Cable Loading[1]

Factors Affecting Transmission

One of the common methods for transmitting voice currents over great distances is the use of metallic circuits carried in cables. As the length of the cable circuit is extended, certain losses are introduced which tend to impair transmission. If these losses were not nullified or counteracted, telephone communication would be limited to an area with a radius of 20 to 25 miles. These losses are due to:

1. Conductor resistance of the circuit.
2. Capacitance of the circuit.
3. Insulation loss.

All of these factors produce the attenuation loss of the circuit. At first glance, these factors would seem to cause a straight-line loss when the attenuation is plotted for a long length of cable. However, this is not the case. To prove this statement, one must consider each loss separately and all in combination.

Conductor Resistance

Conductor resistance, as previously described, depends upon both the size of the conductors and the length of the circuit. For a given size conductor, the resistance will increase in direct proportion to the length of the conductors. However, the resistance will vary inversely with the cross-sectional area or gauge size of the conductors. That is, for a given length, a 22-gauge wire will have less resistance than a 26-gauge wire.

Capacitance of the Circuit

When two wires are placed adjacent and parallel with each other for a considerable distance there is a capacitance effect between the two wires. The longer the wires, the larger the capacitance. In Figure 1, a battery, a push button, and a meter have been connected to one pair of wires in a cable a mile long. When the push button is closed, the meter indicates that a momentary flow of current has charged the cable pair. The reaction in this case is exactly the same as is created when a capacitor is charged. If the push button is opened and closed several times, there will be no further flow of current through the meter, because the cable pair is fully charged, like a capacitor.

[1] *abc of the Telephone, Vol. 4, Outside Plant, 1987, AVO International Training Institute, www.avointl.com/training*

This characteristic in a cable is called mutual capacitance. Mutual capacitance means the capacitance between one wire of a pair and its mate. The standard factory measurements are made while all of the other wires of the cable are connected to the sheath and to ground. While the exact mutual capacitance is measured in this manner, a field measurement of the capacitance of a cable pair can be made using a portable bridge or capacitance meter.

As previously explained, capacitance is spread over the entire length of the cable circuit. Actually there is a definite capacitance. As the length of the circuit is increased, the capacitance of the circuit is increased. The understanding of this fact is most important in understanding the characteristics of long telephone circuits.

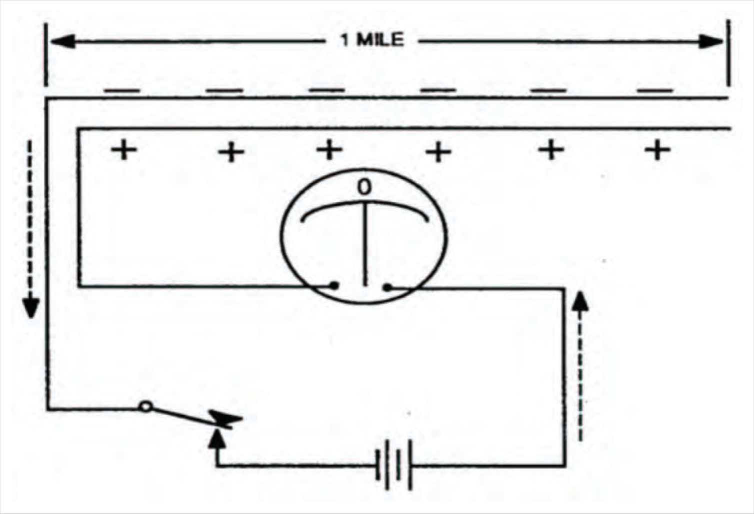

Figure 1: Two wires adjacent and parallel to each other act like a capacitor.

Insulation Loss

To some degree, all materials or substances conduct electricity. Those materials offering the highest resistance to electric current flow are used as insulating agents. A good insulating agent, results in lower capacitance and less insulation loss. To keep insulation loss at a minimum, trees are trimmed along open wire lines and cable splices are dried with dessicant.

Attenuation Losses

A study of the foregoing three factors that combine to cause attenuation losses would form a straight-line curve when plotted on a graph. The graph in Figure 2 shows that the attenuation loss forms a diminishing type curve. This graph has been drawn in accordance with the statement—for every unit of length of a uniform circuit, the attenuation is equal to a definite percentage of the amount of energy entering that particular unit of length. The percentage factor will vary for the different types of cable plant. (See Chapter 1, Vol. 5, abc TeleTraining, Inc. Cable, inside and out, for a more theoretical explanation of attenuation.)

