Tech Note - Theory - 01 Coaxial Cable

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You have a device in your hamshack that is a closed oscillatory circuit, namely your transmitter. We wish to move the radio frequency energy (*RFE*) from the transmitter to an open oscillatory circuit - your antenna - without spilling it all over the place and causing all sorts of unpleasant things to happen.

Until the *RFE* from your transmitter is coupled to and radiated from your antenna, it is of no value.

The device we are going to use to accomplish this transfer of *RFE* is the transmission line. This is how it will take place.

A transmission line is basically a continuation or extension of the closed oscillatory circuit of the transmitter output circuit.

Energy is coupled into the coaxial line when the output impedance of your transmitter and the coaxial line Z_o/Z_c (characteristic or surge impedance) are the same. Energy can be coupled between the two even if the impedances are not the same but at a lower efficiency, however this is another story left to another time. With today's solid state equipment this is usually the case. However there are exceptions.

We now have a situation where *RFE* is being propagated down the inside of the coaxial cable. At the far end we have a load terminating the cable with the same impedance as the coaxial line. The antenna is said to absorb all the *RFE* it receives, actually it radiates almost all of the *RFE* it receives. Because the antenna is an open oscillatory circuit the radiation takes place efficiently and we now have a useful system.

Because of its concentric construction , coaxial cable is blessed with a uniform amplitude response over a wide range of frequencies, as well as a uniform group delay characteristic. (the ability to maintain the phase integrity of wideband signals propagating through it) Additionally it has the ability to completely contain electrostatic and magnetic lines of force, thus preventing losses by transmission line radiation.

The previous is the ideal situation, sounds nice, but in practice may be difficult to achieve under all circumstances, for many factors may effect the results. Now an explanation is in order as to how or why coaxial cable can perform this small miracle!

Coaxial cable is made of two conductors arranged in a "concentric" manner. It is very important that this "concentricity" be maintained uniformly within very close tolerances or the Z_c/Z_o of the line or it will be altered from the desired impedance.

In air filled line, the Z_c/Z_o of the cable is determined by its inside diameter (bore) of the outside conductor, the outside diameter of the inside (centre) conductor, the spacing between conductors and the nature of the dielectric used.

Each unit length of cable is made up of, or possessed of, inductance, capacitance, resistance, to name only three. These and other electrical qualities determine what the Z_c of the line is going to be, and it is expressed mathematically as $Z_c=\sqrt{L/C}$ (See Appendix Item 1).

In more practical terms the formula becomes $Z_c=138 \times \log b/a$; where 138 is a constant and b/a represents the dimensions of the two conductors. Of course we all know what logarithms are!

No math to bore you at this time, I only introduce it to illustrate and provide a relationship between physical and electrical properties of coaxial cable. We will get back to the math when its value becomes more obvious.

I would like to point out that in a properly coupled, installed and terminated line, all of the *RFE* is contained within the confines of the cable. If there is *RFE* on the outside of coaxial cable and it makes its way back to the equipment, some part or all of the installation should be under suspicion and re-examined for possible oversight, and the necessary corrections made.

When coaxial cable is properly installed, it can be a run along side of sensitive RF devices without effecting them. Later we will find out how things become less than ideal.

Copper is used extensively in the electrical as well the electronic industry and coaxial cable is no exception. Copper is plentiful, relatively inexpensive and is possessed of very low resistance per unit length when compared to other conductors.

Copper also has another characteristic which is quite important, especially in radio and or antenna cable construction. Copper has a relatively uniform conductivity characteristic. That stated another way it means a length of copper wire for instance, will conduct all frequencies equally well or at the same rate, whether it is DC, audio, powerline or RFE.

As the frequency of use is increased to the *RFE* level the electrons (current) tend to flow or shift on the surface or skin of the conductor. This is a valuable bit of information and can be taken advantage of as follows.

In all human endeavor, cost is constantly rearing its ugly head so in this instance if we were to take a cheaper but poorer grade of conductor (steel) and giving it a coating of polished copper, a cheaper but good quality RF conductor would result. Sometimes even silver is used in this manner to improve the surface conductivity of a line. By balancing the grade of copper, the thickness of the silver plating etc. a compromise is reached resulting in a superior product at lower cost.

