Balanced Transmission Lines in Current Amateur Practice

Taking a closer look at "ladder line" and its application

By Wes Stewart, N7WS

Introduction

The increased number of hf ham bands, along with the decreased size of the average ham's backyard, has made multiband operation of random-length wire dipoles an attractive option. This has brought about renewed interest in the use of balanced, parallel-wire transmission lines, commonly called "ladder line," to feed these antennas.[1] There is historical precedence for the use of these antennas; however, there are differences between earlier practice and today's methods. Judging by on the air conversations and Internet group discussions, the "conventional wisdom" seems to be that ladder line has such low loss that it can be used in almost any situation without suffering any significant additional loss. Operating on the principle that if it sounds too good to be true, it probably is, I decided to take a closer look at the subject.

This paper presents some of the results of my investigation. In it, I will attempt to correct some of the myths that surround the use of balanced transmission lines by contemporary radio amateurs. I will also present some data; both calculated and measured, on the losses associated with the "450-ohm ladder lines" as they are used today. Space limitations will generally confine this discussion to the transmission line itself. It cannot be over emphasized, however, that the other components that are necessary to utilize ladder line, the tuner or "transmatch" and the balun are an equally important part of the antenna system.

"Old Time" Practice

Balanced two-wire transmission lines are not new; they were common in early ham stations. These early lines were truly "open-wire" and were usually constructed of relatively large wires separated by widely spaced insulators. Wire spacing was on the order of two to six inches. The well-heeled ham used Steatite spacers; everybody else used wooden dowels waterproofed with paraffin or something similar. The lines were typically under tension and dressed carefully away from other objects.

The lines directly fed the antenna, which may or may not have been resonant. Because the antenna impedance almost never matched the transmission line impedance, the lines were resonant ("tuned feeders") and often operated with very high standing wave ratio (SWR). At the station end the line was connected to the transmitter via link coupling to the final stage. Tune up consisted of adjusting the output coupling and plate tuning to maximize the "antenna current" using an RF ammeter[2] or a light bulb for an output indicator. No baluns, antenna tuning units or SWR meters were to be found in these early shacks.

Later the advantages of non-resonant ("flat") lines were recognized. Antennas were made resonant and matched to the transmission line. A procedure for graphically determining SWR and matching the line to the antenna was described in *QST* as early as 1942.[3]

The line construction, care in installation and the inherently balanced systems all contributed to high efficiency in these early applications.

Contemporary Practice vs. "Old Time" Practice.

Speaking generally, there are significant differences between modern usage of balanced lines and earlier practice. First, and the focus of the majority of this paper, is the line itself. As stated previously, the early lines were constructed with a minimum of spacers so the dielectric between the wires was predominately air. Wire size might be 12 AWG or larger. This combination made for an extremely low loss line.

While it is not unheard of today for this kind of line to be used, it is more typical to see a line constructed with a ribbon of polyethylene dielectric separating the wires. TV type 300 ohm "twin-lead" is sometimes used, however, "450 ohm ladder line" is what the majority of hams are using.

This line is basically the same as the TV type line except for some holes ("windows") punched in the dielectric and somewhat wider spacing between the wires. There is much more dielectric between the wires and the wire sizes are considerably smaller than in the typical open wire line. These factors combine to increase the losses over a true open-wire line.

The second difference between "old" and "new" practice is in the tuners used. Yesterday's tuners, when used, were typically constructed using large, air-wound or ceramic supported inductors and air or vacuum dielectric variable capacitors. Usually, the tuner was an inherently balanced tuned circuit with link or balanced tap coupling. The enclosure, if there was one, was large and the inductors were spaced well away from the box to maintain their high Q.

Today's tuners, with rare exceptions,[4] are unbalanced devices. They are likely to have either roller or tapped toroidal inductors and smaller variable capacitors, often with switched fixed values in parallel. Because of their smaller sizes, these components tend to have lower Qs than their larger counterparts. These lower values of Q can be a source of significant loss in the tuner. Roller inductors can be particularly troublesome in this regard.