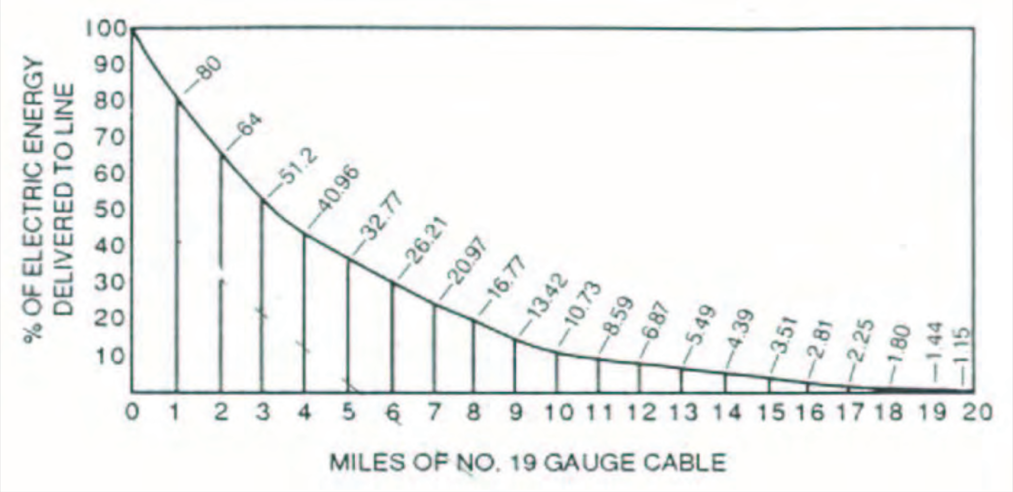

Figure 2: On 19-gauge cable, attenuation loss is about 20% for each mile of length.

Nineteen-gauge cable was used as a basis for the graph in Figure 2. In this instance, the loss factor is approximately 20% for each one-mile unit of length. The loss for the first mile is easily understandable. For any succeeding one-mile section, the loss is approximately 20% of the current value entering that particular section of length. As a result, for the second mile of length, the attenuation loss actually is 20% of 80% of the original current so that the current at that point is only 64.5% of the original current value.

A further study of the graph will reveal that substantial losses are incurred in the first few miles of length. In terms of percent of current loss, the loss of 20% in the first mile is twice as great as the combined loss for the last 10 miles of the cable.

Obviously, when the attenuation of a circuit becomes too great, the signal at the receiving end will be so small that difficulty will be experienced in carrying on a satisfactory conversation. Where attenuation may be too great, steps are taken in the design stages of building the telephone plant to overcome or counteract the losses that are inherent with long transmission circuits.
Line loading is one method by which attenuation can be reduced and transmission improved.

Line Loading

As mentioned previously, in a very long, untreated cable circuit the energy reaching the distant telephone will be insufficient for good hearing. From the energy standpoint, this limitation is peculiar only to long cable circuits. Not only is the volume of energy delivered at the receiver a prime essential in long distance transmission, but also there must be little distortion in the electrical wave.

With these problems in mind, one might suppose that satisfactory transmission over a cable circuit would be limited to a few miles. If longer circuits are desirable, the first solution that might suggest itself would be to increase both the size of the wires used and the spacing between the wires. This would be an expensive method, and more copper per circuit would be required, which would necessitate fewer circuits per cable. More insulation between the separate wires also would increase the size of the cable. This would reduce the number of circuits possible to place in a cable, which would be a disadvantage.

The most practical method of counteracting the attenuation of long cable circuits is line loading. Line loading is merely a means of increasing the inductance per unit length of cable. In Vol. 1, an explanation was given as to how capacitance and inductance can be balanced with a net result that current will flow as if the circuit had neither capacitance nor inductance. Actually, line loading does increase the resistance of a cable circuit. However, the capacitance present in a long cable circuit increases the attenuation to a greater extent than does the physical resistance, thus increasing the physical resistance is justified because capacitance is thereby counteracted. The use of line loading improves transmission efficiency in two ways, namely:

1. By effecting a reduction in circuit attenuation per unit length.
2. By reduced distortion.

By using properly designed loading units, the increase in over-all transmission will more than offset the effects of increased resistance in the circuit.

