Antennas and Feedlines

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Introduction

Ham radio has it's share of mis-information, mis-conceptions and mis-understandings among it's participants; some are serious and some are not so serious. Here are a few examples: There is confusion on when and how to use the transmit and receive XIT/RIT controls on a modern transceiver; lack of knowledge on how to optimally adjust and utilize pass band tuning; mis-understanding of the digital frequency display accuracy versus resolution. There are many others, and I'm sure you can think of some, but we need not belabor the point.

It seems to me that perhaps the most widespread amount of confusion stems from mis-understanding antennas and feedlines. Why do I say this? I say this based on listening to on-the-air conversations. Here are some excerpts I have recorded from actual on the air conversations on the 75 and 40 meter phone bands.

"I can't operate 75 meters because I don't have room for an antenna."

"My swr is 2.5:1 but if I can get it down to 1.1 to 1 my antenna will work much better."

"My antenna works best on this frequency because it is resonant here."

" I had to put up four dipoles so that I can operate 75, 40, 20 and 17 meters."

"My swr was 3.5:1 but my tuner brings it down to 1.15:1."

These statements and others like them betray a lack of understanding antenna and feedline operation. It is the purpose of these notes to attempt to erase some of this confusion and, hopefully, stimulate and extend your thinking as it relates to antennas. In the process, we shall learn how to overcome some serious operational limitations we have placed upon ourselves as a result of these mis-understandings.

The language is very simple. I have shied away from an esoteric and a predominantly mathematical approach in order that the information may appeal to a greater number of hams.

None of the information is new or original. The principles described here were used by hams at least as far back as the 1920's in the past century. Since then countless articles have appeared in the literature including the ARRL Handbook, the ARRL Antenna Book and articles in QST explaining the correct principles of antenna and feedline operation. Why then is there so much confusion?

Why the Problem?

My theory is that it all started immediately after World War 11. The easy availability of surplus military 50 ohm coaxial cable and, shortly thereafter, the appearance of the ubiquitous SWR meter started the ball rolling. Hams began to be preoccupied with reflected power on their coaxial feedlines. Almost immediately there was near universal agreement that reflected power had to be avoided like the plague. Moreover, 50 ohm coaxial cable had to be used because 'it doesn't radiate like open line does.' These hams failed to remember, or chose to overlook, that before the war hams cared not one whit about reflected power on their open wire feedlines and they got along just fine.

What finally sealed the bargain, so to speak, was the appearance of the no-tune transceiver. I do not know if it was pressure from the hams or if it was a sell job by the manufacturers to produce the no-tune transceiver. I suspect it was promoted by the manufacturers in order to save money. At any rate no longer did we have to adjust transmitter tuning controls. Just turn on the rig and press the push to talk switch. This design innovation was hailed as one of the greatest inventions ever and led to a 'Look, Ma, no hands! Ain't it great!?' euphoria among the ham fraternity. There was little concern, if any at all, on just what we gave up when we were rid of those controls.

50 ohm coax, the SWR meter and the no-tune transceiver all conspired in concert to lure many hams into a state of confused ignorance regarding antennas and feedlines.

In spite of all that has been written to dispel the mis-understandings why are they still so persistent? I have no definitive answer. Perhaps hams have not understood the subject sufficiently well. Perhaps they don't believe what they read. Perhaps they are influenced more by what they hear from their peers. Maybe their ideas have been with them so long that it is now impossible for them to change their thinking. Maybe some prefer not to be enlightened. The latter is not meant to be facetious nor sarcastic. I have met many hams who adamantly refuse to believe anything that challenges their long cherished beliefs regardless of any evidence to the contrary.

The Basic Half Wave Antenna

By 'antenna' I mean the antenna itself and excluding the feedline attached to it. The first mis-conception hams have is that the closer the basic dipole antenna is to a half wave length in the band of interest the closer it will approach perfection and the better it will radiate.

That belief is not supported by either theory or practice. Theoretically, the half wave antenna does not radiate any better or worse than any other length. In other words, all lengths radiate equally well. You will not find any statement to the contrary in any reputable antenna text including the ARRL Antenna Book. Nor will you find any claim that the half wave antenna maximizes radiation compared to other lengths.

So why does every antenna article ever published show the half wave dipole antenna as the basic antenna? The answer is because it is the basic antenna. But this does not mean that it is the best antenna. In text books it is the basic antenna because it is the easiest length by which to describe mathematically, graphically and conceptually how antennas in general operate. For one thing the sinewave-like distribution of voltage and current along the wire can be drawn very nicely to exact fit on the half wave wire. Can you imagine what it would be like if your basic antenna text book began by describing a 37/64 or an 9/17 wavelength antenna? It can be done but the drawings and the mathematics would really be messy using such odd lengths. But a half wavelength....well, how elemental can you get?

But why is almost every real world antenna a half wave length long? Now we've come to the crux of the matter. The answer is because, in the practical world, the no-tune transmitter wants to see 50 ohms and the coax cable wants to see 50 ohms and the half wave dipole impedance can be made close to 50 ohms. Everything comes out closely matched and everybody is reasonably happy. It is the half wave length antenna that makes all of this possible. This convenient accommodation to the demands of the transmitter, however, says nothing about the radiating efficiency of the antenna itself. Nor does it make this antenna length the best radiator. The ONLY thing it says is that this length makes the SWR low at the transmitter. SWR describes a condition on the feedline. SWR says nothing about the radiating qualities of an antenna.

