The common theory for coaxial line which has its basis in a circuit model by Heaviside from the 1880's is at odds with the physics expressed by Einstein and Schelkunoff. Previous articles have shown theoretical results and practical applications from a newer understanding. This article further discusses some of what we've missed, why we've missed it, and why it might matter.

Another Look at Transmission Lines

What's this Article About?

This article is written to provide evidence that our common understanding of some very familiar transmission lines is incorrect and that in practice they do not operate as expected. Although these lines have been used within almost every radio transmission, receiving and communication system for well over a century, the standing theory, common wisdom and practice do not completely match either newer fundamental theories nor our actual experience.

In general, transmission lines are structures used to conduct power from a source at one location to a load which is at another place. The transmission lines that will be considered in this article are common parallel conductor lines such as those used to transport RF or microwave power and energy; they include coaxial cable, balanced line and wire-over-ground. The first two are widely found within amateur radio, the third has historically been used as a basis for understanding balanced lines. Waveguide transmission lines such as hollow rectangular guide are sometimes used for microwave communications within the hobby but are not being addressed.

A drawing of the cross section of each of these can be found in The ARRL Handbook, The ARRL

Antenna Book, almost any undergraduate physics text and is also depicted in Fig. 1.

The common theory and application for these lines will be discussed including the bases for understanding their characteristics. This will be followed by a discussion of the problems with these approaches from both theoretical and practical viewpoints. Finally there will be a discussion of why a more complete view has been overlooked and the practical applications, importance and possible value of recognizing these errors.

What Have We Been Thinking?

Common Understanding

Nowadays coaxial cable, “coax”, may be the most common transmission line found within amateur radio and probably within most wireless communications systems worldwide. Although balanced line is still used in many applications, it was perhaps more common in the the early days of radio and for the most part coax has replaced it.

Even so, coaxial cable was one of the first types of transmission line used. It was found in the undersea cables that first connected England to the European continent and subsequently and famously in August of 1858, the first Atlantic cable that connected Ireland to North America. At this time, no well-developed theory existed and there was controversy about how and why it worked. All of this occurred, well before electric current was understood as a quantized charge in motion. Although the first of these cables was short-lived due to failure, by 1866 an undersea cable was in everyday use even before James Clerk Maxwell published *A Treatise on Electricity and Magnetism* in 1873 and before 1897 when JJ Thompson gave the name “electron” to that first discovered sub-atomic particle. Millikan's oil-drop experiment which demonstrated the quantized charge of the electron didn't occur until 1909, well after these cables had been in daily use for many years.

Transmission Line as a Circuit - The Telegrapher's Equation

The theory that describes these lines did not arise all at once. Although coaxial cable had been put to good use beforehand, what we commonly use today to describe coaxial cable is ascribed to Oliver Heaviside's work in the 1880's[1]. This theory is still found in undergraduate physics texts. It was Heaviside who coined many of the terms we use, including “inductance”. He added it to an earlier transmission line circuit model. His accompanying mathematical model is known as the Telegrapher's Equation and this general description can be found in many physics, engineering and reference books today[2].

The Telegrapher's Equation was an improvement on a previous model by William Thomson (Lord Kelvin). The newer model describes a repeating network of series connected infinitesimal inductances and shunt capacitances together with resistive and conductive elements as shown in Fig.2. The “i” subscript on each component indicates that each is an infinitesimal element.

Together these components describe an infinitesimal segment of a total line length which is made up of an infinite number of identical sections. The characteristics of a uniformly repeating structure of this type can be described using image parameter theory[3].

This theory results in a description of real transmission line providing a characteristic impedance, attenuation and velocity factor . Characteristic impedance, also called “surge impedance”, determines the current which flows when an infinitely long line is driven from a source having the same impedance or when a finite line is terminated with a resistance of this same value. Attenuation is a measure of power lost in transmission within and along a cable. It represents power not delivered to the termination point. Velocity factor is a ratio of velocity of power transmission compared to the speed of light, c.

Coaxial Line

In addition to the arrangement of inner and outer conductors shown in Fig. 1, it is presumed that the circumference of the inside of the outer conductor is significantly less than one wavelength.

Because coax has radial symmetry, the values for the incremental components L_i and C_i of the line used in the Telegrapher's Equation and shown in Fig. 2 can be easily calculated by using only a geometric description along with basic electric and magnetic theory. Fig. 3 develops the inductance per unit length, L_i, from Ampere's law while Fig. 4 develops C_i using only geometry and Gauss' Law.

Fig. 5 uses the L_i's and C_i's derived in Figs. 3-4 to arrive at the familiar parameters for coax, including impedance, velocity factor and attenuation. That impedance is

$$Z_{TEM} = \frac{\sqrt{\frac{\mu}{\epsilon}} \ln\left(\frac{b}{a}\right)}{2\pi} \approx 60 \ln\left(\frac{b}{a}\right) \approx 138 \log_{10}\left(\frac{b}{a}\right) \quad (3)$$

This result is the equation for the impedance of coaxial line commonly accepted worldwide. It's found in almost all college physics texts, engineering reference books, handbooks, Antenna Books and VHF Manuals.

