Basics for Beginners

The Whys of Transmission Lines

Part I

BY GEORGE GRAMMER,* W1DF

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To radiate effectively, an antenna ought to be up in the air as high as it can be put. Also, it should not be close to houses, power lines and the like. You may not have an ideal spot, but even so you probably won't have to bring the antenna right into your operating room. So in most cases the situation is this: The antenna is "out there" and the transmitter is "in here"; how is the r.f. power to get from the transmitter to the antenna?

The answer, of course, is a transmission line. Your 60-cycle power comes to you through a transmission line, too. However, there is a difference in the way r.f. lines and 60-cycle lines operate. The reason is the difference in wavelengths. One wavelength at 60 cycles is over 3000 miles. If we wanted to build a half-wave antenna for that frequency it would have to extend more than half way across the United States. So even though you may be 20 miles from a power station, you're only a very small fraction of a wavelength away. The time it takes for power to reach you is so short, compared with $^{1}/_{60}$ second (one cycle), that the standing-wave effects discussed earlier[1] are negligible.

But in transmitting power at a frequency of, say, 7 Mc., the time taken for the power to travel 50 feet isn't at all negligible compared with the duration of one cycle. This means that we can't look upon a transmission line as a simple electrical circuit, which we *can* do at 60 cycles. What is happening at the "far" or "output" end of the line may be quite different from what is happening at the "near" or "input" end at the same instant.

The "Infinite" Line

A useful concept in explaining transmission-line operation is the **infinite line.** This is an imaginary line consisting of two conductors, side by side and close together, extending so far that we can never reach the end.

If an r.f. voltage is applied to the input end of such a line, one terminal will be negative whenever the other is positive, and vice versa. This causes the current to flow in one direction in one wire and in the other direction in the second, as in Fig. 1. Because the currents flow in opposite directions, the electromagnetic fields set up by them are also opposite. The fields therefore cancel each other's effects, or nearly do so (there is always a *little* uncancelled field, because the two wires can't actually occupy the same spot). Since the fields cancel, there is no radiation from the line.

Thus all the energy put into the line travels away from the generator, following the line at almost the speed of light. And since the line is infinitely long, none of the energy ever comes back.

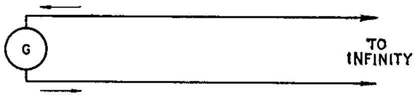

Fig. 1—An imaginary two-conductor line extending to infinity. Arrows show that the current in one wire flows in the opposite direction to current in the other; this relationship is true throughout the entire length of the line, although the actual currents periodically reverse direction as the polarity of the generator's voltage reverses each half cycle.

Characteristic Resistance

Probably the first question you'd ask at this point is this: If the generator voltage is known, how much current will flow in the line? From the discussion of the meaning of resistance in Part II[2] you would be right to infer that such a line must act like a resistance, since energy is being taken continuously from the generator. But how many ohms?

This resistance, called the **characteristic resistance** of the line, has nothing to do with the actual resistance of the conductors. While it may seem odd, the fact is that it is a function of the inductance and capacitance per unit length of line. The resistance actually is determined by the line's L/C ratio. This ratio depends on the diameters of the conductors and the spacing between them. The smaller the conductor diameter and the wider the spacing, the higher the characteristic resistance. Practical values of resistance lie between about 150 and 800 ohms for a

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[1] "Antennas and Feeders," Part I, *QST*, October, 1963.

[2] "Antennas and Feeders," Part II, *QST*, November 1963.

"two-wire" or **parallel-conductor** line as shown in Fig. 1.

It is important to realize that this characteristic resistance does not itself consume any power. The power is merely *following* the line on its way to infinity. The characteristic resistance is simply the ratio of voltage to current all along the line. Since the line is imaginary anyway, we can imagine further that the conductors have no actual resistance and there is no other energy loss along the line. Thus all the power put into the line is delivered to infinity, wherever that may be. This means that the characteristic resistance is "pure" resistance — no reactive effects at all.

Characteristic Impedance

But what if the conductors do have resistance of their own? Practically, of course, they must have. Also, the practical insulation between the two conductors is not perfect; there is some leakage between the two wires. This leakage is equivalent to a resistance (a high value) shunted across the two conductors. In the topsy-turvy world of transmission lines the presence of these two components of resistance gives rise to *reactance.* So if the line is a practical one having losses, the generator doesn't see a pure resistance but sees an impedance containing both resistance and reactance. This is called the **characteristic impedance** of the line.

Because things get complicated at this stage we like to ignore the reactive part of the characteristic impedance, and do so by assuming that the line has no losses. As long as the losses per unit length are small we can get away with it. Fortunately, this is the case with lines used by amateurs at frequencies below 30 Mc. It is even a good-enough assumption in the lower v.h.f. range. When the losses are small the characteristic impedance is *very nearly* a pure resistance equal to the characteristic resistance. The term characteristic impedance is widely used to mean the characteristic resistance of a lossless line. We'll use it that way here, too.

The Terminated Line

An infinite line, even if we could have one, wouldn't be of any practical use. It happens, though, that a line can be tricked into *thinking* that it's infinitely long.

In Fig. 2A, suppose that the line is cut at *XX*. If the generator is moved up to this point it will still see the same characteristic impedance (which is commonly designated Z_0), since what remains of the line to the right of *XX* is still infinitely long. In the same way, the section of line to the left of *XX* "sees" the section to the right of *XX* as a resistance equal to the characteristic impedance. This is true anywhere along the line. It suggests the idea that the line section to the left of *XX* wouldn't know the difference if a resistor having the same value as the characteristic impedance were substituted for all the line to the right of *XX*.