That a low SWR does not validate a good antenna is easily demonstrated. Consider a 50 ohm resistor terminating your feedline. The SWR is a perfect 1:1 but would you use that resistor as your antenna?

So what's wrong with using a half wave length antenna for a low SWR, you ask. Nothing and everything. 'Nothing' is wrong because it is a perfectly workable system. 'Everything' about it is wrong because you un-necessarily impose severe limits on your station operation. A single wire resonant dipole is a high Q device. It is resonant at only one frequency. It presents a 50 ohm termination to the feedline at that one frequency. At every other frequency the resistance at the feedpoint changes. In addition, reactance is introduced and begins to increase. The resistance can be higher or lower and the reactance can be capacitive or inductive. The values depend upon whether the frequency is higher or lower than the resonant frequency. These changes in antenna impedance cause the feedline SWR to increase as you move away in frequency. Our coveted no-tune transmitters do not like that. As a consequence hams using such an antenna restrict their operation to a relatively narrow range of frequencies in the one band where the antenna is resonant. It is important to understand that they operate this narrow band of frequencies not because the antenna works better there but because their transmitters do not allow them to work other frequencies.

The alternative, the details of which are the subject of these notes, is the use of a dipole antenna, not necessarily trimmed to resonance, that is used on ALL bands and ALL frequencies without regard to feedline SWR.

I do not mean to imply that a resonant antenna length and a low feedline SWR do not provide optimum performance. What I mean is that a non resonant antenna length and a feedline operating with a finite SWR can provide just as good performance. Why then should we bother investigating these two phenomena if a resonant length with low SWR is sufficient to attain optimum antenna performance? The answer to this question is that knowing a few simple facts about how an antenna works will enable us to achieve optimum performance over a much wider range of frequencies than we otherwise allow ourselves.

Theoretically, the ideal free space resonant dipole feedpoint resistance is not 50 ohms but closer to 70 ohms. Well, if you want to be super accurate it is a theoretical 73 ohms. The actual resistance is determined by the height above ground and loss due to the antenna surroundings. The reason many dipoles measure closer to 50 ohms is on account of loss. Many hams are either unaware of this loss or choose to ignore it because they are primarily concerned with achieving an impedance that is close to 50 ohms. In essence, they have prioritized a low SWR over antenna system radiating efficiency. I have always thought it strange that they welcome loss, albeit perhaps inadvertently, for the sole purpose of making their SWR meter read lower. Or didn't you know that introducing loss in the antenna and/or feedline makes your SWR meter read lower? This is choosing a low SWR for the wrong reason. And it is counterproductive thinking.

Many hams happily announce that their antenna is broadband. They enthusiastically boast that they can go from one end of the band to the other and their low SWR hardly changes. What has happened is that they have somehow introduced loss somewhere. Loss in the antenna/feedline has lowered the Q, caused the SWR to decrease, and broadened the antenna - all at the cost of radiating efficiency.

When hams put up a dipole and the SWR is not as low as they would like it to be they immediately begin to fiddle with it. They shorten/lengthen the ends, droop the ends, raise/lower it, lengthen/shorten the feedline, change the feedline, change the orientation and who knows what else in order to get the SWR down to 1:1. Fiddling with it introduces loss and perhaps gets the SWR down to 1:1, or close to it. And that makes these hams happy.

What all of this boils down to is that they sacrifice antenna system efficiency in order to satisfy the demands made by the no-tune transmitter. This is going about the problem the wrong way around. They have the thing all backwards. The better way to go is to prioritize antenna efficiency and then go about doing what is necessary to make the no-tune transmitter conform to the antenna specifications.

We now come to a point that should be emphasized. The better (lower loss) the dipole the more restricted the frequency range over which it will operate with a low SWR. So, if your SWR changes rapidly with a relatively small change in operating frequency be thankful, you have a good but, alas, also a restrictive antenna system If you are willing to put up with that restriction, fine. But you don't have to. Let's continue.

A Simple Experiment

One of the main reasons, if not the main reason, given by hams who advocate the use of a half wave length wire is that the current in it is maximum by virtue of it's resonant length. Maximum compared to what? Maximum compared to all other non-resonant lengths. And everybody knows that the more current in the wire the better the radiation. This claim is both true and untrue.

It is true that the greater the current in a given antenna the greater the radiation. It is not true that the half wave wire has the maximum current compared to other lengths. Before you accuse me of blasphemy consider the following. Let's try a simple experiment. Assume a resonant wire and assume that it has a feedpoint impedance of 50 ohms resistive. Now apply 100 watts of RF to it. From elementary ohm's law current is equal to the square root of the power divided by the resistance. In our example, the power divided by the resistance (100 watts divided by 50 ohms) equals 2. The square root of 2 is 1.4. Thus the current in the half wave resonant antenna is 1.4 amps. That's simple enough.

If we believe the 'maximum current' proponents, any other length will result in a lower current. Let's see if this is true.