Transmission Line as a Wave Guide

Besides this circuit model, it is also possible to consider the signal propagating along the line as a wave. The governing equations for this also come from image parameter theory and are like those that describe a wave in free space. Using this method, a source of RF at one end, a transmitter, can be understood to produce a plane wave that propagates longitudinally along the line and delivers power to a load at some distant location. For the lossless line operating in a vacuum as shown in Figs. 3-5 the line transmits all of the source power as a wave from one location to another at a determined by the dielectric that separates the inner and outer conductors – in these Figs. that dielectric is a vacuum and the wave travels at the speed of light in free space, c, so the velocity factor is unity.

For our lossless, vacuum case, except for the delay due to the time it takes for the transmitted signal to arrive at the load, the load will receive exactly the same signal it would had there been no space separating it from the transmitter. From this point of view a transmission line is a wave guide that causes the incident wave to emerge at a distant point. This is like what an antenna does in free space except that instead of the transmitted power diverging in an inverse-square manner the wave remains guided within the bounds of the transmission line and the power is delivered to the termination.

Line Impedance Calculation - an Easier Way

Apart from the image parameter methods, it's possible to arrive directly at line impedance by noting that in a perfect line no energy is lost. From the schematic representation and considering the alternating L_i's and C_i's as passing energy along the line toward the load, the energy stored in capacitance can be equated with that stored in the inductance. From the definitions of energy storage in inductance and capacitance

$$\frac{CV^2}{2}=\frac{LI^2}{2}$$

so the same result for line impedance is obtained as before,

$$Z_0=\frac{V}{I}=\sqrt{\frac{L_i}{C_i}}$$

TEM mode

This wave view of energy in a line has parallels with the idea of a plane wave traveling in free space where the electric and magnetic fields are also at right angles to each other and cross-ways or “transverse” to the direction of the propagation. The energy is guided within a line while it diverges in free space but for both situations the electric and magnetic fields are seen as being transverse to the direction of energy flow.

From both the circuit and the wave analyses this transmission is normally described as being in a transverse-electric-magnetic (TEM) mode. The idea of a transmission line mode relates to the type and direction of the fields associated with a wave. As understood for this line, the electric and magnetic fields within the line and resident in the vacuum between the coax conductors are at all times at right angles to each other as well as to the direction of propagation of the wave so these are considered to be TEM lines. Other transmission line types, such as rectangular metal waveguide or optical fiber might support other mode types.

In addition to a mode type, TEM, TE or TM, a mode number is added and expressed as a pair of numbers in a subscript. These numbers describe an order for the type. When the conductors are perfect the wave is transported entirely in the vacuum around the line[4].

Wire-over-ground and Balanced Line

Besides coax, other TEM transmission lines and wave guides are known. Balanced line and wire-over-ground are of particular interest to radio communications, have relatively simple structures and have also been in wide use for more than a century. Balanced line is perhaps second only to coax for popularity in amateur radio stations.

Wire-over-ground can be viewed as the asymmetric form of balanced line. While its applications generally appear less frequently, it can be simpler to analyze than balanced line. Once analyzed, the parameters of wire-over-ground along along with the idea of symmetry across an image plane, shown in Fig. 1b, can be used immediately to understand balanced line as well.

Because wire-over-ground does not have a simple geometrical symmetry like coax, the derivation of the L_i's and C_i's used to model it is more difficult. For it, the electric field lines emanating from the conductor are not the same in all directions. It's not a radially symmetric line. But electrostatic theory can be used to describe these fields so the L_i's and C_i's parameters can still be obtained. These can then be used to provide impedance, attenuation and velocity factor values for balanced line in the same way they were obtained for coax. When this is done, referring to Fig. 1c, the resulting impedance for perfectly conducting wire-over-ground transmission line operating in a vacuum is found to be approximately

$$Z_0 \approx 138 \log\left(4\frac{h}{d}\right), \text{ for } h \gg d$$

Using the symmetry of balanced line, seen in Fig. 1, balanced line can be viewed as “back-to-back” wire-over-ground lines and has precisely twice the impedance which is approximately

$$Z_0 \approx 276 \log\left(2\frac{S}{d}\right), \text{ for } S \gg d$$

For each of these TEM descriptions, when there is no resistance, dielectric or permeable material present, the loss is zero and the velocity factor is unity. Like the one for coax, these equations are also commonly found in text books and references.

Common Practice

During the first part of the 20th century use of balanced line exceeded that of coax. It was found in many commercial HF broadcasting stations where a 600 ohm line impedance was popular. Amateur operators used it as feed line for dipoles and other wire antennas. When amateur activity resumed after the second World War, coaxial cable began to replace it. Although wire antennas were still used, Yagi/Uda antennas, ground mounted verticals and ground-planes became more common than rhombics, vee beams, Windoms and end-fed wires. From HF through UHF, multi-element Yagis were found to be easy to mount and rotate and could conveniently provide considerable forward gain. At HF, the tri-band Yagi became a common fixture in amateur stations. All of these antennas were easily fed by coax, or at least coax in conjunction with a balun.