This is why you may find some coaxial cable conductors are silver plated, although they may carry the same generic designation as the plain copper cables. This is a tip off that the manufacturer is trying to build a quality product.

That is one part of our cable defined and described as a good low loss conductor, it should also be reasonably flexible and posses strength. Enlarging the size of the conductors (diameter) will improve the skin effect. For example in the broadcast industry, where large size cables are required due to the high power levels involved, the centre conductor would be made of a thin walled hollow steel tube with a coating of high grade, well polished copper. This will reduce the overall weight, increase the strength, important where very long runs are involved, reduce the cost, produce a larger skin area to handle high power levels, all very desirable features.

In the cables Amateurs may encounter, the centre conductor can be solid or stranded. The stranded cable is used where a high degree of flexibility is required at a barely perceptible level of increased loss of performance. You would hardly notice the difference unless you were feeding your antenna with a thousand metres of coaxial cable. The use of stranded centre conductor is irrelevant, it is mentioned here as from time to time it becomes a contentious issue created by uninformed individuals.

The next part of the coaxial cable is the dielectric. If you look up the word in a dictionary, it is described as a form of insulation. In coaxial cable the dielectric is that material that separates the centre conductor from the coaxial outer conductor. In present day cable it usually takes the form of polyethelene.

The dielectric must posses several characteristics other than being a good insulator. True, it should be a good insulator to begin with especially because of the punishment Hams are likely to inflict on it.

It should also be reasonably flexible without losing its dimensions or shape, impervious to moisture, strong and have a low temperature co-efficient to name a few.

Various materials can be used as a dielectric in coaxial cable but all of the solid ones which are suitable are blessed with the same shortcoming. This is the fact that the dielectric property is not uniform with frequency. The higher the frequency in use the greater the dielectric losses become. That's one of the reasons why the cable sold by the local wireless shack, which has been designed with materials suitable for 11 metre operation and very low power levels is such a poor performer when attempts are made to use it at frequencies above 30 mhz.

Dry air is the best of the most common dielectrics, also the cheapest and through the use of air dielectric quality can be improved. With the choice of a better quality solid dielectric to start, then during the manufacturing process by blowing dry air or nitrogen into the material so that we have a foam like structure, while still maintaining the integrity of strength, flexibility, form factor, crushability, improved insulating/weight mass structure etc., we create a dielectric of superior qualities. In the process we gain another big bonus. The velocity factor is improved. From solid to foam filled we can go from 0.66 to. 82 or better. Compare this with commercial grade air line under pressure with a VF of 0.95 at 10 times the cost. The velocity factor and size of the coaxial cable are a direct indication of the losses that can be expected with a unit length of a particular cable.

This type of dielectric has produced a significant improvement in coaxial cable. This will raise the 3dB loss point of coaxial cable resulting in improved performance, lower losses which are important considerations at VHF - UHF operations. Once again, cable that was designed for 11 metres is not going to cut it at 150 mhz. and up. You have to remember it was made for a specific market that was/is very competitive and price is all important!

A little more information about dielectric properties is in order. How well the material will support the migration of copper molecules between the two conductors. This is usually very low due to the small diameter of the centre conductor and small surface area. This not a serious immediate problem but over a period of time it will manifest itself in the degradation of the cable and if moisture is allowed into the cable the process is speeded up considerably. This degradation results in the Z_c of the cable changing and over time will render the cable unserviceable.

The life span of most inexpensive coaxial cable is in the area of 5 - 15 years depending on how and where it is used and installed. When moisture enters the cable the useful life span can be very short.

TIP #1: when purchasing coaxial cable that you know came from a fresh roll and you don't plan on using it immediately but will be storing it in your basement or garage for an extended period of time seal the ends with candle wax. Let the melted wax drip right into and around the open ends. When you go to use the cable you only have to cut a half inch or so off to get rid of the wax.

I have successfully stored coax with this method over periods of many years. If however you picked up a piece of used cable at a flea market its probably already too late, especially if its been stored in another Ham's basement or garage for a few years.

Next we come to the outer conductor, with fully flexible cable this material is made into a woven shield composed of very fine almost hair like strands. It should be a tight enough weave to produce 95% shielding at a specific frequency usually the same as the 3dB point in its attenuation specs.