The third difference is in the use of baluns in today's systems. Baluns have been well described in the amateur literature[5] and their function will not be discussed in detail here. Baluns operated in severely mismatched systems can be a significant contributor to overall system loss, however.

Why ladder line?

The usual rational for using ladder line is the fact that its attenuation is lower than commonly available coaxial cable. Secondary advantages are its lower cost and weight as compared to coaxial cable. Unfortunately, one popular myth is that the line attenuation is insignificant and isn't even a consideration in an antenna system.

While a line with low matched-loss is always desirable, it is particularly so when operating at the elevated SWRs encountered when feeding off-resonant or harmonic antennas. To see why this is true, and to debunk the myth, we will examine the sources of line attenuation and its effects.

Line Attenuation—the Matched Case

When a transmission line is terminated with load impedance that matches the line impedance, the line is said to be "matched." When the line is matched, all of the power reaching the load is absorbed, there are no reflections on the line, the SWR is 1:1 and line attenuation is at its minimum value.

Attenuation in this context describes the ratio of power applied to the input end of a line to the power at the load end. Attenuation is usually expressed either in decibels or in nepers where:

$$Attenuation = 10\log\left(\frac{P_{in}}{P_{out}}\right) \quad \text{(dB)} \qquad Attenuation = \frac{1}{2}\ln\left(\frac{P_{in}}{P_{out}}\right) \quad \text{(nepers)} \qquad (1)$$

There are two primary sources of loss in a transmission line: 1) loss due to the finite conductivity of the conductors and 2) loss in the dielectric that separates the conductors. In the case of unshielded balanced lines, there can also be loss due to radiation[6] or coupling into other structures. This third loss is difficult to quantify, as it will be highly dependent on installation. However, with proper installation and operation at hf to vhf, it should be negligible.

Descriptions of conductor and dielectric losses can be found elsewhere,[7] so they will not be discussed in detail here except to note that conductor loss depends both on the metal from which the conductor is made and the frequency, because of the frequency-dependent skin depth effect.

In a two-wire (copper) transmission line with a well-developed skin effect, the matched loss is given by:

$$A = 4.34\left(\frac{\frac{0.2\sqrt{F}}{d}}{Z_o}\right) + 2.78F\sqrt{e_r}\,Fp \qquad \text{(dB/100 ft)} \qquad (2)$$

Where d is the conductor diameter in inches, F is the frequency in MHz, e_r is the effective dielectric constant, Fp is the power factor of the dielectric and Z_0 is the line impedance. The first term in (2) describes the conductor loss while the second term describes the dielectric loss.

There is another misconception that is common in the amateur community, the idea that the dielectric is a major source of loss. For polyethylene, the most commonly used transmission line dielectric, the power factor is 0.0002 and the dielectric constant is 2.26 throughout the hf and vhf range.[8] Using these values in (2) demonstrates that the dielectric loss *per se* is negligible. For constant line impedance and constant wire spacing, an increase in the effective dielectric constant requires that the conductor diameter must be decreased. This can be seen in the following equation for the impedance of a two-wire transmission line:

$$Z_0 = \frac{120}{\sqrt{e_r}}\cosh^{-1}\frac{D}{d} \qquad (3)$$

Where D is the center-to-center spacing between wires in the same units as d. The decreased wire diameter and attendant increased skin effect loss is the cause of the increased line attenuation.

Line Attenuation—the Mismatched Case

For a linear source, maximum power is transferred to a load when the load impedance is the complex conjugate of the source impedance. When a conjugate match does not exist, there is a “mismatch loss.” Mismatch loss describes the ratio by which the power transferred from the source falls short of what would be delivered if the source and load were conjugately matched.

It is entirely possible to have a situation where a matched (properly terminated) transmission line presents a mismatched load to the source. For example, a 100-ohm line, terminated in 100 ohms could be the load for a source with 50-ohm output impedance. In this case, the generator will not deliver all of the available power into the line, although, the line will be operating with a 1:1 SWR and line attenuation will be minimal. Introduction of a lossless conjugate matching network between the source and line can correct this situation and restore full power transfer into the line.