Loading Analogy

The theory of line loading and how it reduces attenuation, or “dying out,” in a circuit can best be understood by a mechanical analogy of five steps.

1. Line loading reduces the “dying out” effect of a long cable circuit. A light string fastened securely at one end, as shown in Figure 3A, can be compared to the fine wire of a cable circuit. Waves of motion are created in the string by a snapping movement of the hand. As the waves proceed along the light string they tend to die out before reaching the other end.
2. By using a heavier string (Figure 3B) the waves can be propagated further along the string. Even in this case the pattern is lost and distorted before the wave reaches the other end. When the heavier string is used, inertia, analogous to inductance, reduces the attenuation or dying out of the wave. Also, the velocity of the moving wave is lowered, with consequent less distortion of the wave pattern.

3. A large weight or load has been added at midpoint of the light string, as illustrated in Figure 3C. When waves are created in the string they tend to die out in much the same manner as illustrated in Figure 3A, until the weight is reached. At this point they die out altogether. This illustration demonstrates why loading cannot be added to a circuit in a large quantity at one point in the circuit.

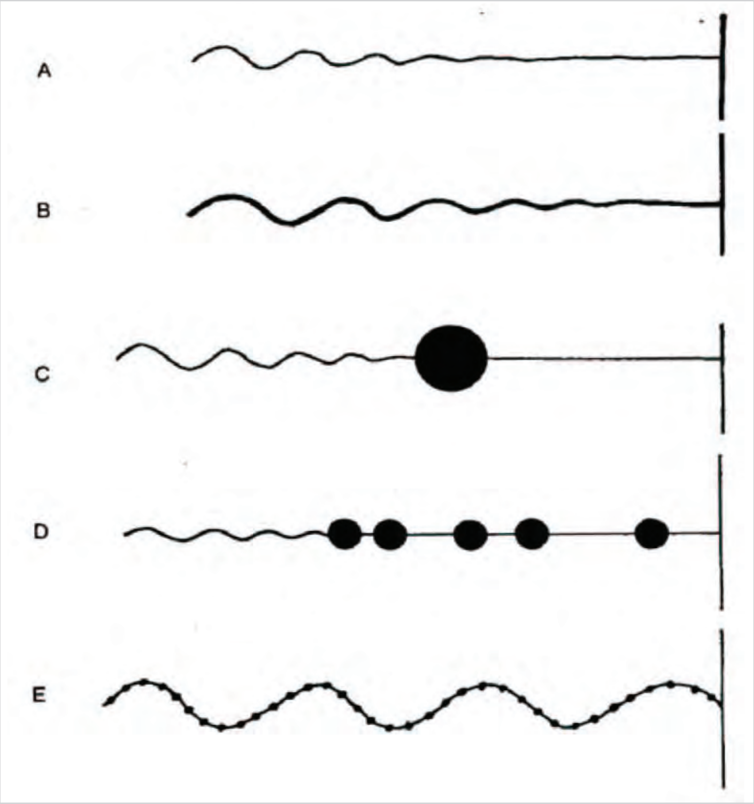

Figure 3: Bead-and-strength analogy shows how loading propagates the voice signal.

4. The large loading weight used in Figure 3C has been broken into smaller pieces in Figure 3D and placed at random over the string. Even though the weights are scattered and reduced in size, the waves will not pass the first weight. Obviously this fact rules out the possibility of adding large amounts of inductance at any point in the long cable circuit.
5. In Figure 3E, the total load has been distributed among several tiny weights equally spaced along the entire length of the string. In fact, there are so many weights that a number appear in each wave length. The wave propagated over the string loaded in this manner has less attenuation and less distortion than when a heavy string was used in Figure 3B.

Loading Practice

Line loading of a circuit is supplied in the form of loading coils inserted in the circuit at regularly spaced intervals as with the small weights on the string. The spacing of the loading coils generally should be accurate to within 2%. In actual practice, this method of adding small amounts of inductance into the circuit at regularly spaced intervals is more effective than attempting to add all the loading at one spot.