Let us now lop off some wire from each end of our halfwave antenna in order to shorten it. The feedpoint impedance will no longer be 50 ohms. It will change to a lower value. Let us say that we have cut off enough wire to lower the feedpoint impedance to 25 ohms. Now feed the same 100 watts to the antenna. We can calculate the current as we did before. This time the current will be the square root of 100 watts divided by 25 ohms which is 4. The square root of 4 is 2. The current in the short non resonant wire is 2 amps. 2 amps is greater, not less than, 1.4 amps. The half wave wire does not have the maximum current. The short non resonant length antenna has more current! How will both antennas radiate? Everything else being equal, exactly the same!

But wait! But wait! I hear you saying that you cannot put 100 watts into a non resonant antenna and that there will be reflection on the feedline. Objection over-ruled. A simple matching network at the antenna to transform the 25 ohm radiation resistance to 50 ohms will take care of that problem. The feedline is terminated in 50 ohms and so there will be no reflection on it. Furthermore, since there is no reflection on the feedline because it is terminated in it's characteristic impedance it necessarily follows that all of the 100 watts will be transferred forward, But let's not get sidetracked from what I am attempting to describe - that contrary to popular opinion the current in the half wavelength antenna is not larger than that flowing in the short non resonant antenna. The half wave antenna does NOT have more current in it because it is resonant.

Before we leave the experiment we just conducted let's look at one additional example. If we were to lengthen the resonant antenna the feedpoint impedance would increase and we would calculate less current than that which flows in either the short antenna or the half wave one. Once again the 'maximum current' proponents will have us believe that we should expect less radiation.

This time let's lengthen the antenna so that each leg is now .64 wavelengths long. This, without doubt, is a non resonant overall length. The antenna is too long. The feedpoint impedance will be about 126 ohms and the current will be a measly .9 amps. Is this antenna an inferior radiator? By no means. It is called a double extended zepp antenna and it is a 3 dB better radiator than the half wave resonant antenna. So much for the superiority of the half wave antenna over every other length by virtue of it's being resonant.

In view of the extreme simplicity of the foregoing mental experiments many hams steadfastly refuse to believe what is so easily demonstrated and measured. This is perhaps the most baffling aspect of this whole subject regarding antenna operation - this stubborn refusal to accept mathematical proof as well as the results of simple and straightforward measurement.

Let's continue as we examine a random length non resonant wire in greater detail.

The Random Length Antenna

I stated that theoretically any length wire is just as good a radiator as the resonant half wave long dipole. If this is so, why are random length antennas not normally used? The answer is again the demands made by the no-tune transmitter. A random length dipole does not have a feedpoint resistance near 50 ohms which is the load impedance that no-tune transmitters want to see when connected to their coaxial feedline.

If the dipole length is longer than the resonant length, the resistance component of the feedpoint impedance increases. If the length is shorter than the resonant length the resistance decreases. In addition, the random length feedpoint impedance will acquire a reactive component as well. The no-tune transmitter connected to a coaxial feedline does not like that. It either throttles back the power output or shuts it down completely. But note that this is the result of the transmitter being unable to work into an impedance other than 50 ohms and not a result of faulty or irregular antenna operation.

Before we leave the random length wire we need to consider another aspect of this type of antenna. The question is bound to be asked. If a wire of random length radiates equally well does this mean that we can use a 1 foot antenna on 160 meters? The answer may surprise you. Theoretically, a 1 foot antenna located in free space can provide very reasonable operation on 160 meters. In the practical world it is another matter altogether.

The problem is feedpoint impedance compared to the loss in the material out of which the antenna is made. In such a short antenna the radiation resistance is extremely small - an exceedingly small fraction of one ohm. The total feedpoint impedance is made up of this radiation resistance plus the ohmic and skin effect resistance in the metallic material and additional loss due to the surroundings in which the antenna is installed. In a very short wire, the radiation resistance is so small compared to the total loss resistance that whatever loss resistance is present constitutes a very large percentage of the total impedance. In this case, an overwhelming percentage of the RF power fed to the antenna is wasted in the loss resistance and only a very tiny percentage is left over to actually radiate into space. The result is, in the practical world, a very inefficient radiator.

The foregoing implies that there is a practical limit on how small we can make an antenna and still obtain reasonable radiating efficiency. More on this later.

The No-Tune Transmitter

There is nothing magic about the 50 ohm impedance that our no-tune transmitters want to see. The designers could just as well have chosen some other value. In the past, variable tuning controls allowed our transmitters to work into other values of impedance. But our transmitters do not provide us that luxury anymore. We are stuck with 50 ohms. What all of this means is that if the transmitter were somehow able to once again work into other impedance values we could use random length wires as antennas. The random length wire would radiate with an efficiency equal to the resonant length wire. The implication in this statement is that a shortened or non resonant antenna such as a 40 dipole used on 75 meters would operate with high efficiency. We would also free ourselves from being preoccupied with pruning the antenna. There would be no need to do so. Just string up a wire in whatever space is available and be done with it.

Another and equally important implication in the statement is that the ham operator would no longer be restricted to operation over a relatively narrow frequency span but could utilize the antenna over the entire band.

If only we could make the transmitter cooperate! If we could do that it would be a great increase in our station operating flexibility don't you think?