When the load impedance, Z_l, does not match the line impedance, a portion of the power delivered to the load is reflected back to the source. One of two things can happen to this reflected power; it is either dissipated by the source or it is re-reflected back into the line. The first case is typical in laboratory signal generators, where either a lossy pad or an isolator dissipates the reflected power.

The second case is typical of our transmitting situation, where the load does not match the line and the resulting line input impedance does not match the “nominal” transmitter output impedance. Here either the transmitter tank circuit or “antenna tuner” can be used to create a conjugate mismatch that causes the re-reflection. Walter Maxwell in his book, *Reflections*,[9] offers an excellent description of conjugate matching.

In this second situation, absent any voltage breakdown, the line attenuation is increased because of increased circulating current in the line. It is important to note that increased current flows through all parts of the feed system on the antenna side of the match point, including the tuner and any balun. The loss in the tuner can be evaluated separately.[10] The effect of balun loss is less easy to analyze; though as an approximation, the loss can be treated as an increase in the line loss. A decibel loss in the balun can be just as detrimental as a decibel loss in the transmission line.

In order to determine system loss, it is imperative that accurate values for line impedance, line loss and load impedance are known. If precise electrical lengths of line are required for matching transformers or stubs, the velocity factor or phase constant must be known as well. Because published data are not readily available for typical ladder line, one must either calculate or actually measure the line's electrical parameters.

It is tempting to use the previous equations to calculate these parameters. Unfortunately, for the polyethylene-insulated types, e_r is not known so Z_0 cannot be determined. If one trusts the published Z_0 (I don't) and you need to cut a line to some particular electrical length, you can "back into" e_r by measuring the physical properties of the line and re-arranging (3).

The Measurements

Absent trustworthy calculated data, one is left with making electrical measurements. Skilled amateurs, with rather simple instruments, are sometimes capable of making astonishingly accurate measurements. More often however, the operator is less aware of the equipment limitations and/or is misled by the instrument maker's advertising. Simplified "antenna analyzers", especially those with digital readouts can lull the user into unjustified confidence in the accuracy of his measurements. A major problem with simple equipment is the fact that the better the thing is that we're trying to measure, the harder it is to get accurate data! This is especially true when trying to measure small attenuation values. Popular methods of determining line loss such as shorting the far end and measuring SWR and calculating the loss are particularly suspect, especially so when the line loss, hence the return loss is very low.

Because I'm blessed with access to high quality instrumentation, I decided to obtain some samples of readily available ladder line and gather data on them under laboratory conditions. I procured samples of four different types of "450-ohm ladder line" from *The WireMan.*[11] These were WireMan types 551, 552, 553 and 554. The samples are all of the "window" line type, with two conductors held approximately 0.8 inches apart by a polyethylene ribbon that has rectangular holes punched in it. The primary difference between types is in the conductor size and wire type.

The equipment used for the measurements was a Hewlett-Packard vector automatic network analyzer (VANA). This instrument is capable of making error-corrected (See Appendix A) one or two-port measurements over the frequency range of 45 MHz to 26.5 GHz. For the measurements presented here, the frequency range was limited to 50 to 150 MHz. and the two-port (through) configuration was used.

One problem in the use of ladder line is the necessity to perform an unbalanced-to-balanced transformation. For these measurements, the problem is more complicated. Both measurement ports are coaxial and the line is balanced, so a balun is required at each end. I used baluns consisting of four one-inch long type 47 ferrite sleeves slipped over the lengths of RG-142 coax that were used to extend the measurement ports of the VANA.

The effects of the coax and balun interconnects were removed by performing an open-short-load-through calibration at the balanced output terminals of the baluns. During the through calibration, the balun outputs were connected center-to-center and shield-to-shield respectively. As a test of balance, after performing the through calibration, the balun connections were reversed. The change in the indicated insertion loss was less than 0.1 dB.

