%
1. 0-loss inductor					
8.11	27.11	51.5 – j0.1	2.00	2.33	99.2
2. Inductor Q = 200					
8.09	27.12	51.2 – j0.1	1.99	2.34	98.7

The use of either type of L-network yields the same result. With a coil Q of 200, the efficiency drops to 98.7%, for a net gain decrease of 0.02-dB. The SWR bandwidth is numerically slightly below the limits we found for the pre-matched antenna, but the difference would be very difficult to measure under the best range conditions. L-networks, then, can be a highly effective method of achieving a match between a resonant driver and a 50-Ohm cable when the transformation ratio is about 2:1.

3-Component Networks

In practice, we would likely not go beyond the 2-component L-network in effecting a match between the 25-Ohm driver and a 50-Ohm cable. Every extra component is one more source of system failure due to any number of conditions. However, because we encounter many claims that suggest significant inefficiencies for 3-component networks, relative to the simple 2-component L-network, we should at least see what the models might suggest.

Fig. 4



Three-Element Network Matching Systems

Fig. 4 outlines the main candidates for matching service. We have low-pass PI and T configurations and a high-pass T arrangement. (A low-pass T is also possible but hardly ever appears in practical systems.) The outlines show the components used in the model. I have not tried to optimize the components for the lowest value of delta or loaded network Q, but selected components that might be close to those employed by radio amateur implementations of these networks.

The version of EZNEC used in this exercise creates 3-component networks by placing two L-networks back-to-back. The center component is split between the two Ls. In some cases, this creates a parallel set of components in each L, and in other cases, it splits the center component into series elements. For practical cases, you may divide the center component of the 3-element network into two equal values whose combination results in the calculated component value.

Performance with 3-element networks					Table 5
A. Low-pass PI: Cld (148 pF) L (0.2 μH) Cso (260 pF)					
Gain dBi	F-B Ratio dB	Feed Impedance R +/- jX Ω	SWR @ 28 MHz	SWR @ 29 MHz	Efficiency %
1. 0-loss inductor					
8.11	27.13	50.4 + j0.6	2.24	2.64	99.2
2. Inductor Q = 200					
8.01	27.13	49.6 – j0.2	2.19	2.65	96.9
B. Low-pass T: Lld (0.33 μH) C (160 pF) Lso (0.2 μH)					
Gain dBi	F-B Ratio dB	Feed Impedance R +/- jX Ω	SWR @ 28 MHz	SWR @ 29 MHz	Efficiency %
1. 0-loss inductor					
8.11	27.13	51.2 + j0.9	2.05	2.54	99.2
2. Inductor Q = 200					
8.04	27.13	50.7 + j0.9	2.03	2.50	97.6
C. High-pass T: Cld (257 pF) L (0.21 μH) Cso (100)					
Gain dBi	F-B Ratio dB	Feed Impedance R +/- jX Ω	SWR @ 28 MHz	SWR @ 29 MHz	Efficiency %
1. 0-loss inductor					
8.11	27.13	50.1 + j0.1	2.09	2.51	99.2
2. Inductor Q = 200					
8.04	27.13	50.2 - j0.6	2.04	2.52	97.7

Table 5 presents the results of modeling each 3-component network as a lossless network and then as a network where the inductors have a Q of 200. The lowest efficiency obtained (from the low-pass PI network) is 96.9%, which decreases the gain to 8.01 dBi. Even though the gain decrease is only 0.1-dB relative to a lossless system, we might be able to improve the value by selecting components for the PI that result in a lower value of delta. The practical question becomes the feasibility of the component values under network re-calculation vs. the small improvement we might see in the model numbers, given that the lossy and lossless versions would show no detectable operational differences. Perhaps the greatest improvement might be in the SWR bandwidth values.

The T networks have lower values of delta and thus show slightly higher gain values, along with slight improvements in the 28-MHz and 29-MHz 50-Ohm SWR values. The bottom line is that a three-component network need not show operationally detectable reductions in performance over the simpler 2-component networks, although the numerical results may show some differences. Nonetheless, for practical reasons, such as reducing the number of items that might fail under operational duress, the simplest possible networks are preferable.

The Beta Match

What we now generically call the beta match originated from work at HyGain. The "beta" moniker has stuck, although a number of writers avoid the term to skirt any copyright or patent issues. However, it is convenient to use the term and then to break down methods of implementation according to the type of so-called beta component. All forms of the match rest on the same basic principle.

We begin with a slight revision to the basic antenna we set up at the start of these exercises. As shown in **Fig. 5**, we simply shorten the driver element until it exhibits approximately the "right" impedance as a value of R - jX Ohms. The performance of the pre-matched antenna does not differ from the performance of the same antenna with a resonant driver.