Think again about what this means. If we succeed in somehow 'coaxing' or 'fooling' or adjusting the transmitter into working with any antenna feedpoint impedance then not only could we use a regular half wave antenna on the next lower frequency bands but also on all of the higher frequency bands as well. Thus a 40 meter dipole would work with high efficiency in the 75 meter band and on all of the bands up to 30 megahertz. And if we do not have the room for even a half wave antenna on any amateur HF band we can still use a non resonant random length on all bands with equal results.

The alternative is that since most of us have room for a 40 meter dipole but do not have room for a 75 meter dipole we don't operate 75 meters. We also do not operate 20 meters because the antenna won't load up there. The result is that our operation is very restricted. I do not see how there can be any question but that the first alternative is the preferable one.

The Fix

(finally)

The fix is absurdly simple. It is based on an approximately 80 year old technique. It is called an antenna tuner.

At this point 7 out of 10 hams will refuse to read any further. Goodby 70 percenters and thanks for sticking around this long.

As for you remaining 30 percenters, let's continue as we explore this mysterious and hated gadget. Yes, hated. Most hams despise tuners. That's why 70 percent just left us. They will have nothing to do with them. And, as I implied in the previous paragraph, they do not even wish to understand them. Why is this?

There are several reasons given why hams reject tuners. Here are the two more commonly offered. They are lossy and they are a pain in the neck to use.

Of course some tuners are lossy. But tuners are not inherently lossy. Manufacturing considerations have caused some tuners to be lossy. A perfect tuner is completely loss less. A nearly perfect tuner is nearly loss less. A lousy tuner has significant loss. But is this not true of everything in this world? Why should it be any different with tuners?

The claim that they are a pain in the neck to use is a curious one. What this usually means is that they require constant adjustment as you QSY up and down the band. A properly adjusted tuner will always present a perfect 1:1 swr to the transmitter. This is in spite of the fact that I often hears hams saying that they can get the swr down to, say, 1.5:1 by adjusting their tuner. Something is wrong if that is the best they can do and suggests that they do not know how to properly adjust them or the tuner is deficient in some respect.

A properly adjusted tuner can provide a near perfect 50 ohm load to the transmitter over a very considerable frequency span. Besides, it is not necessary to continually adjust the tuner. If you QSY a sufficient amount to cause the SWR to increase to as much as, say, 2.5:1 you will gain nothing by re-adjusting the tuner to an SWR of 1:1. So all told is this too great an inconvenience compared to the benefits gained?

Before you hasten to answer consider again what the trade offs are. We are talking about being able to operate on every band and on every frequency with a single moderate length wire versus operation on one band and over a narrowly restricted frequency span within that one band. If this is not sufficient incentive to stick with me then join the 70 percent that left a while ago. Go do something else. What follows won't gain you anything.

I said that reducing SWR from 2.5:1 to an SWR of 1:1 won't gain you anything. That's not exactly true. There is a difference. How much of a difference? let's find out.

The difference is 0.7 dB. This represents less than one eighth of an S unit. Look at the S meter on your rig. How far apart are the S meter markings? I bet that they are about 1/4 inch or so. Mentally divide the distance between two S units into 8 parts. The difference in signal strength is one of those marks. Yet many hams worry themselves sick over an SWR reading of 2.5:1.

S meters should read 6 dB per S unit. Most will read about 3 or 4 dB or thereabouts. Yes, this applies to that multi kilobuck beauty sitting on your desk - 'tis sad but true. Moreover, it will be a variable over the scale. Since that is the case in the real world, make that two divisions in the example described above. So it's two divisions instead of one. Big deal.

Finally, once again, a correctly adjusted tuner will always present a perfect 1:1 SWR to the transmitter. An inability to do this indicates a defective and/or a mis-adjusted tuner.

More on Tuners

A tuner is an impedance transforming device. It transforms the impedance presented to it at the station end of the antenna feedline to the impedance the transmitter is designed to work into - almost universally 50 ohms resistive. The tuner transforms the impedance at the end of the feedline to 50 ohms in order to make the transmitter happy. Later on we shall explore in a little more detail the impedances seen at the input end of a transmission line. The no-tune transmitters we use nowadays do not provide variable tuning and loading controls. Do you know what function these two controls accomplished in the past? They are nothing more than an antenna impedance transforming network. In other words, an antenna tuner! When we gleefully got rid of these controls we not only threw the baby out with the bathwater, we threw the tub out as well. In a very real sense, then, we are simply putting back the amplifier tuning controls we rejected when we embraced the no-tune transmitter.

Look at the schematic of your modern no-tune transmitter power amplifier output circuit. See all of those capacitors and coils between the transistor collectors and the coaxial antenna connector? You know what that is? In addition to providing a filtering function it's an antenna tuner. It transforms a load of 50 ohms to the load value the output transistor collectors want to see - typically less than one ohm in a 100 watt transmitter. So all tuner haters paid big buck to buy rigs that come with build-in antenna tuners. How about that. The problem is that these networks only function at one impedance value - 50 ohms. There is no adjustment to make the transmitter work with other values.

Well designed tuners utilize only two electronic components - capacitors and inductors. Capacitors are so good that they do not contribute any significant loss in the circuit. In other words they have very high Q. Capacitor Q is much larger than the Q exhibited by coils.