Most coax cables are specified at 30 mhz., 100 mhz., 500 mhz., and 1 ghz. as reference points on their respective attenuation scale. It is only common sense that a cable with a weave that has 95% effective shielding at 27 mhz. is going to leak like a colander at 148 mhz. with all the other attendant problems the leaking will create.

It is at this point we start to look for some serious specifications and start to ask some serious questions before we plunk down our dollars at the vendors table.

TIP #2: If the woven outer conductor is silver plated or if you find the cable has two layers of shield or both inner and outer conductors are silver plated or if highly polished copper is used in the cables construction, you now have an indication that the manufacturer was attempting to put some quality into his product. If you find such cable at a flea market take a firm grip on it for you have a superior cable in your hand, but be prepared to pay somewhat more for it than what you would for the run of the mill cable.

TIP #3: If the braid looks discoloured ask the vendor if he is prepared to strip the outer jacket back about a foot. If its still discoloured at this point and the dielectric is not milky white but an off yellowish hue, pass it by.

Its probably old cable or moisture contaminated. Not good! Unless of course you are interested in a leaky dummy load for your HF station. The integrity of the shield must be maintained, the reason being that each and every wire in the braid where it comes in contact with another wire must have absolute positive contact, otherwise the pattern is broken, leakage takes place, losses increase, VSWR increases and all kinds of other undesirable things begin to happen.

Last but not least is the outer jacket of the coaxial cable. This may come in various colours to match the interior decor of the ham shack but contribute nothing to the electrical value of the cable.

It should be made of material that will stand up to abrasion, flexing, weather, sunlight, moisture etc. If it looks pretty but fractures easily when flexed it is of inferior quality and there appears to be no shortage of cables of that type being passed off as low loss cable.

There is a very good plasticizer used in the the manufacture of the PVC jacket that gives the cable all of the good qualities we have mentioned. This plasticizer is carbon. When used in the mix, the jacket is smooth, flexible, stays shinny and outwardly keeps its like-new appearance. This makes it a fast seller at flea markets.

With all the attributes carbon plasticizer has, it has one serious drawback. Carbon is a very good migrator. Combined with high levels of ultra violet radiation from the sun the carbon will migrate from the outer jacket through the shield spaces into the dielectric and over time will change the composition of the dielectric, subsequently changing the $\mathbf{Z_c}$. of the cable. This is strictly indoor cable not subject to UV radiation. The UV radiation will also change the composition of the outer jacket allowing it to crack more readily allowing moisture to enter which will further degrade the coaxial cable. This type of cable should be secured in conduit if used outdoors. An expensive undertaking to say the least.

Fortunately the manufacturers have resolved this UV radiation problem by using another plasticizer but at an added cost. You are all probably familiar with the various designations used for coaxial cable: RG8, RG11, RG213 etc. etc. Look for the designations RG58/CU, RG8/AU RG213/AU etc. on the outer jacket (See Appendix Item 2). This is an indication that firstly (A)U the jacket is of the noncontaminating type and secondly A(U) it contains material that retards the effects of UV radiation (a class II cable). If the cable has only what appears to be house numbers you will need a cable chart from that company to be able to determine if the cable falls into the category you are looking for. Use your own judgment to buy or not to buy. Registered equivalent types I and II will be or should be designated on the outer jacket. By the way, the designation RG8 is no longer a standard designation for cable. It was discontinued about 10 years ago. However there is a lot of cable out there with that designation coming in from off shore. The only specs that type of cable will have is whatever the manufacturer wishes to give it.

The useful life expectancy of cable of type I or II manufacture is increased considerably, especially in areas of high air pollution. Properly installed, sealed and handled, it should be good for 15 - 20 years. It has been found that in areas of high air pollution even the best of cables life expectancy will be reduced so today this is a wide open question. If you live down wind from one of these monsters a good indication is the outward signs on your tower. If it is corroded and rusty or shows signs of attack then your cable which is made of material less sturdy than steel, is probably in poor condition too.