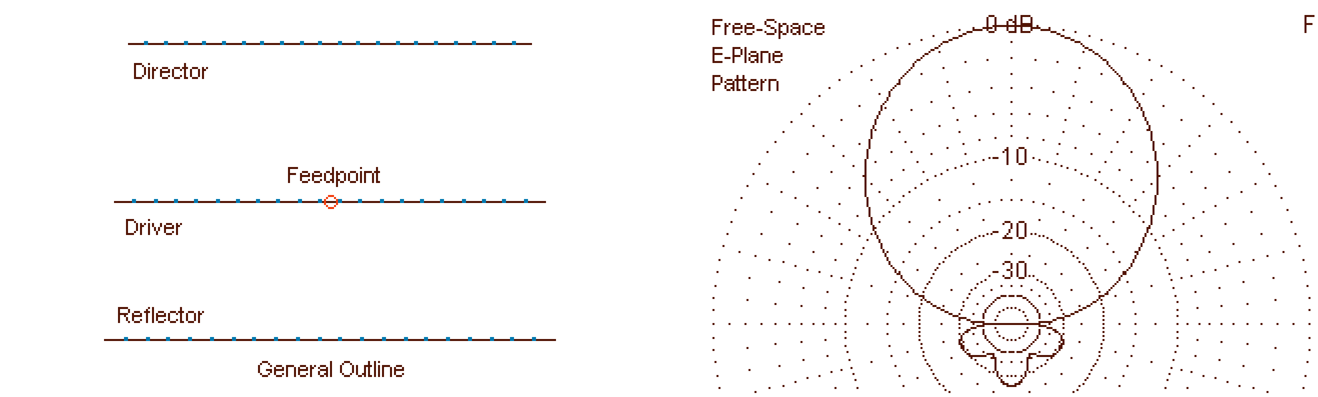


Fig. 5

Wires

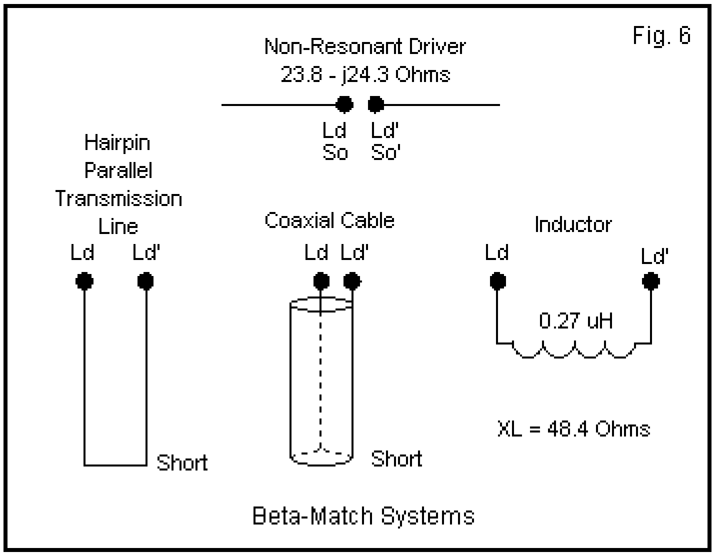
Wire Create Edit Other — Non-Resonant Feedpoint Version — Basic Antenna for Match-Loss Exercises

☐ Coord Entry Mode ☐ Preserve Connections ☐ Show Wire Insulation

Wires

No.	End 1				End 2				Diameter	Segs
	X (ft)	Y (ft)	Z (ft)	Conn	X (ft)	Y (ft)	Z (ft)	Conn	(in)	
1	-8.595	0	0		8.595	0	0		0.5	21
2	-8.00833	5.2	0		8.00833	5.2	0		0.5	21
3	-7.722	11.212	0		7.722	11.212	0		0.5	21

The "right" driver impedance is a composite of source resistance and a series capacitive reactance. The required capacitive reactance is a function of two factors. One the the resistance that we want to convert to 50 Ohms. The other is the calculated value of a series capacitor in an L-network that would effect the impedance transformation. Since the antenna feedpoint impedance contains both the load value of R and the L-network C-equivalent value of the series XC, we only need to add a single shunt or parallel component across the feedpoint terminals to complete the L-network. (By lengthening the element, we might work in the other direction, obtaining a value of R and an inductive reactance. Then the shunt component would be a value of C. This system has application, but the series XC version is the more common.) **Fig. 6** shows some common variations in typical beta matching schemes.



The feedpoint portion of the sketch shows the source impedance that we shall use for our exercises. It is close to but not precisely optimal, a fact that will give use a view of the beta-match flexibility. The lower left sketch replicates one of the most common forms of beta components, the so-called hairpin. The hairpin is simple a parallel transmission line length, shorted at the far end, and designed to show the required inductive reactance across the terminals of the driver. (Some versions of the hairpin ground the center of the short to bring the driver to a DC and static discharge ground. Theoretically, the ground should make no difference in the length of the line, but some sources show different calculation sets for ungrounded and grounded hairpins. In all cases, the length of the hairpin requires adjustment for resonance of the antenna system at the design frequency, so the difference may be academic.) For the hairpin versions of the system (ungrounded), a chose 600-Ohm line, with a resulting very short required length. Presuming that the line is uninsulated, I used 600-Ohm ladder line loss factors in checking the seemingly lossy version of the hairpin.