Unfortunately, we cannot make coils as good as we can make capacitors. Their Q is lower. Coil Q is what determines loss in a tuner. Given the truth of that statement, we need to use the highest Q coils we can manage in order to keep tuner loss low. This means physically large coils in physically large enclosures. With moderate care in manufacture and assembly into the tuner, coils can be constructed with Q values in the 400 to 800 range. This is entirely more than adequate and will insure a low loss tuner when used with any reasonable antenna impedance likely to be encountered in the typical ham installation.

Despite their high Q, hams don't like large coils. It's the old 'I don't want a tuner that's three times bigger than my rig' syndrome.

So what does the average ham, those who use tuners anyway, settle for? One of those tiny automatic tuners! Have you every taken the cover off one of those things and looked inside? What a gosh awful mess of teensy tiny parts all jammed together! What do you suppose is the Q of those coils? And is it not curious that many of the hams that hate tuners nevertheless crave the automatic ones? I could never figure that one out. But here, once again, we find hams sacrificing efficiency for expediency. Remember the 'look, Ma, no hands' syndrome?

A single capacitor and a single coil can transform, or match, any impedance to any other impedance. So a tuner need not be a complicated gizmo component-wise and circuit-wise

Whatever inherent loss there is in a tuner is a variable quantity. A given tuner may show detectable loss when operating into certain values of load impedances and no detectable loss when operating into other load impedances. The loss is not a constant across-the-board parameter. So far in our discussion we haven't really looked closely at the feedline. What about the feedline? How does it fit into the equation?

The Feedline

Everybody knows that the feedline is required to convey RF power from the transmitter to the antenna. For this mundane purpose everybody loves 50 ohm coaxial cable.

Mundane purpose? Hardly. Let's take a closer look at feedlines. Feedlines at the lengths found in a typical ham installation, in addition to acting as conveyors of RF energy, act as transformers. They can't help it and they have to do it. This is neither a desirable nor a non desirable condition . It just is and so we have to account for it.

Feedlines terminated in their characteristic impedance, and lengths that are multiples of an exact half wave length, act as 1 to 1 transformers. They do not change the terminating impedance into something else. But when any other length line is not terminated in it's characteristic impedance they change the impedance into something else at the transmitter end. The value of that 'something else' is a function of antenna impedance, line loss, and the length and characteristic impedance of the feedline. It is this transformed impedance, not the antenna impedance, that tuners transform to 50 ohms to make transmitters happy.

Contrary to popular belief, an open wire feedline even if operating with a very large SWR will not radiate if installed correctly. Furthermore, also contrary to popular belief, coaxial lines can radiate even when used with a balun unless the entire antenna system is absolutely symmetrical in every respect not only to itself but to all surrounding objects as well - a situation hardly ever satisfied in actual practice. I doubt if even as few as one in a million amateur antennas meet this criteria. In other words 999,999 antennas out of a million amateur antennas that use coaxial feedlines that radiate to some extent!

Since nothing is perfect in this world, all feedlines are lossy. Some lines are more lossy than others. Open wire lines are the least lossy. I'm not talking about ladder or window line. I mean real open wire line. Ladder line is lossier. Coaxial cable is lossier still. RG-59 is lossier than RG-8, and so on. It should be obvious that we want to use the lowest loss line we can manage.

It is next to impossible to make open wire line with a characteristic impedance of 50 ohms or even 70 ohms. Typically, open wire line has a characteristic impedance in the range 300 to 600 ohms. When we use one antenna on all HF bands, the radiation impedance at the feedpoint is going to vary all over the place. On some bands it will be low and on some bands it will be high. In addition, depending on the length of the wire and the frequency, reactance will be present as well as resistance. This means that when we attach a 600 ohm line to the antenna the SWR on it will also vary wildly all over the place. It is not uncommon to measure SWR ratios as high as several hundred or even several thousand to one under these conditions.

Great Scott!!! Several hundred to one??? How can such a system possibly work? All of the power will be REFLECTED!!!

And so it will. Many hams are not clear on what happens to reflected power yet they are absolutely certain that they want no part of it. Theory, practice and measurement show that all reflected power is re-reflected at the tuner and it gets sent back up to the antenna where it is radiated into space. Surprise!

It works this way, RF is dumb. It has no intelligence. It has no mind of it's own. It acts the way the laws of physics describe. Reflected power is a result of an impedance mismatch. When reflected power travels back down the line, it meets a mismatch at the tuner. The mismatch will be either a virtual open or a short circuit depending. This is a perfect impedance mismatch and so all of the RF, following the rules of physics, is reflected and travels back up toward the antenna. In other words, the RF doesn't differentiate between an impedance mismatch at the antenna and an impedance mismatch at the tuner. RF, being dumb, has no concept of traveling left or right nor up and down on a feedline. Power undergoes reflection at both points because it sees an impedance mismatch at both points. Period.

Another Experiment

Not convinced? OK. Let's do an experiment. Assume a 100 watt transmitter connected to a length of 50 ohm coaxial cable. The length does not matter. It can be 32 feet, 48 feet, 89 feet - it doesn't matter. Assume a second piece of 50 ohm coaxial cable connected between the far end of the first cable and an ideal dipole antenna cut for 7 megahertz. An ideal and perfect dipole will have a feedpoint resistance of 70 ohms (73 ohms actually but let's not quibble) plus a reactive component of 40 ohms inductive reactance. Make the length of this second piece of cable exactly 14.72 feet. Why this length? Because this length of coax will transform the antenna feedpoint impedance of 70 ohms resitive and 40 ohms capacitive, to a 50 ohm resistance. Unfortunately, in addition to this 50 ohms of resistance, there will also be a capacitive reactance of 38 ohms at the junction of the two pieces of cable. Let's immediately get rid of that pesky reactance by connecting a coil at the junction to tune it out. Phtt! Its gone.