Coax has also been widely used in instrumentation where its shielding characteristic, flexibility and robustness have made it ideal for interconnecting sub-circuits as well as equipment bays in test and measurement systems. While 50 ohms became a standard for these uses, the use of 75 ohm coax blossomed with the advent of CATV and cable systems. These uses for coax from audio frequencies up to beyond 100 GHz are widely found today.

The success of the theory and application of coax made it a candidate for making precise measurements and even for defining impedance itself. Vector network analyzers (VNAs) are a general class of measuring equipment which can be used to measure the electrical parameters of electronic devices. These are stimulus-response equipment which present a signal or wave to a device-to-be-measured or device-under-test (DUT) and compare it to the signal that is returned by means of reflection from or propagation through it. In order to provide accurate measurements, VNAs often use error correction and a form of calibration prior to measurement of a DUT. Calibration consists of measurement of known devices, called “calibration standards” which makes it possible to account for, and subsequently remove, hardware errors within the measuring equipment itself. The measured results can be viewed several ways but one popular way is through the use of S Parameters. Measuring this way allows the measured values for the DUT to be referred to the standards used to calibrate the VNA and can produce extremely accurate, precise and repeatable measurements. While there are many calibration methods and many types of standards, some of the most popular ones involve using the characteristics of a section of precision transmission line. By relating the exact impedance, attenuation and phase constant of the line to the measurement, very precise DUT measurements can result.

In 1990, the US National Bureau of Standards (now the National Institute of Standards and Technology) considered using the physically measurable properties of precision coax lines and the capacitance per unit length of coax as a means of defining impedance itself[5,6].

Coaxial cable has been tremendously successful. During the 137 years since Heaviside offered his theory for transmission lines, including coaxial cable, both that theory and the practice involving it have served to move technology and science forward. Amateur radio and technology in general have benefited greatly.

Problems with the Common Understanding

With this long history for Heaviside's model, the question might reasonably be asked “What could possibly be wrong?”

In spite of the long-standing acceptance and successful application, of both theory and practice, there are still inconsistencies when comparing with modern physics theory and with what we actually measure and experience. Heaviside's model is at odds with more modern theory and does not precisely agree with our experience. In this section these problems will be discussed and some practical consequences of them will be described.

Wave Impedance and Velocity Limitations

Since Einstein's publication of his theories of relativity a century ago, it has been generally understood that no mass can travel faster than the speed of light in a vacuum, c. In fact mass cannot travel even this fast. Even small masses require increasingly greater energy in order to accelerate them, as their speed increases. This effect can also be described as an increase in mass of an object as velocity increases.

Einstein's theory also provides for the equivalence between energy and mass. From this it is accepted that energy has the same velocity limitations as mass. It is now widely believed that energy cannot be transported at a speed in excess of the speed of light. This limitation is thought to apply to all mass and energy, in any context or situation, anywhere in our universe.

In 1938, Schelkunof, described the radiation impedance of free space, and what he termed the “intrinsic impedance”of any medium[7]. He showed that the relationship between the electric and magnetic intensities of a wave propagating in any medium can be expressed as an impedance in a way that is parallel to the way the ratio of voltage and current describe impedance in a circuit. Because the impedance of a wave in the medium of free space is bounded it sets a maximum for the impedance of any electromagnetic wave.

It is presently widely accepted that a wave in free space propagates at the speed of light, c, and that the impedance of space itself determines this maximum and which for a planar wave is about 377 ohms. Taken together with Einstein's theory, this requires that no wave of any kind, either guided or free,can propagate faster than c or at an impedance greater than that of free space.

But the impedance calculated for a plane wave in coax from Heaviside's Telegrapher's Equation, as derived in Fig. 6, can ***exceed*** *the accepted maximum for a wave in space when the ratio of outer to inner conductor diameters exceeds* $e^{2\pi} \approx 535$. Heaviside's model for coaxial line is therefore inconsistent with the physics expressed by Einstein and Schelkunoff.

Something is incomplete or wrong with one or more of these theories.

What's Really Going On?

At this point the reader may also be asking something like “Why don't Gauss' and Ampères laws applied to coax tell the whole story correctly? If Heaviside's theory is wrong, what's right?” Only a partial answer will be provided, one that generally describes a more complete model for the operation of this common type of line but is not a closed-form solution or even a complete picture. And as fascinating as it is, an answer the second question will not even be attempted.