Because of space limitations in the laboratory, each sample was cut to a length of exactly twelve feet. During each measurement, the sample was stretched horizontally without any twists and at least two feet of clearance from any objects. A 201-point stepped-frequency sweep was made on each sample and the data were stored on magnetic disk for later analysis.

A second measurement was then made after wetting the line with water to simulate what might happen in a typical outdoor application. Initially the water tended to bead up and run off, making it difficult to make meaningful measurements. I believe that a typical line used outdoors would quickly lose its water shedding ability as it degrades from sunlight and accumulates dust and other pollutants. To simulate this, I added a wetting agent to the water to create a water film on the surface. The results of this are probably worst case and not something that would necessarily be encountered in a typical installation.

Figure 1 shows the results of the measurement of a typical sample. At first glance, the figure may be disconcerting, so a few words of explanation are in order. The network analyzer test ports are by design, well-matched 50-ohm terminations and the analyzer measures the "s-parameters"[12] of the device under test. Consequently, when the impedance of the line under test is other than 50 ohms, there is a mismatch loss, as was discussed earlier. This situation is different from the way that we normally operate our lines in antenna feeder applications, but it is the easiest way to characterize the line over a broad frequency range..

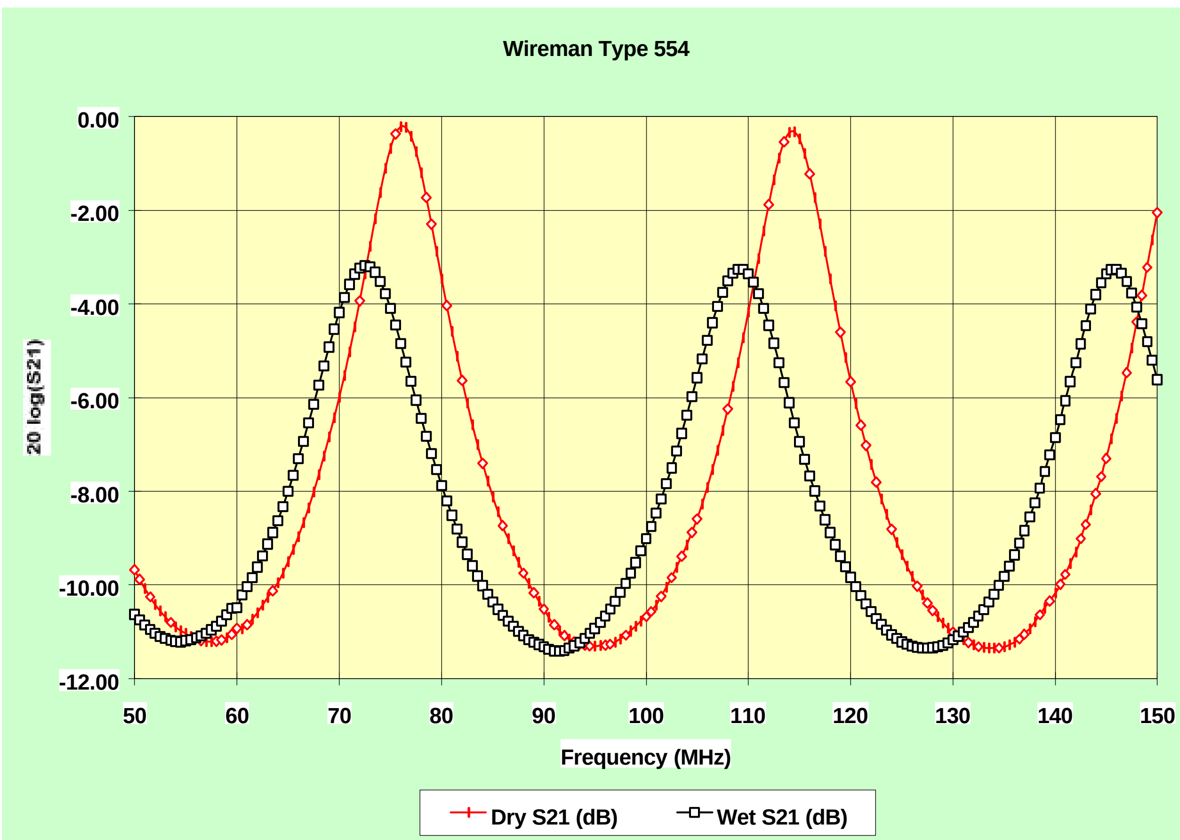

Figure 1. Plot of the forward transmission coefficient (s_{21}) of 12 feet of WireMan type 554 line in a 50-ohm system. Shown is the response with the line both wet and dry. Note the large change when the line is wet.