Loading is merely lumped inductance inserted at periodic intervals of approximately every 6,000 ft. along the circuit. The exact interval depends upon numerous factors, but always must be small enough to obtain the effect of increased distributed inductance with the accompanying reduction in attenuation.

A loaded circuit actually is a number of sections consisting of series inductances and capacitance. Each section is acted upon by the voltages set up across the capacitance of the preceding section. The result is increased voltage and slightly decreased current. This is the essence of the power transmission line where line losses are overcome by greatly increased voltages.

To summarize, loading a circuit reduces the energy loss, but also further improves transmission by eliminating distortion effects. Loading coils are designed to increase the impedance or self-inductance of a circuit, and in so doing, balance the capacitance of the cable pair.

Requirements of a Loading Coil

A loading coil must meet a number of requirements other than to provide a means of placing inductance in a circuit. These other requirements are:

1. There must be a minimum of resistance in the windings.
2. There must be minimum losses in the core.
3. The inductance created by both windings of the coil must be in perfect balance.

The first requirement is obvious. In as much as the loading coil is placed in series in the circuit, the actual resistance of the coil must be held to the absolute minimum. The loading coil merely adds inductance to the circuit. The loading coil does not add any energy to the circuit. Therefore, the resistance of the circuit must be kept as low as possible.

The action of the magnetic field created by loading coil places inductance in the circuit. An important requirement is that a permeable core be used in the coil in order that a field of the required strength can be created with a minimum number of turns of wire in the coils.

To reduce magnetic losses, a continuous doughnut shaped core is used. The first loading coils had doughnut shaped cores, consisting of a coil with many turns of insulated thread-like wire. A typical loading coil core is made of an alloy which can be magnetized easily, and, equally important, will lose its magnetism immediately when removed from a magnetic field.

A small, compact coil is important for field installations. Loading coils are mounted on spindles which are manufactured in several sizes to hold a few or a great number of coils. These pots are placed in manholes along underground cable runs, or on elevated platforms in overhead construction. When required, individual coils can be placed in a splice.

The third requirement stated that the inductance created by the windings of the loading coil must be in balance. For all practical purposes, the inductance created by the loading coil must be divided accurately into two parts. One half of the inductance is inserted in one wire of talking circuit. The other half of the inductance is inserted in the other wire. In this manner the circuit balance is maintained.

Loading Coil Design

A complete loading coil is shown in Figure 4. Note that the two windings have the same number of turns and are placed in opposite directions around the core. The current flows in opposite directions through the windings. The magnetic field created by both windings will be in the same direction around the core. The magnetic field moving through the core, first in one direction, then in the other when the current reverses, adds the inertia characteristic inductance to the circuit.

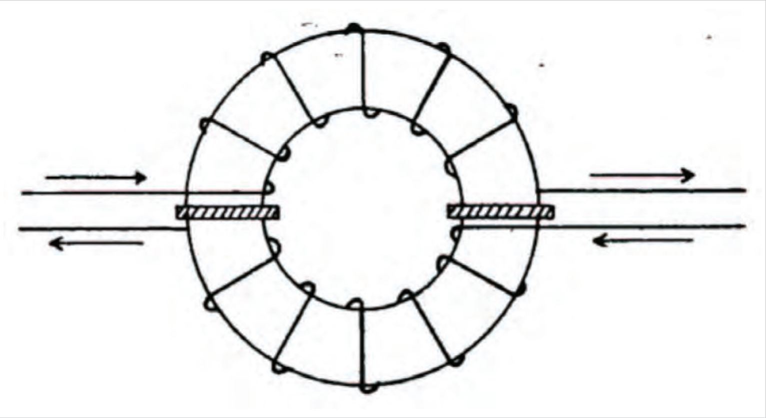

Figure 4: Loading coil design

Typical Loaded Cable Plan

In engineering a plan for cable loading, the distance between the central office and the first distributing point is broken into sections approximately 6,000 ft. Thus, mention of a section would mean 6,000 ft. of cable, and a half section, 3000 ft.

An important requirement in the loading plan is that the spacing of the first coil from the office should be selected at a point where the capacitance of the outside conductors, plus the capacitance of the subscriber multiple and associated cabling within the office, equals the capacitance of a normal half section. To meet this requirement, the first loading point will be located less than 3,000 ft. from the central office.