With the inconsistencies between standing theories noted above, what is needed is another opinion, another way of looking for an answer. Since circuit theory has become suspect it is worth considering the theory around waves. Fortunately some of this has already been done[8]. A very general treatment of propagating waves within cylindrical structures has already been performed. The treatment is general so that the structures considered can be be a “long cylinder of something embedded in a long cylinder of something else”. Candidates include not only coaxial cable but hollow circular metal waveguides and even dielectric guides such as fiber optic cable. The theoretical possibility of two principle modes within these structures has been shown. The two modes that are possible, and it appears that there are only two, are TEM_{00} and TM_{00}, here the “00” subscripts mean “principle mode” and exclude any potential higher order modes such as those that might be supported on coax that has circumference approaching or exceeding a wavelength. TEM has the same meaning already described and TM means “transverse magnetic”. The difference with a TM mode is that the electric field does not have to be at right angles to the direction of the propagation, it can be lying in the direction of propagation. This treatment suggests that to resolve the inconsistencies noted we might look for the presence of a TM_{00} mode in coaxial cable, wire-over-ground and balanced lines.

So the best simple answer may be that in coaxial cable, any coax of any possible impedance, there are *always* two modes present. Coax operates as a hybrid of two simultaneous modes and the amount of each mode present is determined by the length and geometry of the line. The TEM impedance and transmission parameters calculated for coax by Heaviside's equation do not by themselves completely describe coax. For low impedance coax, the TEM_{00} mode is responsible for supporting almost all of the energy transported between source and termination. The TM_{00} mode is also present but has a longitudinal electric field component that is much smaller. It requires only an inner conductor to propagate and is greatly suppressed by close proximity of the outer conductor. It exists as a single conductor transmission line. For the TM_{00} mode to become significant or dominant the cable must be longer than one half-wavelength and its impedances much higher than 50 or 75 ohms. Although runs of coax many wavelengths long are often found in amateur and commercial communications, coax cables of impedance higher than about 100 ohms are quite rare. High impedance coax is more difficult to fabricate and is generally used only in “low capacitance” applications such as connecting the short passive AM radio antenna in a car to the dashboard-mounted receiver. Because coax that is simultaneously many wavelengths long and very high impedance is extremely uncommon, the TM_{00}

mode propagating on it has been unrecognized and difficult to detect.

From another point of view, both of these wave modes are always present but each is also always in some degree of cutoff – neither mode ever supports one hundred percent of the transmitted power. A longer description and explanation along with the results of measurements and computer simulations is available[9]. TEM_{00} mode experiences cut-off due to its geometry, the $\frac{b}{a}$ ratio of outer/inner conductor diameters. TM_{00} modal cut-off is due to the line length. For conductors less than one half wavelength long the mode is not fully initiated.

Heaviside's circuit model only admits the possibility of a TEM mode. The TM mode has no counterpart in conventional circuit theory or schematic representations which use lumped elements. For this reason, it does not appear in traditional analyses.

It can be seen that these explanations have an implication – namely that the *aggregate* impedance of ideal coaxial line due to the two modes must never quite reach the impedance of free space. The impedance is perhaps best thought of in terms of it's inverse, an admittance, which is always the result of the sum of two admittances. One admittance relates to the current involved in supporting the TEM_{00} mode and the other the current in the TM_{00} mode. In a vacuum, the TM_{00} mode impedance is bounded at about 377 ohms so the line never has an admittance lower than 1/377 mhos. In fact, it is always precisely this value. Thus there is a minimum for the aggregate admittance for the two modes, bounded by the characteristics of free space. The aggregate impedance of coax of any impedance is always less than that of free space. “Coax” in a vacuum with an infinite geometry, having an outer conductor that is an infinite number of center conductor diameters removed from that center, *must* have an aggregate impedance of no more than 377 ohms. The approach to this situation creates a single conductor transmission line.

High impedance coax is difficult to make. Aside from the mechanical problem of fabricating very thin center conductors, as the geometry gets very large the impedance only *approaches* 377 ohms. Increasing the geometry by making the center conductor thinner is difficult and has less and less effect on the aggregate impedance as impedance increases. Increasing the outer conductor diameter instead of decreasing the inner diameter eventually results in coax circumference that supports higher order modes and is therefore generally viewed as unsatisfactory.

This is also the reason that long balanced lines of greater than 754 ohms are not possible. In the limit, a very high impedance balanced line becomes parallel but independent TM_{00} lines. Although coaxial lines made with a spiral center conductor, possibly called “delay lines”, may be marketed as having higher impedance, they do not act accordingly once they become long in terms of the wavelength of the supported energy. This is why 400 ohm coax or 800 ohm balanced line is never found in practice. If

Einstein and Schelkunoff theories are to be correct, such lines cannot even be fabricated or exist in our universe.