What have we got left? Our first piece of cable is now terminated in a pure 50 ohm resistance. This means that there will be no power reflected from the junction. The second piece of cable, however, will have power reflection on it because it is not terminated in it's characteristic impedance by the antenna.

The SWR meter in the rig will indicate a perfect 1:1 SWR because the first piece of cable has no reflected power on it. However, power reflected by the antenna will flow down the second piece of cable toward the junction. The power does not pass through the junction. The SWR meter in the rig confirms this. So what happens to the reflected power when it reaches the junction?

Stop here for a moment and ponder that last question. What do you think happens? Ready to go on? OK, let's do so.

Energy can exist only in certain forms. It can be transformed into and exist as electrical energy, mechanical energy, chemical energy, light energy, heat, radiation and maybe others.

If we are to believe that power causes some strange effect when reflected back toward a transmitter then we would expect to see something similarly strange occurring at the junction. But if you put your hand at the junction you will not feel heat. The junction does not jump around indicating mechanical energy. If you hold a bucket under the junction you will not see any chemical substance condensing or dripping into it. If you look up at the junction at night you will not see light emanating from it. If you bring a receiving antenna close to the junction you will not detect radiation from it. It remains electrical energy and is not changed into something else. Furthermore, it does not accumulate at the junction. If it did we would, with the passage of time, see a tremendous amount of power continually piling up at the junction. This, of course, is absurd.

What happens to the power? It is reflected at the junction and goes back up to the antenna just as I said before. Theory and measurement confirm this.

A Closer Look at Reflection

Let's look at this amazing phenomena of reflection a little closer. The events concerning reflection can probably be most easily described in the following manner. Let's say 100 watts is supplied by the transmitter and travels up toward the antenna and the impedance mismatch is such that 10 watts gets reflected. This means that 90 watts is radiated. The ten reflected watts constitutes a ten percent reflection due to the antenna mismatch. The reflected ten watts reaches the tuner and sees the perfect mismatch. Consequently all of it gets reflected back up toward the antenna. The ten watts reaches the antenna and 1 watt gets reflected back down the feedline: our ten percent reflection remember? The leftover 9 watts adds in phase to the 90 watts being radiated and the total radiation is now 99 watts. The 1 watt that is reflected sees the mismatch at the tuner. This 1 watt is reflected and reaches the antenna and .1 watt gets reflected due to the ten percent reflection. The remaining .9 watts adds to the 99 watts and now 99.9 watts gets radiated. This process continues, rapidly reaches the steady state and all of the power ends up being radiated continuously. Isn't that totally Cool?

But most hams do not use tuners. What happens to their reflected power? The reflected power acts on the output circuit of the transmitter to reduce the power output. It is reduced by the amount of reflection. That's all. In this case it does NOT get re-reflected back up toward the antenna where it can radiate into space. The result is that less power gets radiated. The reflected power does NOT cause heating or any other nasty effect in the transmitter other than to reduce the amount of available power. Hams who will not use tuners actually prefer, by implication, and perhaps unknowlingly, this mode of reduced power operation.

I should explain that since reflected power does not cause any harmful effect in the transmitter then why do they throttle back? The answer is that the reflected impedance (reflected voltage divided by reflected current) into the transmitter causes the operating current or voltage to increase beyond the design limits established for the final power amplifier transistors and associated components. It is the change in impedance - NOT the reflected power as such - that causes the throttle back effect in order to protect the transistors by preventing their being subjected to voltage and/or current values beyond their rated specifications.

There is another very simple experiment that many hams, even if witnessing it, would refuse to believe. If two 100 watt transmitters, one connected to a half wave resonant antenna through a perfectly flat coaxial line and the other connected to a non resonant antenna through a tuner and a 600 ohm line with an SWR of, say, 400 to 1, a distant receiver or field strength meter would see the same signal strength from these two transmitters.

Before we leave the subject of these fascinating devices I want to point out that power traveling from left to right through a tuner passes from the input to the output with no trouble along the way. However, power trying to pass through the tuner from right to left in the opposite direction gets totally reflected. It is this property that makes tuners so ideally suited to the application. No, the tuner has no intelligence, it just follows the laws of physics. It has to do with the way the phases of the traveling waves combine at the tuner. Rigs without an antenna tuner or an equivalent network DO NOT provide this 100 percent re-reflection of power - on the contrary, they throtle back the power when the SWR increases beyond a set limit. The rig with a tuner continues to deliver full power to the antenna regardless of the feedline SWR. The tunerless rig does not.

So where are we at this point? Tuners release us from the constraint imposed by the antenna system that restricts us to one band operation and a narrow frequency span. It this all that there is to it? Not quite. We need to understand the effect of feedline loss.