The most important thing to remember is use care during installation. It should be properly supported, no sharp bends, the PVC jacket can get quite hard on a real cold day and should not be stressed under these conditions since its more prone to fracture. Also on a real hot summer day the PVC jacket can get quite pliable and stretch under stress. If you have 60 - 100 feet of cable hanging down the tower and its only supported at the top, its likely to stretch or distort its shape and as its shape changes so does its $\mathbf{Z_c}$.

TIP #4: For cable installation pick a day with low humidity and a comfortable working temperature. After installation, make sure that all connectors are sealed.

Then, you can feel assured there will be no problems involving moisture.

50 OHMS OR WHAT ?

Have you ever wondered why some cable has a $\mathbf{Z_c}$ of 50 ohms and another 75 ohms and still another 90 or 52 ohms? Well so did I. They are all relatively alike, surely there must be a purpose for all these differing impedances. I became curious and to my surprise nothing in the popular literature of the day would shed any light on this question. Even went so far as to contact the manufacturers of the most popularly sold cables but no help there. One answer I got was "well that's the impedance the customer orders". Kind of like the chicken and egg deal.

I resorted to digging into some pretty heavy stuff in textbooks and slowly a picture began to appear which started to remove the mystery.

To begin with, the standard coaxial cable line impedance ($\mathbf{Z_c}$) for RF power transmission in North America is almost exclusively 50 ohms. Why was this value chosen over all the others that seem to be available?

In concentric transmission lines, the energy or electromagnetic wave is propagated through a dielectric medium bounded by two coaxial cylinders. Since current penetration at radio frequencies is quite small (skin effect) approx. 0.01 to 0.001 mm 100 mhz to 1 ghz., petty small! The only real important dimensions of coaxial cable are the diameter (d) of the centre conductor and the bore (D) of the outer conductor.

For coaxial cable with small line losses such as used by Amateurs, the characteristic impedance (**Z_c**) is defined by the formula **$Z_c=\sqrt{L/C}$** this in turn is mathematically reduced to **138.16 X log D/d** divided by the $\sqrt{E}$ (See Appendix Item 3), where 138 is a constant, L and C are the inductance and capacitance per unit length, E is the dielectric constant of the medium between the concentric cylinders. E is 1.0 for air and is the standard against which all other dielectrics are compared.

A representative outer conductor bore values for airline with a one inch diameter centre conductor are as below

30 ohms - 1.65 inches
50 ohms - 2.3 inches
75 ohms - 3.5 inches
100 ohms - 5.3 inches
150 ohms - 12.2 inches

Different impedance values are optimum for different parameters. Maximum power (current) carrying capacity, for instance occurs at a diameter ratio of 1.65 to1 this happens to correspond to 30 ohms **Z_c**. (in the UK, I believe they still have and use cable such as this).

The optimum diameter ratio for voltage breakdown however is 2.7 to1 and this corresponds to an impedance or **Z_c** of 60 ohms. This is still a standard cable in Germany and other European countries.

However power (current) carrying capacity based on breakdown voltage ignores the current (electron) density which is high at low impedances such as 30 ohms. Attenuation due to conductor losses (skin effect) alone is almost 50% higher at 30 ohms **Z_c** than at the minimum attenuation **Z_c** of 77 ohms (diameter ratio of 3.6 to1). This ratio however is limited to only about one half the maximum power of the 30 ohm line. There is a whole lot of compromising going on here governed by the laws of physics. It now became obvious and I would suspect that in the early days (1942 & WW II) what was called microwave power (and today to Amateurs is the 2 metre band) was rather hard to come by and therefore coaxial lines would not be subject to an over abundance of power (watts) or taxed to capacity, so a line that presented low attenuation was the overriding factor which led to the selection of 77 (75) ohms as a standard for CW (radar) transmission. This resulted in a lot of hardware of certain fixed dimensions. Later when low loss dielectric materials were developed that made flexible "microwave" cables possible, the dimensions remained unchanged, to permit mating with existing equipment.

The dielectric constant of polyethylene, which is used almost exclusively as a coaxial cable dielectric whether foamed or solid is 2.3 to1. The impedance of 77 ohm airline is reduced to 51 ohms when filled with polyethelene.