To get a better understanding for the simultaneous presence of the two modes one might choose either a theoretical or a practical example. Since we find Heaviside's equation and circuit theory not up to the task of describing more than the TEM mode we must turn to other human or computer analyses. The wave model has helped us to look for the TM mode but may seem less tangible than a picture. Toward that end, Fig. 7 shows a computer simulation of the electric field calculated for a length of coax, entering at a hole in a conductive disk on the left, with only the center conductor continuing on to the right. This simulation creates a three dimensional matrix around the entire structure and then uses a finite element analysis to solve Maxwell's equations for all of the three dimensional space within it. The example structure in Fig. 7 has two identical ports connected by a single conductor. It can be thought of as a transition between conventional 50 ohm coax and a “coax” which has its outer conductor removed to a very large distance. The form of the representation in Fig. 7 shows one of those ports and a segment of single conductor continuing on. It only presents the electric field in a plane intersecting the central conductor, it's presented as a two dimensional plot, the strength of the field is indicated by color while the direction is shown by an arrow. Near the coax connector, within a few ten's of conductor diameters where the ground plane is acting as a sort of stand-in for the absent coax outer conductor, the electric field lines seem to all extend from the line back to the plane. They produce current in that plane which is returned to the outer conductor of the coax coming in from the left. But away from the port and disk and toward the center and right sides of the plot the field lines follow a path directly away from the conductor and then curve back down and terminate back on it at another location. In this region the structure supports a longitudinal electric field component. Adjacent to the region where the conductor current is maximum and the voltage on the line is minimum these field lines are entirely longitudinal. This pattern moves along as the wave propagates and repeats every half wavelength along the line. The electric field associated with this section of the line is no longer transverse but is part of a propagating, “traveling” wave along the single center conductor. All of these field lines are associated with the TM mode and this is a single conductor transmission line. In this particular example, there is a standing wave on the line, indicated by varying e-field envelope magnitudes, which is due to reflection from the second port. This reflection occurs because the simple conductive disk does not optimally convert from the lower impedance TEM wave in the coax to the higher impedance TM wave on the single conductor. As a result there is both a reflection and radiation in the vicinity of each port.

An animation that shows the electric field strength represented in color but without field direction, while the wave moves along a SWTL between two simple conical structures can be found at http://www.sonic.net/~n6gn/animation.html.

Another question that may arise is “How can a single wire hooked to a connector mounted on a ground plane *not* be an antenna, it has no shield, why doesn't it radiate? To answer this, consider coax cable and the reason it doesn't radiate. The lack of radiation, that is, the lack of any "disturbance" in regions far from the coax, is not due to the outer conductor somehow magically holding at bay the basic physical effects of an accelerating charge. The conductor isn't that kind of barrier. Rather, *the coax outer conductor in the TEM mode is a region where a reverse current, equal to the center conductor current flows.* It is symmetry rather than some special property of the outer conductor material that keeps there from being any detectable signal in the far field, beyond the coax. Coax shields because of symmetry not because it's outer conductor is an impenetrable wall. This can perhaps be appreciated more easily by considering balanced line. In that case, the parallel conductor doesn't wrap itself entirely around the other, potentially giving the illusion of a barrier. The common explanation for non-radiation is that as long as the lines are close together, when the reverse current is equal to the forward current the result in the far field, way off to the side of the balanced line, is that the effects of the two currents sum to zero and cancel. This is both the explanation for the lack of radiation from balanced line and the basis of the admonition in practical handbooks to not run balanced line too close to other material. Standoff insulators are often used as supports for long runs of balanced lines to avoid this.

The TM region shown in Fig. 7 also does not radiate because there is symmetry. But unlike the TEM case where the symmetry is provided by a returning ground current, here there is symmetry along the conductor. For every longitudinal electric field line there is a twin that points in the opposite direction. In any region many conductor diameters' away from the TEM structure and with no other material in the space adjacent to the line, all of these field lines cancel, there is no far field and no radiation, there is only a propagating TM wave along the conductor.

Why Hasn't This Been Noticed Before Now?

At this point another question might arise, something like "If this is such a fundamental inconsistency, why hasn't anyone noticed before now?". This question may be even more interesting than exploring the theory and applications that result from a changed view of transmissions lines. The search for a good answer can lead into entirely unexpected areas. For the moment though, these will not be explored.

There may be several reasons this inconsistency hasn't been noticed previously, but a major one is that it wasn't expected. The great success of Heaviside's model has kept anyone from noticing.

Another reason may be that when someone did notice that there were unresolved "fundamental difficulties" with capacitance (Richard Feynman), inductance or lumped element circuit models[10], these were ignored.

When propagation along a single conductor was noticed, it was attributed to another cause. In 1950 Georg Goubau presented a paper in which he described a single wire transmission line, however, he erroneously premised this invention on the necessity for slowing the wave using special conditioning of the conductor in order to avoid radiation[11]. It was not recognized as a TM mode having symmetric longitudinal electric field. This error has been promulgated in engineering courses, reference books, handbooks and in a QST article[12] since that time.

Yet another reason it's been missed, perhaps the best one, is that for practical coaxial lines, below about 125 ohms impedance and for lines that are short compared to a wavelength, the error is extremely small. Coaxial line is *almost* entirely TEM at 50 or 75 ohms and Heaviside's theory describes it well. Coax is generally considered “improved” when it is fabricated in a way that produces low attenuation at high frequencies at the same time it supports high transmitter power. Large center conductor size enhances both of these attributes and to a lesser degree large outer conductor diameter does as well. Practical considerations tend to favor lower impedance coax. The value of 50 ohms became a standard as a compromise between best power handling capability and lowest attenuation for coax constructed from copper. At 50 ohms impedance, the TM mode in coax is almost entirely suppressed.