Feedline Loss

Loss in the feedline is obviously undesirable. If we have a resonant antenna that reflects no power in a matched line the power radiated is nevertheless reduced by an amount lost in the line due to inherent line loss. This loss (heat) is distributed all along the entire length of the feedline and so we cannot normally detect it by feeling the line. Unless, of course, it is grossly excessive; but we shouldn't be using such a feedline in that case - nor, for that matter, touching it. Ouch!

We have seen that when we use an antenna on all bands the line SWR can reach extremely high values on some bands. The inherent loss in the line will cause a significant amount of additional power to be lost as heat when operating under abnormally high SWR conditions. But this undesirable condition can be alleviated if we use a feedline with the lowest possible loss. The lowest loss line we can manage is the open wire feedline - two larger gauge wires separated at wide intervals by good insulators. A well designed and installed open wire line has an inherent loss not exceeding .01 dB per 100 feet. Under most operating conditions, loss due to this cause will be negligible or nearly so.

While on the subject of feedlines, if your SWR changes if you add an 8 to 12 foot length of RG-8 to your existing coaxial cable feedline, easy to do with one barrel connector and a connectorized 8 foot length of coax, you got problems. For one thing, your SWR readings are meaningless. Your meter is not giving you accurate line SWR readings. You don't know what the SWR is. The problem is that you have what is called an 'antenna' or a 'common-mode' current on the line. This means that your feedline is not only radiating but messing up your meter readings. A balun at the antenna or at the transmitter may or may not help. Good luck.

From what we have learned so far, it should now be obvious that the measurement of SWR is not such a trivial matter as many think. It is subject to error. The error is due largely to the presence of antenna or unbalanced current on the shield of the coaxial feedline and also feedline loss. Not to mention inherent meter inaccuracy especially when reading low SWR values. It is not always easy to mitigate or correct the error due to these causes.

Antenna systems used with open wire line and a low loss antenna tuner avert preoccupation with SWR. The tuner tunes the entire antenna system, including feedline, to resonance. And because we are not primarily concerned with the SWR on the line, it conveniently drops out of the equation. In other words, we simply do not care what the SWR is.

I have mentioned antenna efficiency several times. What are we talking about?

A half wave antenna on 40 meters, made out of 12 gauge copper wire and installed 35 feet above average ground has a radiating efficiency of 98.67 percent. This means that if 100 watts reaches it, 98.67 watts will be radiated. 1.33 watts are lost as heat in the ground due to the antenna not being sufficiently removed from ground.

When this same antenna is used on 75 meters, a situation many hams consider totally impractical, the radiation efficiency decreases to 95 percent. If 100 watts is applied to the antenna, 95 watts gets radiated. Is that excessive loss? It's .22 dB or about one twenty seventh of an S unit - or about nine thousanths of an inch on your S meter! This same antenna, used on 1.9 megahertz, a situation many hams consider absolutely impossible, heretical and insane, will have an efficiency of 86 percent. If 100 watts is applied to the antenna, 86 watts will be radiated. We lose 14 watts. How serious is this?

lthough the use of a 40 meter dipole on 75 meter is a no brainer, the use of a 40 meter dipole on 160 is beginning to stretch things a bit. We can expect some degradation but how serious will it be?

The loss of the 14 watts is .66 dB. There will be additional loss in a typically 60 foot long 600 ohm feedline due to a very high SWR. The SWR will be a whopping 4000:1 at the antenna and 1000:1 at the transmitter. Total loss, including antenna loss, line loss and typical tuner loss will be about 9 dB. This represents one and one half S units. If you are listening to two signals, one with a signal strength of S9+9 and the other at S9 can you tell the difference? How much difference can you discern? Is one signal readable and the other not? Or, if you are listening to a signal from a station using a full size 160 meter dipole and the signal is S9 the signal from the same location using the 40 meter antenna will be S7 and a half. Let's call it an S7 signal just to be on the safe side. Is that S7 signal a readable signal? You can carry on an awful lot of QSO's with an S7 signal strength. Remember, this is with a 68 foot dipole on 160 meters compared to a full sizer at 270 feet.

The results using this antenna on 75 meters is so good that there is no discernible difference worth discussing.

The vast majority of hams will not, under any circumstances whatsoever, attempt to use their 68 foot dipoles on 75 meters. Yet many of these same hams have no qualms about using a 12 foot mobile whip on this band. Go figure.

Just how short can we go? It all depends. It depends on how much you are willing to sacrifice in efficiency. The shorter you make an antenna the less efficient it will be. It is a gradual, sliding curve. There is no sharp line denoting a go no-go boundary.

Baluns

Baluns are not normally a part of the all band antenna system we have been discussing. However, in recent times, baluns are being incorporated as part of an antenna system by more and more hams. Why are baluns used? Because many hams think that they perform a matching function. They also think that a balun prevents radiation from coaxial feedlines.

Many hams think that a balun will force a match to 50 ohms from any antenna impedance. That is why they use impedance transforming baluns. A balun will transform an antenna impedance but not necessarily to 50 ohms. It all depends on the electrical characteristics of the balun and the feedpoint impedance of the antenna.

There are, basically, two types of baluns: voltage baluns and current baluns. Voltage transforming baluns are notoriously lossy. Most commercially available transforming baluns are voltage baluns. Under many circumstances, transforming baluns do not transform impedances according to their specified ratios. They are also prone to torroid core saturation which causes distortion of the radiated wave. Distortion of the radiated wave manifests itself as harmonic radiation. This is bad.