This is actually so. If a line of any length is **terminated** in a resistance equal to its characteristic impedance the voltages and currents are just the same in that section as they would be if the line were infinitely long. If the line has no losses, all the power put into it at the generator end is delivered to the terminating resistance.

Matching

The terminating resistance doesn't have to be a resistor. It can be any device, such as an antenna, that uses up power and thus has an equivalent resistance. If the power-consuming device doesn't inherently have the right value of resistance to match the line, its resistance can be transformed by means of circuits (such as those described earlier[3]) that will make it "look like" the proper value. Matching of this sort is done more often than not; only occasionally does the load have the right value of resistance, in itself, to match a practical line impedance.

One final point about a **matched line:** If the line has negligible losses, an ammeter inserted anywhere along its length will give the same reading. Also, a voltmeter connected across it at any point will give the same reading. There are no standing waves of current or voltage such as we find along an antenna, even though the line may be many times longer than the antenna. But this is true *only* when the line is terminated in its characteristic impedance.

Standing Waves on Lines

Now let's look at a line that *doesn't* simulate one that is infinitely long. The length of a matched line didn't matter, because all the power kept going in the same direction — to the load. If the line is not matched, its length becomes quite important.

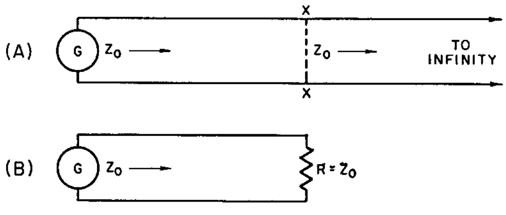

Fig. 2—An infinitely-long line can be simulated by terminating an actual line in its characteristic impedance.

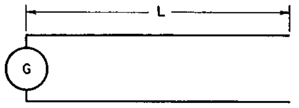

Fig. 3—A line with no termination—simply an open circuit.

To take an extreme case, suppose the line just stops, as in Fig. 3. The power goes out from the generator to the open end, at which point it has no path left to follow except to turn back and head toward the generator. This it does, just

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[3] "A.C. in Radio Circuits," Part III, *QST*, May 1963.

as in the case of the antenna discussed in Part I. In coming back it sets up standing waves of voltage and current, just as it did along the antenna.

Here, too, the current and voltage distribute themselves along the line according to the wavelength. If the line length *L* is just one-quarter wavelength, the current and voltage distribution are as shown in Fig. 4A. If you will imagine the line to be unfolded so that the wires extend in opposite directions from the generator, you can see that this is the same voltage and current distribution that we found along a half-wave antenna (Fig. 3, Part I). The line, too, is resonant to the generator's frequency. The total length for both wires is still a half wavelength, although the line as a whole is only a quarter wave long.

Odd Lengths

If the line is less than a quarter wave, as in Fig. 4B, there is room only for the outer sections of the standing waves. The line is not resonant in this case. The generator sees it as a reactance, and in order to put maximum current into the line the reactance must be tuned out by adding reactance of the opposite kind. Inductive reactance is needed here for **loading** the line.

In Fig. 4C the line is more than a quarter wave long. Here we have not only the standing waves we had along the quarter-wave line but the beginning of another set, too. This line is not resonant, either, and again it looks like a reactance to the generator. However, in this case its reactance must be tuned out by using capacitance for loading.

Finally, Fig. 4D shows a line a half wavelength long. Each wire is like a half-wave antenna. Since one terminal of the generator is always positive when the other is negative, and vice versa, the voltages and currents are always opposite in polarity along the wires, just as in the other cases. The half-wave line is also resonant at the applied frequency, since each wire will accommodate exactly a complete standing wave, no more and no less.

This could be continued on for still longer lines. In doing so we should find that the line is always resonant when its length is exactly a multiple of one-quarter wavelength. It is *not* resonant at any other lengths.

Quarter- and Half-Wave Resonance

Comparing A and D in Fig. 4, you can see that there is a difference even though both can be considered to be resonant. In A the voltage is zero at the generator, but the current has its highest value. In D the current is zero and the voltage has its highest value. Since the impedance seen by the generator is equal to voltage divided by current, the impedance at the input end of the line must be extremely low in A and extremely high in D. If there were no power lost in the line the impedance values would be zero and infinity, respectively. However, no line can be completely free from loss, so we don't have to worry about what might be meant by zero and infinity. Practically, the impedance is a very low resistance in A and a very high resistance in D.

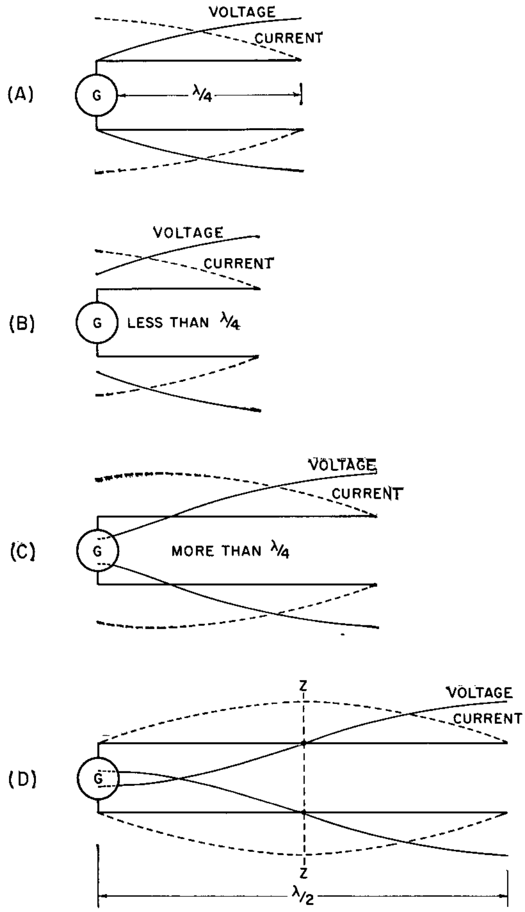

Fig. 4—Standing waves along open-circuited lines.