The figure displays "s_{21}", the forward transmission coefficient, expressed in decibels. Both the "gain" of the line, which of course is negative, and the effects of mismatch are expressed in the data. As presented, there isn't too much to be gleaned from the figure except that velocity factor, hence the effective dielectric constant, can be determined by computing the electrical length of the line and comparing it to the known physical length. The frequency where the line is a half wavelength long is easily determined by determining the frequency spacing between the ripple peaks. Other line parameters can be determined by mathematical means, however, I used another powerful tool, *ARRL Radio Designer* software,[13] to determine the line impedance, velocity factor and insertion loss per unit length.

ARD features a circuit optimizer that can be used to adjust various circuit parameters to closely approximate given target values. A circuit block using the *ARD* two-wire transmission line model was created with the physical line length fixed at 144 inches and the line impedance, dielectric constant and loss coefficients set as optimizable values. The measured s-parameter data sets were used as circuit modeling goals and the optimizer was turned loose to "make the model's response look like the measured data." In addition to the polyethylene-insulated lines, an air-insulated line made from 16 AWG enameled wire; spaced 0.75" was also measured as a "sanity check." The measured parameters of this "open-wire" line correlate well to the values calculated using (2) and (3). The results of the computations are shown in Table 1 below.

Line Parameters @ 50 MHz								
	Line Dry				**Line Wet**			
Type	**R_0**	**ε_{eff}**	**V_p**	**dB/100'**	**R_0**	**ε_{eff}**	**V_p**	**dB/100'**
551	405	1.23	90.2%	.33	387	1.34	86.4%	5.8
552	379	1.19	91.7%	.38	362	1.28	88.4%	5.2
553	397	1.23	90.2%	.38	381	1.33	86.8%	4.8
554	359	1.16	92.8%	.41	343	1.27	88.7%	6.1
16 AWG @ .75"	399	1.01	99.5%	.30	No Change	No Change	No Change	No Change

Table 1.

A couple of things are immediately obvious from the table. First, the impedance values are considerably below the "450 ohm" value commonly ascribed to ladder line. Second, is the large increase in attenuation that the lines suffer when they are wet. While these data are less accurate than when the lines are dry, they certainly point out a troubling trend.

The reason for lower accuracy of the wet measurements is that it was difficult to maintain uniform "wetness" during the several seconds it took to make the measurements. Nevertheless, this lack of control is not much different from the actual conditions a line might encounter in the field. Anecdotal evidence from users of ladder line confirms the changes in tuning required when lines are subjected to rain and snow; the data show why this is the case.

The loss at other frequencies can be estimated using (4) below. The equation neglects the effects of dielectric loss but is accurate enough for any practical calculations.

$$dB(f) = \sqrt{\frac{f}{50}}\,dB(50) \tag{4}$$

where *dB(f)* = the loss per 100 feet at frequency, *f* , and *dB(50)* = the loss data from Table 1.

The impedance of a transmission line is usually complex, i.e. it has a reactive as well as a resistive component. Line reactance can be found from:

$$X_0 = -j\frac{a}{b}R_0 \quad (5)$$

where α = line loss in nepers per unit length, $R_{o,}$ is the resistive part of the line impedance and the phase constant, β, in radians per unit length is found from:

$$b = 2p\frac{\sqrt{e_r}}{l} \quad (6)$$

Once Through—with Numbers

A popular multiband wire antenna is the so-called *G5RV.*[14] This antenna is rarely used as was intended by Varney, but for some reason, the 102-foot length has taken on mystical properties, so I used it for an example. I assumed that the wire was at a height of 40 feet and was fed with 100 feet of WireMan type 554 line.