Many hams think that a balun will completely eliminate radiation from their coaxial feedlines. It will do so only if the line is exactly symmetrical to the antenna and surroundings, a situation, as explained before hardly ever achieved in practice. At best they will reduce radiation from the line but don't look for complete cancellation.

A balun will equalize the currents in both halves of a dipole provided it is current balun. A voltage type balun does not do such a good job at this as a current balun.

Many hams think a transformer balun does indeed work as they intended because their SWR went down when they put one in. This is possible but only over a short span of frequencies in a one band antenna. More realistically it is more probable that loss has been introduced into the system. Loss anywhere always makes the SWR read lower.

Everything considered, it is doubtful that baluns provide any worthwhile improvement in the average HF antenna installation as far as radiation efficiency is concerned. They should definitely be used with directional antennas such as are used in the VHF and UHF bands however.

Another place where baluns can be profitably used is on the input side of an antenna tuner - not at the output side where most manufacturers place them . Why do they do this? I do not know. I know of no manufacturer that has ever justified a design of this type on a technical basis.

A Few Words on the Antenna Book

I assume most hams are familiar with the ARRL Antenna Book but not necessarily with any of the other standard texts on the subject of antennas. Therefore these few remarks apply specifically to the ARRL book.

It is extremely important that we not read anything into the book that is not there just as it is equally important to heed what it does say. Consider this sentence that occurs under Antenna Fundamentals, page 2-1, 16th edition: '.....the current flowing in the antenna is largest, and the radiation therefore greatest, when the antenna is resonant.' It is careless interpretation of sentences such as this one that is one of the causes for so much of the mis-understanding regarding antennas.

The thought process that results in misinterpretation is as follows: 'Current is largest in a resonant antenna. The half wave antenna is a resonant antenna. Therefore maximum current flows in and maximum radiation occurs in the half wave antenna.' The error is in assuming that the half wave antenna is the resonant antenna being referred to. This is an unwarranted assumption. The sentence does not mention nor does it refer to the half wave antenna, The term 'resonance' when applied to distributed circuits, of which an antenna is but one example, is the absence of reactance. This is verified by the sentence immediately preceding the one just quoted. It says, 'In any circuit that contains both resistance and reactance, the largest current flows (again, for a given amount of power) when the reactance is "tuned out" - in other words, when the circuit is made resonant at the operating frequency.'

This clearly says that an antenna is resonant when the reactance is eliminated. This is exactly what a tuner does when used with a random length wire. When the reactance is canceled, whether by pruning the wire or by the use of a tuner, the antenna is made resonant and current is maximized compared to the current that flows before the reactance is eliminated.

That an antenna can be made resonant by merely canceling the reactance is verified again by the information provided in the next quotation.

This information appears under Short Antennas, page 2-42. 'It is a mistake to assume that there is anything sacred (in effectiveness, at least) in using a resonant antenna .....at other lengths .....the impedance looking into the terminals of the antenna contains reactance as well as resistance. The reactance presents no problem, because it can be "tuned out". The antenna system can thereby be resonated, even though the antenna itself is not resonant. The purpose of resonating either the antenna or the system as a whole is simply to allow power to be fed to the antenna easily.'

At the risk of redundancy, let me summarize what this means. It is clear from the context that the term 'resonant' in the quotations do not refer exclusively to a halfwave length wire but to any wire that has no reactance.

From all of this we see that there are two types of resonant wires: a wire that is physically a half wave long and a wire that is a random length but whose reactance component has been canceled or tuned out. Thus resonance can be achieved by either of two means: physically pruning the wire or electronically tuning it. Whichever method is used, maximum current flows in both wires compared to the current that flows before the wire was prunned or the reactance tuned out. Note once again that it does NOT say that a half wave long wire has maximum current compared to any other length. And it does NOT say that the half wave wire is the better radiator.

Some Practical Real World Results

As I said at the beginning of these notes, hams have been exposed to this sort of information for many many years and the majority still refuse, judging from their on-the-air comments, to believe most if not all of it.

So I will give it one final try with published documentation that shows what can be accomplished with a 40 meter antenna on 160 meters.

The station W6WQC was first place, Low power category, Los Angeles section, in the 1992 160 meter contest. This station was second place in the Santa Barbara section in the years 1993, 1994, 1995, 1999 and first place in 2000 and first place in the 160 meter contest from the Los Angeles section in 2004. Lest you think that there is something special about the antenna that is optimized for 160 meters, I was first place in the 10 meter contest, Los Angeles, section in 2004. These results are easily verified by referring to the QST issues reporting the contest results. This was in competition with stations using full size 160 meter wires.

Conclusion

A random length dipole of reasonable length, not necessarily resonant on any amateur band, can be used on all amateur HF bands and used on any frequency within those bands with acceptable radiating efficiency. It requires the use of a low loss antenna tuner to tune the system to resonance and to provide a 50 ohm load to the transmitter. It requires the use of a low loss transmission line.

The alternative, to approach but not equal, this performance is to erect separate antennas for each band and then solve the problem of bringing all of the feedlines into the shack. Even then, operation will be restricted to a relatively narrow band of frequencies within each band.

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