A quarter-wave line open-circuited at the far end acts like a series-resonant circuit. A half-wave line open at the far end acts like a parallel-resonant circuit.

The Short-Circuited Line

Instead of being left open at the far end as in Fig. 3 the line could be short-circuited as in Fig. 5. Once again, energy traveling out from the generator must turn back when it reaches the short circuit. However, in this case there can be no voltage across the short circuit, although the current can be large. This is just the reverse of the open-circuited case of Fig. 3.

If you will look at Fig. 4D, you will see that just the same condition exists at the point ZZ,

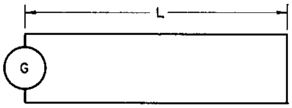

Fig. 5—Short-circuited line.

one quarter wavelength from the end of the open line. The voltage between conductors is zero (if there are no losses) at this point. This means that a short-circuit could be placed across the line at ZZ without disturbing the currents or voltages. Since it is a quarter wavelength from ZZ back to the input end of the line, this section of line also is resonant.

It is apparent from this that what the generator sees when looking into a quarter-wave short-circuited line is the same as what it sees when looking into a half-wave open-circuited line. That is, a quarter-wave short-circuited line is equivalent to a parallel-resonant circuit. The voltage and current distribution are as shown in Fig. 6A.

By carrying on this line of thought it is easy to demonstrate that a half-wave short-circuited line is equivalent to a series-resonant circuit. The current and voltage distribution are given in Fig. 6B. Lines of other lengths are not resonant, and will act like almost pure reactances. Table I summarizes this.

Table I
Transmission-Line Behavior

Length	Open-Circuited Line	Short-Circuited Line
Less than ¼ wave-length	Capacitive Reactance	Inductive Reactance
¼ wave-length	Series-resonant circuit	Parallel-resonant circuit
Between ¼ and ½ wave-length	Inductive Reactance	Capacitive Reactance
½ wave-length	Parallel-resonant circuit	Series-resonant circuit

The line behavior goes through the same series of changes with each added quarter wavelength.

Why Open- and Short-Circuited Lines?

Offhand, you might think that open- and short-circuited lines are about as useless, practically speaking, as an infinitely-long line. However, the fact is that they are quite useful.

In the first place, a resonant line can be substituted for a resonant circuit, and often is. The resonant line is especially useful at v.h.f. and u.h.f., where it may offer the only resonant-circuit structure that it is physically possible to use. Here is where the multiple resonance that goes with a series of quarter-wave sections often saves the day. A conventional *LC* circuit does not have this feature, and there is a limit to how large, physically, such a circuit can be made for a given frequency.

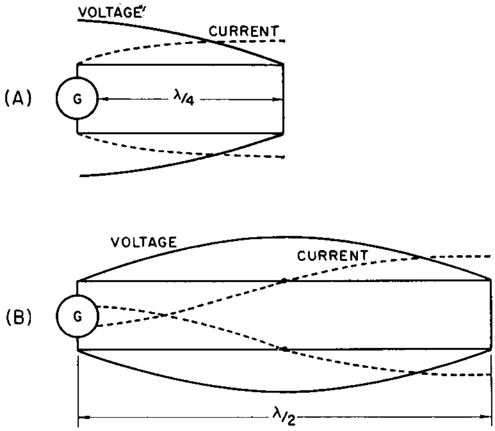

Fig. 6—Voltage and current distribution along resonant short-circuited lines.

Second, nonresonant sections of line can be used in place of coils and capacitors, simply by adjusting the length to give a desired value of inductive or capacitive reactance. This is frequently done in antenna matching systems.

Finally, there are applications where multiple resonance in a line lets us do things like short-circuiting a harmonic of the transmitter while the fundamental frequency goes through unaffected. For example, a short-circuited line having a length of one-quarter wavelength at the fundamental frequency has a very high impedance — nearly an open circuit — and can be connected across another transmission line with little effect on the power flowing through it. But at the second harmonic it is a half wavelength long, and it will act as a short circuit across the other line at that harmonic (and all other even harmonics).

Basics for Beginners

The Whys of Transmission Lines

Part II — Standing-Wave Ratio and Line Losses

BY GEORGE GRAMMER*, W1DF

You have seen, in Part I,[1] that the power put into a matched line nearly all gets to the load at the output end. A small amount is used up by the losses in the line itself; this is converted into heat. We are assuming here, of course, that the line conductors are so close together that there is no radiation because of incomplete cancellation of the fields. If the spacing between the conductors is of the order of 1/100 wavelength this is a good assumption, providing the currents and voltages in the line are **balanced.** Line balance means that the current and voltage in one wire are exactly duplicated in the other, except for reversed polarity.