An alternative version of the hairpin of transmission-line inductive reactance uses simple coaxial cable for the beta component. A 50-Ohm line requires almost 10 times the length of the high-impedance hairpin. Like the parallel line, the far end is shorted to create a transmission-line inductively reactive stub. The effectiveness of this system depends on the line we choose and its losses.

The final version of the beta match replaces the transmission-line inductively reactive shorted stub with a simple solenoid inductor having an inductance at the design frequency that yields the required reactance across the driver terminals. Some writers have criticized the use of a beta inductor as too lossy compared to a hairpin. We may test this claim by using another new EZNEC feature, the ability to place a load in a shunt or parallel connection across the source and still maintain R-L-C load components and frequency nimbleness. The interface recalculates the NT equivalent of the shunt-connected load for each frequency step in a sweep.

Beta Match					Table 6
Basic antenna performance: 3-element Yagi with a non-resonant driver					
Design Frequency = 28.5 MHz					
Gain	F-B Ratio	Feed Impedance	SWR	SWR	Efficiency
dBi	dB	R +/- jX Ω	@ 28 MHz	@ 29 MHz	%
8.11	27.13	23.8 – j24.3	1.99	2.49	99.2
Note: SWR relative to 23.8-Ω reference					
Transmission line inductive reactances					
Gain	F-B Ratio	Feed Impedance	SWR	SWR	Efficiency
dBi	dB	R +/- jX Ω	@ 28 MHz	@ 29 MHz	%
A. 600-Ω, VF 1, 5.2"					
1. 0-loss					
8.11	27.13	48.6 + j0.1	1.94	2.53	99.2
2.. 0.06-dB/100' @ 10 MHz					
8.11	27.13	48.5 + j0.1	1.94	2.53	99.0
B. 50-Ω, VF 0.67, 50.0"					
1. 0-loss					
8.11	27.13	48.6 + j0.1	1.95	2.52	99.2
2.. 0.6-dB/100' @ 10 MHz (RG-213)					
8.04	27.13	47.8 + j0.1	1.89	2.54	97.6
2.. 1.3-dB/100' @ 10 MHz (RG-58)					
7.96	27.13	46.9 + j0.1	1.83	2.56	95.7
Shunt inductor (0.27 µH)					
Gain	F-B Ratio	Feed Impedance	SWR	SWR	Efficiency
dBi	dB	R +/- jX Ω	@ 28 MHz	@ 29 MHz	%
1. 0-loss					
8.11	27.13	48.5 - j0.9	1.92	2.52	99.2
2.. Inductor Q = 200					
8.09	27.13	48.3 - j0.8	1.91	2.52	98.7

Table 6 shows the results of testing the three types of beta components across the driver terminals. Even with its typical loss factor entered in, the 600-Ohm open line shows no loss in gain. The beta inductor with a Q of 200 also shows almost no gain loss and only a 1.5% decrease in efficiency. The most questionable beta component of the lot is the 50-Ohm RG-58 shorted line. With a loss of 1.3 dB/100' at 10 MHz, the line drops the array gain to 7.96 dBi, 0.15-dB lower than the pre-match antenna. The efficiency is 95.7%.

Conclusion

Although we might suggest that, if a builder prefers to use 50-Ohm cable for the beta shunt inductive reactance, a lower-loss cable might be superior, the actual perceptible performance loss would be virtually non-existent. Other factors, such as the loss in the cable between the antenna system, including its beta match (or any of the other matching systems modeled), and the transceiver would be higher than the losses in the matching system. Indeed, the lesson of these models is that a requirement for impedance matching at a beam's feedpoint is not necessarily a count against the beam design.

Other performance factors for the beam, such as its performance bandwidth (including gain and front-to-back ratio as well as SWR), the evenness of gain across a band, etc., may count for more than the need for a matching system. In fact, the physical construction of the beam and its ability to survive adverse weather may be more significant to a choice of beam designs than the feedpoint impedance. Of course, these priorities assume that the matching system, whatever the specific type, uses high quality components and houses them (where necessary) in ways that do not shorten their life or yield increasingly poor performance with time.

These notes have not included the gamma match among the matching systems considered because gammas require additional lengths of tubing or rod, and NEC does not handle well junctions of wires having different diameters. However, for modeling information of gamma matches, see the pair of gamma studies in this section of the index.

To repeat the question I posed nearly a decade ago: "Who's Afraid of a Little Matching?" When carefully done for lower-impedance Yagi beams, no one should be.