Using *EZNEC*[15] I calculated the feed point impedance of the wire at the middle of each of the hf ham bands. Then using a *Mathcad*[16] worksheet and equations from a paper by Macalpine[17] I calculated the SWR at both ends of the line, the input impedance at the station end of the line and the total line attenuation. (See Appendix B) For those without *Mathcad*, later versions of Dean Straw's *TL* program[18] will compute the line reactance in addition to a number of other useful parameters, including the total mismatched line loss.

Space doesn't allow the presentation of data for each band but the worst case occurs on the 160 meter band, where the antenna is considerably shorter than one half wavelength long. The 1.9 MHz. matched line attenuation of 0.08 dB increases greater than 10 dB due to the mismatch. When the "wet" attenuation value is used, the total line attenuation is greater than 22 dB.

Another item of note is the effect that changing the length of the line has on the total line attenuation. One might expect that a change in line length from say 100 feet to 50 feet would reduce the loss by one half (3 dB), but in the previous example, it actually decreases 5 dB. In other words, it pays to do the calculations.

Closing Thoughts

Contrary to the conventional wisdom, ladder line is not a panacea for every transmission line problem. As stated in the introduction, when planning an antenna installation, it is important to look at the transmission line and antenna as an "antenna system." This paper has attempted to provide useful data on one piece of the system; the electrical characteristics of solid-dielectric ladder line. I hope that the material presented serves to inspire the reader to take a critical look all of the factors included in a system analysis: performance, cost, ease of installation and maintenance before committing to a particular antenna design.

Acknowledgments

I am indebted to my friends John Munger, N7WB, and Chris Wassenberg, for their review of the manuscript and their thoughtful suggestions for improvements. Any errors or omissions, however, remain the responsibility of the author.

Appendix A. Error correction and network analysis.

Any electrical measure has a fundamental accuracy limitation, as there are always some errors involved. A simple example would be the use of a low impedance voltmeter to measure a high impedance source. The meter loads the source so the reading is lower than the true open-circuit voltage. There is a measurement error caused by the less than ideal instrument. However, if both the meter and the source impedance are known, the open-circuit value can be calculated. The results can then be "corrected" for the measurement system error.

In network analysis there are several sources of measurement errors. A detailed discussion of these is well beyond the scope of this paper but simply put, by measuring one or more "standard" or "known" devices, the systematic errors can be identified. Once identified, modern microprocessor-controlled analyzers can remove these measurement errors and "correct" the answers.

Typically, the known devices include, but are not limited to, an open circuit, a short circuit, a precision termination (load) and for two-port (insertion) measurements, a through connection of the measurement ports. Each of these standards has an expected response, which when not realized, indicates the presence of systematic error. For instance, a perfect short-circuit should create a 100% reflection with a 180° phase shift. If anything other than this is measured, it indicates an error that can be accounted for in the measurement of the device under test. To characterize all of the systematic errors, both the *magnitude* and *phase* response of the standards must be measured; hence the terminology "vector" network analyzer.

Once this process, commonly called *calibration*, is complete, modern network analyzers are capable of amazing accuracy. Amplitude resolutions of hundredths of a dB and phase resolution of fractions of a degree are readily achieved. For reflection measurements, equivalent directivities of 50 dB or better are possible.

If, as in the case of the measurements presented in this paper, it is necessary add some cable between the instrument test port(s) and the device under test, the calibration is performed at the far end of the intervening cable, thereby removing its effects. The major accuracy limitation in the measurements is the result of uncertainties in the reference standards. For instance, the open circuit has some residual capacitance that is normally taken into account with precision calibration standards but was not done for these measurements. Nevertheless, it is believed that the data presented herein are sufficiently accurate for amateur applications.

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[18] *TL.EXE,* *******NOTE TO EDITOR. YOUR NAME HERE***********************************