But what if the load connected to the far end of the line does not exactly match the line's characteristic impedance? A case like this falls somewhere between the perfectly-matched condition and the extremes of the open- and short-circuited lines. Some of the power reaching the far end of the line is absorbed by the load, but some of it also bounces back toward the input end. A **mismatch** is said to exist when the load resistance isn't the same as the line's characteristic impedance. The worse the mismatch, the greater the proportion of power reflected back.

Losses

The principal effect here, at least in transmitting, is that the line uses up a little of the power on both the outgoing and return trips. Aside from this, the power that is reflected from the load is by no means "lost". It's like the change you get when you pay for a 69-cent item by handing the clerk a dollar bill. The money returned goes back in your pocket. The reflected power on a transmission line, too, is unused: it simply subtracts from the power the transmitter put *into* the line, and the power input to the final stage is correspondingly reduced.

Even though some of the power is handed back to the generator (the transmitter) we can still put the full output of the transmitter into the antenna. This is simply a matter of the coupling between the transmitter and line. The coupling that would deliver the transmitter's output to a matched line won't do it if the line isn't matched. But by changing the coupling as required, the transmitter can be loaded just as well. A little less power will reach the load than would get there if the load matched the line properly, because of the extra line loss. But the difference on this account is too small to cause any worry, if a low-loss line is used. Even with lines which, when matched, have fairly high losses, the *extra* loss caused by mismatching isn't much if you aren't mismatched by a factor of more than 3 or so.

On a perfectly-matched line there are no standing waves because no power is reflected from the load end. On open- or short-circuited lines there are large standing waves. Along such lines the voltage and current go to zero, or very close to it, at the nodes.

When a line is mismatched, but not open- or short-circuited, there are standing waves because some of the power is reflected. But only *some* of it. The reflected voltage and current can't completely balance out the **incident** voltage and current (the voltage and current traveling *to* the load) at the nodal points unless there is just as much coming back as is going out. Since this is not the case, there are no points of zero voltage and current along the line. Instead, there will be points of *minimum* current and points of *minimum* voltage. Likewise, there will be points where the voltage and current will be maximum.

Standing Waves on Mismatched Lines

If we went along a mismatched line measuring the amplitudes of the current and voltage, without paying any attention to polarity, we would find that both vary along the line. Fig. 1 is typical of what might be measured. The points of maximum and minimum are still one-quarter wavelength apart, as in the cases discussed before. The ratio of the current at *B*, a maximum point, to the current at *A*, a minimum point, is called the **standing-wave ratio.** Measurement of the maximum and minimum voltages would give the same ratio as measurement of current.

If very little power is reflected from the load — i.e., the line is nearly matched — there is relatively little variation in the current and voltage along the line, so the standing-wave ratio — usually abbreviated to **s.w.r.** — is low. The greater the mismatch the greater the reflected power and the larger the **s.w.r.**

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[1] "The Whys of Transmission Lines", Part I, *QST*, January, 1965.

S.W.R. and the Load

It happens that the standing-wave ratio can be measured more readily than the current or voltage, or even the load resistance. So it is customary to measure the s.w.r. in order to find out whether the line is matched. There is a very simple relationship between load resistance, the characteristic impedance of the line, and the s.w.r.:

$$S.W.R. = \frac{R}{Z_o} \text{ or } \frac{Z_o}{R}$$

where R stands for the load resistance and Z_0 stands for the line's characteristic impedance. The reason for the choice in this formula is that it is customary to put the larger number on top, so that the s.w.r. is expressed as, for example, 5 to 1, rather than 1 to 5.

Actually, you don't need to know R at all in making most adjustments of load resistance. If you're shooting for no reflected power — that is, an s.w.r. of 1 to 1, meaning that the maximum and minimum values are the same — you adjust for the smallest possible s.w.r. When you have it you know you're right.

Fig. 1 shows the voltage high and the current low at the load. It could be the opposite. The drawing is for the case where the load resistance is larger than Z_0. The reverse would be true for a load resistance smaller than Z_0. The first case approaches the open-circuited line as R is made larger, and the second approaches the short-circuited line as R is made smaller.

With a mismatched load resistance, as in the cases discussed earlier, the generator sees a pure resistance when the line is some multiple of a quarter wave in length. Thus this same length indicates resonance. At all other lengths the generator will see reactance along with resistance. Table 1 in Part I can be used to find the *kind* of reactance, if the short-circuited column is used for loads less than Z_0 and the open-circuit column is used for loads greater than Z_0.

Resistance Only

Finally, a warning: To avoid confusing you with a lot of qualifications, in what was said above we have omitted one very important point. *The load has to be a pure resistance if any of this is to be true.*

Mostly, you will be working with loads that are "pure," or nearly so. You can't get an s.w.r. of 1 to 1 unless the load *is* a pure resistance; any reactance in it throws the whole thing off. So if you've been able to get the s.w.r. to 1 to 1 or close to it, you can take it for granted that the line behavior will be as described.

Practical Lines

Quite a few varieties of manufactured transmission lines are available. The ones that are of interest to amateurs are usually in stock at radio supply stores, since they are also used for television receivers. There are two general types. One is the parallel-conductor type we used for purposes of discussion in Part I. The other is the **coaxial line.** This also has two conductors, but one of them is a tube and the other is a wire centered in it.

The coaxial line, familiarly known as "coax" (pronounced with two syllables), obeys the same laws as the parallel-conductor line. All we have said so far applies to both types of line. However, the coax line has some distinctive features. The current is carried by the inner conductor and the *inside surface* of the tubular outer conductor. The *outside* surface is "cold" for r.f., if the line is properly used. In other words, the active part of the line is shielded from outside influences. This means, too, that there can be no radiation from the inside of the line.