Mathematically **Z_c**=77 divided by the $\sqrt{E}$ (See Appendix Item 4). this becomes 77 / s.r. of 2.3 and results in 50.77 ohms (E is dielectric constant). This 51 ohms is still with us today along with 51.5 52, 53 ohms even though the standard for works of precision as far as most other products made in the modern sense is now an even 50 ohms. Even though minimum attenuation is a desirable factor in signal transmission, equipment with a known amount of attenuation is a valuable tool for precision or laboratory work in test and development.

One of the mystifying characteristics of coaxial cable for the newcomer to Ham-dom (and some old-timers I would suspect) is the velocity of propagation or velocity factor (vf for short) *RFE* travels with the speed of light as it is electromagnetic in nature, or 300 million metres per second. However this holds true only in free space. In a transmission line, factors in the construction of the line will modify this velocity of propagation. The ratio of the speed of *RFE* in a given line to the speed of *RFE* in free space is known as velocity factor (sometimes called vel) This factor is dependent on the characteristics of the dielectric material used for the spacing in the line and / or supporting insulators. Coaxial cable is basically a lowpass medium which accounts for the increased losses with escalating frequency.

If an electrical length is measured on a transmission line, it will be different from a wavelength at the same frequency measured in free space. Because the frequency of *RFE* remains constant whether the wave is traveling in free space or on a conductor the wavelength must change when the velocity of propagation changes.

This is usually one of the cable parameters listed in cable specs and goes hand in hand with the cable attenuation figures. The higher the velocity the lower the attenuation at specific frequencies.

Since its invention more than a hundred years ago by Werner Von Siemans, a German Engineer (1823-1883) Who later became Sir William after becoming a British Subject. He worked on long distance telegraphy for the British Post and Telegraph. Coaxial cable was a solution looking for a problem until video transmission came along in the 1920's. Now lately coax has been rediscovered by the data industry needing a wideband medium which is not too expensive and simple to install by relatively untrained people. When compared to the old twisted pair type of transmission line used in the telephone, audio and data industry, coax is far superior and has practically eliminated the use of twisted pair.

I'm going to wind up the information on coaxial cable with a description of new type of cable that has slowly been accepted by the Ham community. It is commonly known as the poor hams hardline. It has been used by the commercial two way industry for at least 15 years. Mine has been in service for at least that long and its as good as the day it went up.

It is slightly more expensive depending on where and how you buy it, but in any event well worth the investment. I cant even guess at what the life expectancy will be but venture to say it will still be up there after the next wind storm brings the beam down.

It is constructed in the usual coaxial manner, but incorporates methods and material that are both novel and innovative.

Firstly: The centre conductor is made of a larger gauge of well polished copper wire, this is a plus for reasons already covered.

Secondly: The dielectric is a rigid but flexible foam type blown either with dry air or nitrogen, both excellent foaming agents with superior dielectric properties. The velocity factor of this cable is 0.82, right up there with the best. Ideal for 2 metres and 440 and up.

Thirdly: It is double shielded. The first layer of shield is made of what appears to be aluminum foil, but it is not. It is actually a very fine skin of mylar which has been aluminized on the side in contact with the 95% woven tinned braid. Mylar is a strong, flexible, impervious to moisture and an excellent high voltage insulator. The best part of using the mylar is it will completely stop the migration of carbon, copper and aluminum molecules into the dielectric. The PVC jacket has a carbon plasticizer with a UV retardant agent included.

We now have a coaxial cable with a number of desirable characteristics previously unavailable at such a modest cost. In applications where great flexibility (mechanical) is not required it should be the cable of first choice for anyone who is serious about vhf/uhf operation they would be well advised to choose this type of cable. If mechanical flexibility is an issue, this can be made up with pigtails of RG214AU or RG9BU. This cable usually comes with the 9900 series of designations 9913 etc.

Appendix

Item 1

$$Z_c = \sqrt{L/C}$$

$$Z_c = 138 \log \frac{b}{a}$$

Item 2

"RG8U" was Military nomenclature for "RADIO GUIDE Nr. 8 UNIVERSAL"

Item 3

$$Z_c = \sqrt{L/C}$$

$$Z_c = 138.16 \log \frac{D/d}{\sqrt{E}}$$

Item 4

$$Z_c = 77/\sqrt{E}$$

$$Z_c = 77/\sqrt{2.3}$$

$$Z_c = 77/1.56165$$

$$Z_c = 50$$