Spacing of subsequent coils should be as near the recommended 6,000-foot spacing as is practicable. As mentioned previously, trunk cable loading should be held to spacing with not more than 2 percent variation. Subscriber loop loading usually permits a broader latitude in spacing irregularities. Maximum irregularities in spacing for subscriber cables may amount to a plus or minus 500 to 1000 feet, depending on the characteristics of the coil being used.

The end section between the last loading coil and the subscriber station affects the transmission gain obtainable from that particular coil. As a general rule, if the station is less than one-half of a section from the last coil, that coil will cause a loss rather than a gain in transmission. When the end section increases beyond a half section up to approximately three full sections, the gain provided by the last coil increases. However, for maximum transmission gain, the distance between the last coil and the station should not exceed 18,000 ft.

The broad latitude in spacing between the last coil and the subscriber station simplifies the loading of cable serving areas far distant from the central office. Certain complements of the cable can be loaded with a particular point along the route as a loading objective. The last coil is located approximately 3,000 ft. from this point and the variation in end section lengths up to 18,000 ft. will care for the entire area served by that complement.

If areas, located further from the central office are to be served, other complements of the cable would have to be loaded in a pattern conforming to the requirements of a further distant first distributing point objective. Maximum distances between central office and subscriber station should be between 50,000 and 55,000 ft. if satisfactory transmission is to be secured.

In planning a loaded cable installation, the loading of 26 or 24-gauge subscriber loops to avoid the use of 22-gauge loops seldom will prove practical. However, loaded 22-gauge cable very often will be more economical than unloaded 19-gauge cable.

Figure 5 illustrates how loading coils can be spaced in accordance with a 17,050-foot first distributing point objective and still serve subscribers' lines located 27,500 ft. from the central office. While this plan is based on underground cable manhole and duct layouts, similar spacing can be secured by judicious selection of loading points for aerial cable construction.

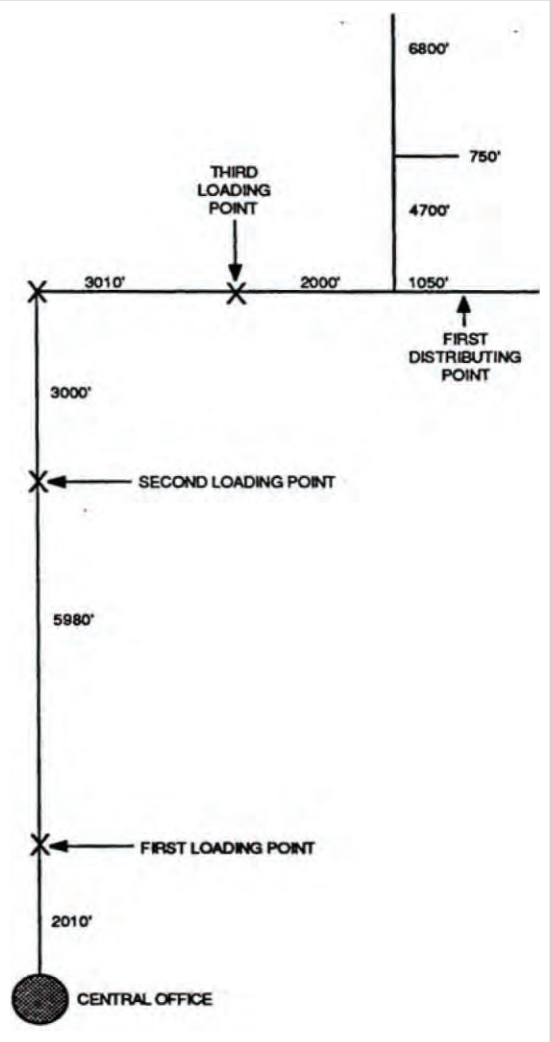

Figure 5: Cable loading plan

In summary, loading of subscriber or trunk cable should be the first consideration when the operating company seeks to reduce transmission loss to areas located a considerable distance from the central office.