Substantially all coaxial line in use by amateurs is the flexible type having a braided-wire tube for the outer conductor. Multistrand wire is often used for the inner conductor, although in some small-diameter lines a solid wire can be used without affecting the flexing. The insulation between the two conductors is a flexible solid plastic — polyethylene.

Velocity Factor

The presence of this solid insulation does two things: It increases the power loss, as compared with air insulation, and it reduces the speed at which power can go through the line. This means that the wavelength in coax cable is shorter, for the same frequency, than in air. The formula for

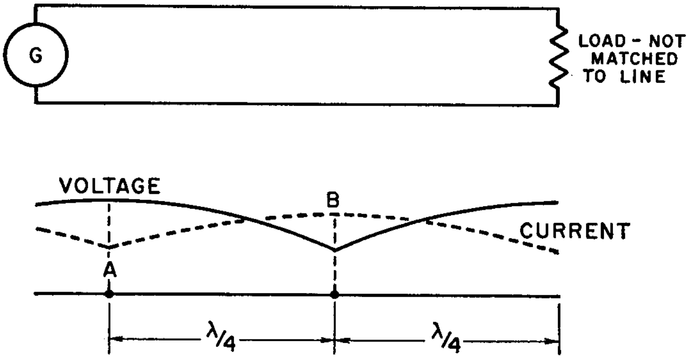

Fig. 1—The standing-wave ratio is the ratio of the current amplitude at B to that at A, or of the voltage amplitude at A to that at B.

Table I
Transmission Lines

Type	*Description*	*Characteristic Impedance, Ohms.*	*Velocity Factor*		*Matched Loss in Db. per 100 Feet*					
				3.5 Mc.	*7 Mc.*	*14 Mc.*	*21 Mc.*	*28 Mc.*	*50 Mc.*	*144 Mc.*
RG-58/U	Small coaxial	53.5	0.66	0.68	1.0	1.5	1.9	2.2	3.1	5.7
RG-59/U	Small coaxial	73	0.66	0.64	0.9	1.3	1.6	1.8	2.4	4.2
RG-8/U	Medium coaxial	52	0.66	0.3	0.45	0.66	0.83	0.98	1.35	2.5
TV Twin Line, Standard	Parallel-cond., solid insulation	300	0.82	0.18	0.28	0.41	0.52	0.6	0.85	1.55
TV Ladder Line, 1-in. spacing	Parallel-cond. air-insulated with spacers	450	*	*	*	*	*	*	*	*

* Not known. Velocity factor approx. 95 per cent. Losses very low in comparison with solid-insulation types.

wavelength given earlier has to be modified by a correction factor, called the **velocity factor,** on this account. For polyethylene-insulated solid-dielectric coax the velocity factor is 0.66. A line one-half wavelength long at 7.1 Mc., for example, would be 0.66 times 69.4 feet (a half wavelength in space), or 45.8 feet long.

Line Losses

If we should divide a line into sections of equal length and measure the power going in and coming out of each, we should find that there is the same *percentage* loss in each section. Suppose that 100 watts goes into the first section and 10 per cent of it is dissipated in heat in that section. Then 90 watts comes out to go into the second section. In the second section 10 per cent represents 9 watts, so now we have 81 watts left to go into the third section. This section loses 8.1 watts, and so on. This sort of power change is exactly what the decibel represents so nicely, so we can express line loss as so many decibels per unit length. The custom is to give the loss in decibels per 100 feet of line.

The loss becomes greater as we go higher in frequency. Losses in db. per 100 feet for the lines most used by amateurs are given in Table I. These losses are for lines that are properly matched by the load. If there is a mismatch the loss will be higher. However, as we said earlier, the additional loss isn't usually serious unless the mismatch is 3 to 1 — that is, an s.w.r. of 3 to 1 — or more. Even then it is not considerable unless the line has high loss when matched.

Parallel-Conductor Line

The most common type of parallel conductor line is TV lead-in, consisting of two wires separated by a web of polyethylene approximately ⅜ inch wide. It is sold under several trade names, and has a characteristic impedance of about 300 ohms. As shown by Table I, its losses are lower than the losses in coax. This is true of good-quality line, which you can be sure of getting only when you buy a well-known brand. Some of the "bargain" unbranded line is very poor, so it is best to steer clear of it.

The lowest-loss line available is the ladder type, consisting of parallel wires separated about an inch. The wires are held apart by small rods of polyethylene at intervals of a few inches. Thus most of the insulation is air, which has negligible loss.

There are many other types of line, both coaxial and parallel-wire, than those listed. Some have different characteristic impedances, and a few varieties have lower losses or greater power-handling ability. However, the types mentioned are easy to get, and are satisfactory for most amateur installations of medium power.

Basics for Beginners

The Whys of Transmission Lines

Part III — Putting the Antenna and Line Together

BY GEORGE GRAMMER*, W1DF

The half-wave dipole is the basis for most amateur antenna designs. Different types of lines can be used to feed power to it. The line should just carry power to the antenna and not get into the radiating act itself. When this is so, the dipole does all the radiating, and one dipole is the same as another no matter how power may be fed to it. This obvious fact is too often overlooked. Amateurs frequently let themselves be dazzled by some trick name tacked on a dipole-plus-feeder combination, but names don't do the radiating.