In the early 1980's during the development of the Hewlett-Packard HP8510, the first fully integrated, error-correcting VNA, precision air-dielectric coaxial lines were measured very carefully. At its inception, this equipment was perhaps the most accurate of its kind in the world. At that time an anomaly was noted for 15 cm long precision “air lines” in the vicinity of 2 GHz where their electrical and physical length becomes one wavelength. It was noticed that the measured impedance for these lines was slightly lower above 1-2 GHz than it was at VHF and below and that there was an interesting slope versus frequency to the precise value. At the time, the entirety of this very small difference in impedance, a small fraction of an ohm, was attributed to effective diameter variation of the coaxial conductors due to skin effect[13]. By design, in coax, VNAs *presume* a TEM measurement plane and the error correction processes attempts to remove any components that don't meet that presumption. The air dielectric lines being measured were also *presumed* to match Heaviside's model and to be solely TEM.

In the past, longer, higher impedance lines have been more common than they are today. The early commercial radio sites of Marconi, RCA and GE often used 600 ohm ladder line to feed large wire arrays. On occasion, these lines were longer than one half wavelength. Although measurement equipment was perhaps not as precise then as now, older texts describing engineering and practices for these feed lines mention an “end effect” (not to be confused with the term applied to the shortening of antennas having thick conductors) for these lines[14]. But even at these higher impedances the deviation from theory could be absorbed by transmitter matching networks and was not recognized as an underlying characteristic of the transmission line itself.

Applications – Theory and Practice

Some practical examples of TM_{00} mode lines as well as the application of this newer model, this new theory, have already been published in QEX and elsewhere. The line has been labeled “surface wave transmission line” (SWTL) and a simple way to build one that exhibits much lower loss than even the best coax has been provided. Because it has an impedance of 377 ohms, much higher than coax, currents are smaller and ohmic losses are much less than for coax. Ways to apply this newer theory to that of antennas and also a way to build a very broad band antenna using SWTL techniques have been shown[15,16,17].

Photo 8 shows an application of a SWTL that was used to feed a high altitude balloon-supported 2m antenna to provide very significant signal increase and DX. This photograph shows a balloon-aerostat that supported a SWTL-to-balanced line adapter integrated with a 2m "halo" antenna. This arrangement was tethered by a single .32 mm diameter copper wire that also operated as the SWTL. A flared horn SWTL adapter was mounted at the ground end. An additional safety tether made from dental floss was also fitted. By simply letting out or reeling in the tethers, the antenna could be allowed to rise to whatever elevation was desired. Comparisons of signal/noise ratio at WSPR spotting stations up to 140 km distant from this SWTL-fed antenna at an altitude of about 50 meters with a ground mounted four-element Yagi at about 7 meters elevation showed on the order of 25 dB advantage in spite of the lower gain of the halo. Attenuation for this SWTL at 2m was under 1 dB although the simple adapters contributed almost 4 dB of additional loss.

As radio amateurs, our interactions with antennas may be where we encounter this mode most often but it may be helpful to consider additional methods and areas where the effects of the TM_{00} mode can be consequential and useful. To do this, it is useful to think about how we access the mode.

In order to "connect to" and observe the TM_{00} mode we usually approach from a TEM starting point. Our radios and measuring equipment couple to it by way of some kind of connection in "non-free space". Our access uses dielectric or conductors, permeable matter or lossy elements. We must interact with the wave by way of some kind of material. But any material distort the fields and, at least to some degree, cause the TM_{00} mode to be altered or diminished. Our connection to the mode must be through a sort of adapter, a transition. It may be a coax-to-waveguide adapter since the mode is a wave and coax is a convenient common line type. In other articles, I've called these structures "launchers" since they serve to launch the wave onto the single conductor that supports the mode. See the referenced articles for information on how to construct a simple very low attenuation SWTL.

The launcher can be thought of as having two functions. One is to convert a lower impedance to that of free space. Typically this might be a 50 to 377 ohm conversion. The second function is to convert the TEM component of the hybrid wave that has a transverse electric field, to the TM component that has longitudinal components. To minimize radiation, this second part needs to be done in a manner that minimizes longitudinal asymmetry. The ground plane shown in Fig. 7 does act as a launcher, but not as an ideal one. At the coax end on the left, the lines returning from the center conductor to the plane, within the first twenty or so conductor diameters of the plane, have no symmetric counterparts along the line. This means that unlike the longitudinal lines well away from the plane, they produce radiation in the far field. For this reason, Even a perfect launcher connected to a line terminated by a distant, planar short at right angles to the line does not receive back as reflection all of the incident power. The short does not act as a perfect mirror, as it might for TEM mode, so the returning wave is attenuated from the incident one because there is radiation in the vicinity of the short. The effect of this region of radiation is also visible in models of antennas described elsewhere. A simple monopole or dipole effectively has an image plane located at its feed point. A previous QEX article has shown this radiation from the feed point and its contribution to the far-field pattern[18].