Terms of Measurement

A pair of wires has four primary electrical parameters:

- Resistance (symbol "R," measured in ohms)
- Inductance (symbol "L," measured in henries)
- Conductance (symbol "G," measured in mhos)
- Capacitance (symbol "C," measured in farads)

As a practical matter, henries, mhos and farads are much too large for use and, therefore, millihenries, micromhos and microfarads are used for measurement. All increase linearly with length of the pair, so they are usually expressed in terms of size per unit length, commonly the mile. Series resistance and inductance are proportional to the length of both conductors in the pair, so they are given per loop mile.

Resistance, Loop Mile

Series resistance depends on the cross-sectional area of a conductor. Double the area and the resistance is cut in half. The fact that there are two conductors in a loop does not reduce the resistance by doubling the area; the same current flows through both wires, going out on one wire and back on the other. Thus the resistance per loop mile is twice the resistance of a single wire. To get a feel for magnitudes, 24 gauge copper wire is about 271 ohms per loop mile.

Inductance

Series inductance is a complicated function of the size of the wires and the spacing between them. The larger the spacing between the wires or the smaller the diameter, the larger the inductance. In open wire construction, the spacing can be fairly large, but in cable, it is approximately twice the thickness of the insulation. This makes the inductance very small (on the order of 1 millihenry or 1 x 10-3 henries) per loop mile. Even when we multiply the inductance by 2 π times the frequency (say, 1000 Hz) to get its ohmic equivalent, 6.28 ohms is seen to be negligible compared with 271 ohms of resistance.

Conductance, Capacitance

Shunt conductance and capacitance are both functions of the spacing of the wires and the insulating material between them. Air is the best material to minimize both parameters, but other materials must be used in cable design. Leakage conductance at voice frequencies is on the order of 1 micromho (1 x 10 6 mhos) while capacitance is in the neighborhood of 0.08 microfarad (0.08 x 10 farads). Capacitance is lower in open wire lines with their larger spacing, of course. Although it would appear that cable capacitance is negligible compared to conductance, we must once again multiply it by 2 π f to get the proper equivalent. Thus 0.08 microfarads at 1000 Hz has about 502 micromhos of equivalent conductance and swamps the numerical value of G.

Leakage conductance is usually measured in ohms, since this unit is more familiar than the mho. To convert from one to the other, one simply takes the reciprocal. Thus 1 micromho is the equivalent of 1,000,000 ohms, or one megohm. One megohm per mile cannot be maintained under trouble conditions, and low leakage (or high conductance) has many undesirable effects.

The only parameters that have any practical impact on transmission at voice frequencies in cable pairs are series resistance and shunt capacitance. Thus an equivalent circuit such as Figure 6 can be used for studying such lines. In this circuit, resistance and capacitance are shown as discrete circuit elements; actually, both are distributed evenly along the pair. By dividing a given length into a larger number of discrete sections with smaller numerical values, the distributed nature of the line can be approximated to any degree desired.

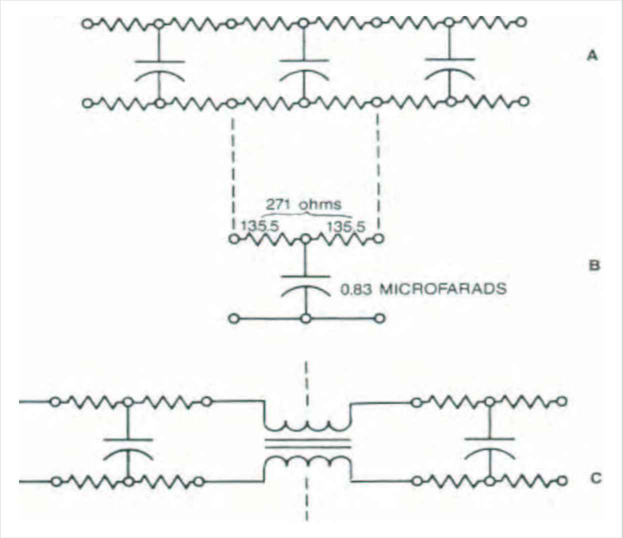

Figure 6: (A) Equivalent circuit of a telephone line. (B) One section of line, with values for one mile of 24-gauge wire. The "T" form simplifies calculations. (C) Leading coil is placed between sections of cable; half of coil is assigned to section on left, and half to section on the right.