The best place to feed a half-wave dipole is at the center. The dipole is a balanced antenna — that is, it is symmetrical about its center. To maintain this symmetry a balanced line — *i.e*, a parallel-conductor line — should be used. The dipole *can* be fed at one end, but this also upsets the symmetry of the system.[1]

If the impedance at the center of the antenna matches the characteristic impedance of the transmission line the two can simply be connected together and the line will operate without standing waves. One advantage of this matched operation is that the line length has very little effect on the coupling required between the line and the transmitter. Another is that the losses in the line are least, for a given length, when the line is properly matched. The line losses can either be very important or completely unimportant. They are quite important at v.h.f. even when the best possible job of matching is done. They are unimportant at the lower frequencies, even with a considerable mismatch. The only exception here is when a major error is made in selecting the proper type of line for the use to which it is to be put.

A matched antenna system is actually matched only for one frequency. At best, the system will stay matched over only a small band. As the 7-, 14-, and 21-Mc. bands are narrow, in terms of percentage, an antenna that is matched at the center of one of these bands should work over the entire band without having the s.w.r. get too large at the band edges. But you can't do quite as well with antennas of this type on 3.5 and 28 Mc. Here it is best to cut the antenna for the section of the band that interests you most.

Matched Antenna Systems

Since the dipole has a center impedance of about 70 ohms, it will match a line having a characteristic impedance of 70 ohms, or something close to it. (A small — e.g., 20 per cent or so — discrepancy doesn't cause any difficulty. When 70-ohm or 75-ohm line is mentioned it is to be understood that any impedance in that immediate vicinity is meant.) There is a polyethylene-insulated two-conductor 75-ohm line available for this purpose (Amphenol 214-023). The antenna is simply cut in the center and a connection made to each line conductor, as in Fig. 1A.

In spite of the fact that it is desirable to keep the system balanced, a good many amateurs use 75-ohm coax for the same purpose, as in Fig. 1B. This is not the best practice, although it will work. One side of the dipole is unavoidably connected to the *outside* of the outer conductor as well as to its inside. This makes the outside of the coax line a part of the antenna system. Thus the outside of the line radiates — but not in any predictable way, because everything depends on where and how the line is installed and how

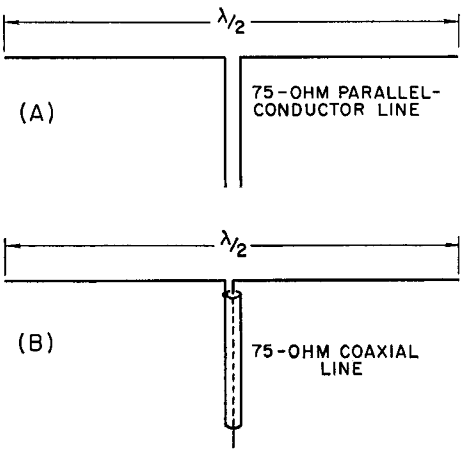

Fig. 1—Using 75-ohm line to match the center impedance of a half-wave antenna. The antenna length in feet is equal to 468 divided by the frequency in megacycles.

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[1] An exception to this is when *two* dipoles are fed from a parallel-conductor transmission line. An example is described shortly.

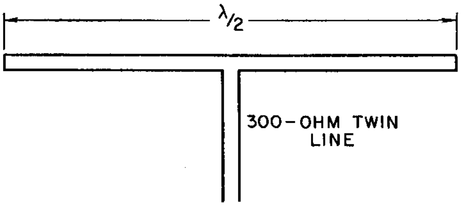

Fig. 2—The folded dipole. The antenna length is calculated in the same way as for a single-wire dipole.

long it is. The principal thing to be said for this system is that the coax line is easy to get.

Very often, 52-ohm (a nominal value) line is used instead of 75-ohm. It is not matched as well by the antenna, but the mismatch is not serious. It has the same disadvantages as 75-ohm coax.

The Folded Dipole

The advantages of matched operation also are realized with the *folded dipole*, shown in Fig. 2. The folded dipole has two half-wave conductors side by side. One is continuous, but the other is cut at the center for making connection to 300-ohm twin line. The two conductors are joined at their ends.

The wires radiate in parallel. In this respect, the pair is equivalent to a single half-wave dipole. But splitting the conductor into two parts has the effect of making the antenna impedance, as seen by the line, four times the impedance of a single-wire dipole. Thus at the point where the transmission line is connected the antenna impedance is approximately 300 ohms — just right for matching 300-ohm line.

Twin line can be used for the folded dipole itself, but ordinary TV line won't stand the mechanical stresses too well if the antenna is long. There is a special heavy-duty line available (Amphenol 214-022) which is better. TV ladder line also can be used for the dipole. The spacing between the dipole wires can be anything up to a few inches, so practically any construction that will keep the wires parallel can be used.

"Open-Wire" Feeders

Fig. 3 shows a half-wave dipole fed at the center through *open-wire* parallel-conductor line. This is line having mostly air insulation, such as the TV ladder line mentioned earlier. Here there is no attempt at matching the antenna to the line. Consequently there are fairly pronounced standing waves on the line. However, the high s.w.r. doesn't cause an undue power loss in open-wire line. The principal penalty is that more attention has to be paid to the coupling between the line and transmitter. The advantage is that the antenna can be made to take power at practically *any* frequency.

A transmission line operating with a high standing-wave ratio is often called a *tuned line* or *tuned feeder.* Actually, the only tuning necessary is that required for coupling the transmitter to the line. The line can be any length. However, it does help simplify the transmitter coupling a bit if a resonant length is used. Such a length, as you have seen, will be some multiple of one-quarter wavelength.[2] The line will "look like" a resistance at its input end in such a case, provided the antenna itself is resonant.