This problem of the associated TEM mode interfering with access to the TM mode also occurs within computer analysis. Even 3D solvers which are able to support and describe a three dimensional structure through complete solution of Maxwell's equations generally have access "ports" which serve to connect a stimulus and allow measurement of a response. For analysis, these connection points are considered to be from a TEM transmission line such that no electric field lines may cross the boundary and terminate outside of the structure being modeled. For this reason, even computer modeling of TM structures must be done with care if precise results are to be obtained. Essentially, a launcher must be included as part of any structure to be analyzed in much the same way as one must be included in any real application.

This connection point, necessary as it is, always complicates our ability to view the mode and manipulate it. But looking through and beyond it, the effects of the TM_{00} mode can be seen in some common areas. Simple antennas have already been mentioned but there are other places familiar to amateurs as well. Among them are the general class of what are called "parasitics" in engineering practice. Common wisdom for construction of VHF or higher circuit cautions a builder to "keep the leads short" and "avoid stray capacitance". This admonition can be understood as a way to avoid the effects of circuit attributes that are not described by a circuit model. These are an observed behavior that is not explained by a model. They go with the real world, and can be a sign that something is not quite right with our theory. Sometimes these effects can be understood by adding an additional element e.g. a parasitic lumped capacitance may suitably represent the effect. Other times this is not the case, for example where mono-block SMD capacitors or small value inductors[19] act as transmission lines. Lumped element models do not always adequately represent or describe our experience in the real world.

Very high impedance transmission lines cannot be easily constructed. Their impedance is always bounded and limited by the characteristics of space itself. This also applies to physically small structures operating at short wavelengths. One device that is sometimes used on a test bench is the active probe. This is usually a small contact connected to a very high impedance, low capacitance amplifier configured to drive the low impedance input of a measuring instrument such as a spectrum analyzer, network analyses or oscilloscope. Even with very small geometry semiconductor amplifiers which have high impedance inputs, such as sub-micron FET devices, these probes have an upper frequency limit. It is not possible to achieve and maintain high impedance at all wavelengths with any design. The limitation is due to the characteristics of space and the presence of a propagating TM_{00} mode which siphons current away from the point to be measured.

The active probe application has a lot in common with active antennas that are often used for amateur ELF, LF and MF operation. These can be created by using a very short antenna with a very high impedance, high resistance and low input capacitance, preamplifier. But even for low frequency uses, space itself can limit the input impedance. The resistive part of the antenna is always in shunt with capacitance which provides a path to ground that limits the signal voltage appearing at the preamp.

Additional information and examples of amateur radio applications of SWTL can be found at http://www.sonic.net/~n6gn.

Dimensionality

When Heaviside sought to describe transmission lines, he used elementals made from available components, C, R, G along with the additional L which he added to produce a better model, a theory, in order to describe a structure that was in character different from those elementals he used. A transmission line by its very definition exists in multi-dimensional space. Today we would say it exists in space-time. Real transmission lines have a cross sectional area as well as a length. They occupy a volume and rest in space-time that exhibits relativistic properties. The definitions of the elements of inductance, capacitance, resistance and conductance did not originally and do not now possess those same dimensional, spacial or temporal qualities. They are approximations, representations or models that *do not actually exist* in our space-time. They are extremely familiar to radio amateurs as well as electronic engineers and have been a great aid in making representations of circuits and devices. Their use has allowed us to draw our schematics on flat sheets of paper. But by their derivation these don't provide everything needed to build a complete description of any real structure. When we say to ourselves “Capacitors are those things that have capacitance.” or “Inductors are those things that have inductance.” we are confusing a representation, a description, a theory with a different real, tangible thing.

With transmission lines our most complete understanding, whether from theory or measurement, comes from contexts that support more dimensions than do the elemental models with which we are so familiar. The TM wave is clearly visible in both measurements and computer models that fully solve the Maxwell/Heaviside equations but they do not show up at all in Heaviside's limited circuit model. Even for measurement, the structures we build or use to access non-TEM waves must have a longitudinal as well as a transverse function in order to properly couple and those waves to become apparent. These structures must be three dimensional.

Why Else Might This Matter?

For many of the transmission lines we use in amateur radio, particularly low impedance transmission lines and lines that are short compared to a half wavelength, the deviation from Heaviside's theory is very, very small. But small discrepancies in existing theory can be a pointer to a need for a newer model and this can in turn foster better understanding of known applications as well as suggest new and better theory and application. Sometimes these small deviations have great consequence.