On the other hand, in this open-wire system the dipole doesn't have to be exactly resonant. Since there is no attempt at matching the characteristic impedance of the transmission line, the antenna doesn't *have* to look like a pure resistance, of just the right value, to the line. The over-all length of wire in the system, including both the dipole and the transmission line, is of more interest. It is this over-all length that determines whether or not the system as a whole is resonant. One line wire plus one side of the dipole (the length L in Fig. 3) should be a whole-number multiple of a quarter wavelength if you want the system to be resonant. The formula

$$\textit{Length in feet} = \frac{234}{\textit{Freq. in Mc.}}$$

will give the length of a quarter wave as accurately as is necessary.

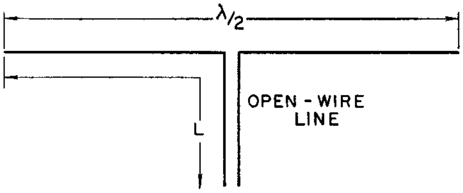

Fig. 3—Half-wave dipole fed with open-wire line.

Multiband Operation

The simplest multiband antenna, and the most versatile, is the one shown in Fig. 4, using open-wire feeder. Since the amateur bands are harmonically related in frequency, we can take advantage of the fact that wires have harmonically-related resonances. The fundamental frequency of a center-fed wire is the one for which its length is a half wavelength. At twice the frequency each *side* of the antenna is a half wavelength long, so at this frequency the transmission line is feeding a pair of half-wave dipoles end-to-end. The current distribution is shown in Fig. 4, which also shows the other resonances up to the fourth multiple.

You should note a few especially interesting things in these drawings. In the second-harmonic case the polarity of the current is the same in both sides of the antenna. There is no reversal such as there is in a continuous wire of the same over-all length. This difference comes about because we have, in effect, two half-wave antennas driven in push-pull, rather than a single antenna a full wavelength long.

There is a somewhat similar situation at the

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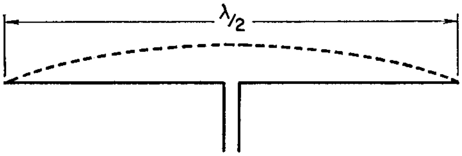
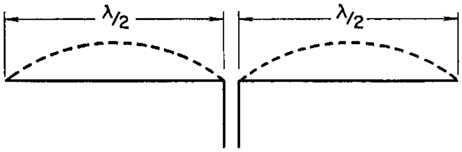
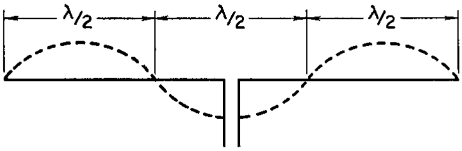
[2] "The Whys of Transmission Lines," Part I, January, 1965, *QST*.



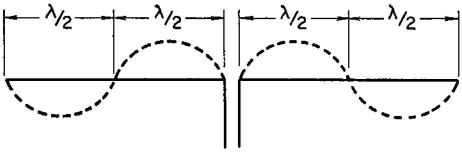
FUNDAMENTAL - F



2nd. HARMONIC - 2F



3rd. HARMONIC - 3F



4th. HARMONIC - 4F

Fig. 4—Harmonic operation of a center-fed antenna. If the antenna is a half wavelength long at 7 Mc., for example, it will also be resonant in the 14-, 21- and 28-Mc. bands.

fourth harmonic. Here, too, the currents in the half-wave sections connected to the line have the same polarity. However, when we go out along either wire we find that the normal reversal occurs in the next half-wave section.

This type of current distribution occurs at all *even* multiples of the fundamental frequency. Note also that at the second harmonic the current is minimum where the feeder is connected. Although the voltage distribution isn't shown, the voltage is highest at these same points, just as in the cases discussed earlier. This means that the impedance is high at the connection point. If the antenna is resonant, it is a resistance rather than an impedance, and is of the order of several thousands of ohms. This same condition exists at all even multiples of the fundamental frequency.

Odd Harmonics

Now look at the drawing for the third harmonic. Here we have the normal current distribution for a wire three half-waves long. The antenna current has its largest value right where the transmission line is connected. The voltage must be lowest at this point, so the impedance (or resonant resistance) of the antenna is low — more like the impedance at the fundamental.

Thus for all *odd* multiples of the fundamental, the current distribution is the same as in a simple continuous wire of the same over-all length, and the impedance at the feed point is low. The impedance goes up a little with each odd harmonic — to a little over 100 ohms at the third harmonic and to about 120 ohms at the fifth harmonic.

Because these figures do not differ too greatly from 70 ohms, it is possible to operate an antenna on its *odd* harmonics when it has been matched on its fundamental. The match is not as good as at the fundamental, but it is not so poor as to result in excessive line loss. Such operation does not really qualify the antenna for multiband work, because only a few bands — not a consecutive series — can be covered.

If the antenna is fed with 50- or 75-ohm line you should not try to operate it at *even* harmonics of the frequency for which it is matched. The line losses would be excessive because of the high s.w.r.

Transmitter-to-Line Coupling

Nowadays nearly all transmitter final tank circuits are designed for coupling into resistive loads of 50 to 75 ohms. A properly-matched coaxial line will "look like" such a resistance, and when a matched coax line is used there is no difficulty in making the final amplifier load up to the rated input. But if the load isn't properly matched, or some other type of line is used, you may have problems. The loading and tuning adjustments offered by the transmitter usually will give you some leeway — even if the matching at the antenna isn't perfect you may still be able to get the power input you want. Again, you may not.

You can get around troubles of this sort by using a special coupling circuit — a *transmatch* — between the output of the transmitter and the input end of the line. As we saw earlier, the input impedance of the line is not the same as the line's characteristic impedance unless the line is perfectly matched by the antenna.[3] If the s.w.r. is greater than 1 to 1 the input impedance may differ widely from Z_0. If the line is connected directly to the transmitter, the latter may see a load that it can't handle. The transmatch takes the line input impedance and transforms it to what the transmitter wants.

It also does two other things. Practically all transmitter output circuits are single-ended — one side is grounded to the chassis, which is the right way to do it for coax line. What to do when a balanced line is used, as in Figs. 1A, 2 and 3? The transmatch easily handles this one; it provides the means for going from a balanced line to coax. In addition, it adds selectivity between the transmitter and the line — selectivity that often is badly needed. It is an

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[3] "The Whys of Transmission Lines," Part II, February, 1965, *QST*.

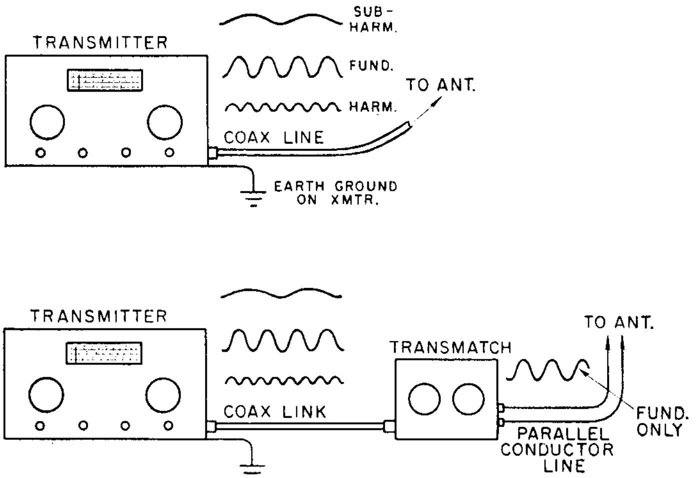

Fig. 5—The transmatch provides means for matching your transmitter's output impedance requirements, for going from a balanced transmission line to coax, and for filtering out frequencies that shouldn't be allowed to reach the antenna.

unfortunate fact that most transmitters "put out" not only the frequency you want, but also harmonics of that frequency — and, in some cases, lower frequencies too, when lower frequencies are present in the stages leading up to the final amplifier. The transmatch is a circuit that, among other things, is tuned to your desired output frequency, and so helps in keeping the unwanted frequencies from reaching the antenna.

Using the Transmatch

Fig. 5 shows how it is connected, and Fig. 6 is a typical circuit. It isn't the only circuit that can be used, but is probably as versatile as any. The circuit formed by L_1 and C_1 is tuned to your operating frequency. If the line is the parallel-conductor (balanced) type the wires are tapped on L_1 at equal numbers of turns from the center. The loading is adjusted by changing the positions of these taps. L_2 couples the power to L_1, and C_2 gives you a means for tuning this link circuit. A coax line goes from here to your transmitter's output terminal. Between these two adjustments you can transform a wide range of line input impedances into 50 or 70 ohms (whichever is the Z_0 of the coax line from the transmatch to the transmitter).

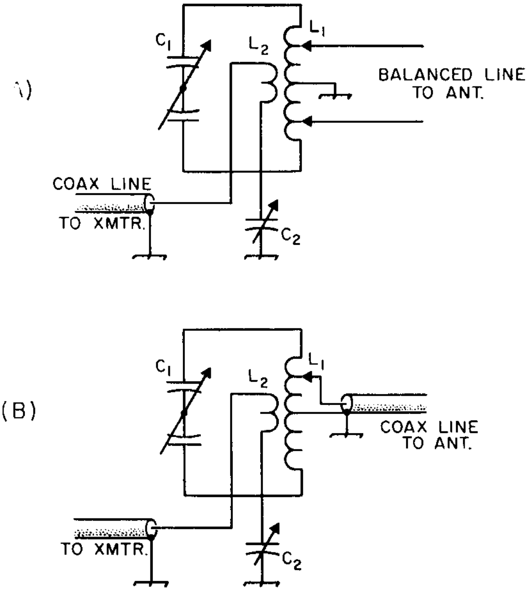

Fig. 6—A representative transmatch circuit.

The method used for coupling to a coax line feeding the antenna is shown at B. It is very similar, the only difference being that the outer conductor of the line is connected to the center of the coil and only one tap is used. The coax link circuit to the transmitter remains the same. So does the method of adjustment.

The benefits of the transmatch circuit do have their price — you have to fix things so L_1C_1 can be tuned to each band you want to use. This usually means that L_1 is a plug-in coil. L_2 is generally made part of the same coil assembly, since it is advantageous to change it, too, for various bands. The same capacitors can be used for all bands, though, over at least the 3.5–30 Mc. range.

The adjustment of a transmatch is easy if you have a bridge such as the Monimatch. Such a bridge is inexpensive and is an almost indispensable station accessory. However, you can arrive at a reasonably satisfactory adjustment simply by varying the tap positions, along with the settings of the two capacitors, while performing the normal tuning and loading operations on your transmitter. After a little cut-and-try you'll find the transmatch settings that let you load up the final amplifier to the input you want.