When Einstein proposed his theories of relativity, a famous evidence of their validity was in a prediction of the orbit of Mercury around the sun. The classical physics at the time was Newton's law of gravitation which, as developed from work by Copernicus and Kepler, provided an excellent explanation and description of the orbits of the planets. But Einstein's theory proposed that the previous predictions would be found to be slightly in error. He suggested that the the orbit of Mercury would not be exactly as predicted by Newtonian mechanics but that the perihelion of Mercury's orbit of the Sun should occur about 43 arc-seconds different from what Newton's theory predicted. When Mercury's orbit was carefully measured Einstein's theory was tested and confirmed. Newtonian mechanics was shown to be inconsistent with the measurement. It was a very small difference but the “fix” required not a simple adjustment to Newton's theory but a completely different view of the gravitational force and of the universe – one in which space-time is warped by the presence of mass.

It is worth noting that the forms of Newton's law of gravitation and Coulomb's equation for charges are identical. The coefficients, the gravitational constant for Newton's law and permittivity for Coulomb's equation, are different but each has a product in the numerator and a distance squared in the denominator. Each of these laws fails upon observation while at the same time the supporting mathematics for each of these becomes undefined at a radius of zero. From observation we do not find that either two masses or two unlike charges completely collapse upon themselves as Newton or Coulomb's “laws” would predict, with the possible exception of black holes which can't actually be directly observed. Additionally, Coulomb's law does not include any mention of the mass associated with the charges being considered. Even though we see the gravitational force to be immensely smaller than the electric force for the charges we call “electrons”, and so any such error compared to Coulomb's equation for force due to charge is small to the extreme, we believe that charge and mass are inseparable. There are *still* errors in our models and our theories!

Summary

This article has presented evidence of theory, simulation, practice and measurement supporting a view for TEM transmission line that is different from what has long been commonly held as correct. Some readers may come from a theoretical perspective, others from a more practical and each with a different experience. Because of this wide range of evidence and views, it is likely that every reader will have different questions and different views to reconcile. To avoid creating an article that is too lengthy, much of the evidence and support for each of these different aspects has been provided by way of References at the end. I urge the interested reader to access and consider these.

This newer understanding, a newer theory which has made it possible to construct lower attenuation transmission lines, very broad band antennas and which holds promise for improvements to the design of existing antenna types has also been discussed. In addition to these direct benefits, because small things can matter, there are other reasons to believe that a better understanding of transmission lines is important. Considering a transmission line as an agent of action-at-a-distance, that is, the transmission of energy across space-time, further investigation and questioning may be fruitful in very fundamental ways.

While century-old approaches have been and continue to be adequate for many applications, they are inconsistent with newer physics theory and these previous theories do not exactly represent what we actually measure and experience. Accepting this may require re-thinking some previously accepted ‘truths’. Some of the subject of this article may seem almost heretical, the inability of circuit theory to completely describe real circuits, the failure of a familiar equation to accurately describe common transmission line types, the suggestion that the units we use are themselves incomplete and the suggestion that previous “laws” are incorrect may be alarming. But if the reader is wondering a little about things previously taken for granted, things previously certain, then perhaps this article has been a success. Someone, perhaps the American author Mark Twain, is quoted as having quipped, “It ain't so much what we don't know that gets us into trouble, it's what we know for sure that just ain't so.” Maybe this admonition can apply to us as we take another look at transmission lines.

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Captions

Fig. 1 Common types of TEM transmission line

Fig. 2 Circuit model for Heaviside's Telegrapher's Equation

Fig. 3 Derivation of Inductance/length in coax using Ampère's law

Fig. 4 Derivation of capacitance/length in coax using Gauss's law

Fig. 5 Heaviside's equation and line parameters used to derive coax characteristics

Fig. 6 The inconsistency between Einstein/Schelkunoff and Heaviside's models

Fig. 7 Anasoft HFSS structure simulation showing e-field intensity and direction on the leftmost portion of a 2-port device. The device has circular planar ports 200mm in diameter and separated 500mm. At the center of each port a .6mm diameter center conductor of a 5mm section of 50 ohm coaxial line continues without any outer conductor, creating a surface wave transmission line. The entire structure is surrounded by a reflection-less radiation boundary. Stimulation frequency is 1 GHz, corresponding to a wavelength of 30cm.

Near the plane, e-field lines return to the plane from the center conductor. This is a largely TEM region. Further out, e-field lines can be seen beginning and ending on the conductor. This is a TM region.

Photo 1 A foreshortened, light weight TM_{00} SWTL-to-balanced-line adapter, balun and 2m halo antenna constructed from Depron® and metal foil, 59 g (2 oz), supported by a helium balloon and tethered by a .32 mm (.013 inch) diameter copper wire SWTL. In operations at 50 m (164 feet) altitude the total attenuation is about 5 dB. 1 dB is due to the SWTL itself and an additional 2 dB at the bottom and top is due to the adapters. For 2m stations 90-140 km (56-87 miles) distant, this arrangement has produced more than 25 dB increase in signal level relative to a 5 element ground-mounted Yagi at 20'. Please see http://www.sonic.net/~n6gn for additional SWTL measurements and applications.

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