The point of all this depends on frequency the sensitivity of capacitors. If a fixed voltage of varying frequency is connected across a capacitor, the current that flows will increase linearly with frequency. This can be seen from the formula for the conductance equivalent of a capacitor: mhos of equivalent conductance = $2 \pi f C$. If conductance exists across the line, some of the signal will be diverted and will not reach the distant end. The higher components of the signal will be diverted more than the lower, and distortion will result.

It also turns out that the velocity of a signal down the line will be frequency dependent as a function of the shunt capacity. Thus higher frequency components will not arrive at the same time as lower frequencies, and additional distortion can be expected.

These problems can be resolved by loading, or inserting inductors in the line, at regular intervals, as described in Chapter 6. The inductors used are small coils that draw no power and do not wear out; thus they offer an economical and efficient way to improve the voice-frequency transmission properties of pairs in a telephone cable.

Loading

Cable pairs shorter than 18,000 feet require no special treatment, but longer loops require loading. Loading is specified in terms of the wire size, the spacing of the coils, and the size of the coils. Thus 19H88 tells us that 19-gauge cable is used, and the spacing of the 88 millihenry coils is 6000 feet. Just as H represents 6000 foot spacings, B and D refer to 3000 and 4500 foot spacings respectively. Other spacings have been used in the past, but the H spacing is most commonly used today

Closer spacing lets the loading coils approximate distributed inductance better, and increases the range over which transmission is improved.

Some submarine cables, where the expense can be justified, are provided with continuous loading by wrapping the conductors with magnetic material; this increases their useful bandwidth into the carrier frequency range. For voice pairs, however, this expense is not required.

Any loading system using discrete coils at regularly spaced intervals has a cut-off frequency; below cutoff, transmission is greatly improved compared to a non-loaded pair, but above it, transmission is rapidly attenuated. The formula given for the cut-off frequency is:

$$f_C = \frac{3.183 \times 10^5}{\sqrt{((L_S + L_P)C)}}$$

where L_S is the loading coil inductance, L_P is the inductance of the cable in the loading section, and C is the capacity of the cable in the loading section. For H-88 loading on cable with 0.083 microfarads of capacity per mile, f_C is 3471 Hz. For B-44 loading on cable with 0.066 microfarads per mile, cutoff is 7786 Hz.

For H spacing, the first loading coil is placed a half-section from the central office, between 2,800 and 2,900 feet from the MDF cable vertical. The remaining loading coils are spaced every 6,000 feet, with the telephone set placed, for best results, no closer than 3,000 feet and no more than 9,000 feet from the last coil.

It is not always possible to locate load coils at the exact point required by theory because of the placement of equipment, natural barriers, etc. Since uniform spacing is important for best results, the following rules have been developed to minimize the effects of adverse spacing.

a. The average loading section length shall be within ± 2% of the standard spacing.
b. Each section length shall be within ± 2% of the average section.
c. The average departure from spacing shall not exceed 0.5% (disregarding signs) of the average section length.

When a choice has to be made, always select a location shorter rather than longer than the ideal length. This allows the short section to be built out electrically. Two types of building out units are available: a building out capacitor (BOC) and a building out lattice (BOL). The first is a small capacitor bridged across the cable pair equal to the capacity of the missing cable length. The second includes a resistor and a capacitor to build out both the resistance and capacity of the missing cable. The BOC units range in size from 6 to 72 nanofarads (6 to 72 x 10^{-9} farads), while the BOL units go from 6 to 92 nanofarads and 5 to 275 ohms. The BOC units are generally used on comparatively short lengths of cable build-out where resistance is of little value. BOL units are used on toll cables of mixed gauges, or load section lengths exceeding about 500 feet.

Theory of Loading

Loading theory is discussed in greater detail in Volumes 7 and 8 of abc TeleTraining's basic series. At this point, a few mathematical hints (which may be skipped at first reading) are offered to provide some insight into loading principles. Starting with a basic formula,

Equation 1:

$$\alpha + j\beta = \sqrt{(R + j\omega L)\,(G + j\omega C)}$$

we can learn a great deal. R, L, G and C are as previously defined; $\omega = 2\pi f$, and j is $\sqrt{-1}$. In the formula, α is the attenuation per mile in nepers; it can be converted to the more familiar decibels by multiplication by 8.686. β is the phase constant in radians per mile, where a radian is ½ π cycles. If we divide radians per second by radians per mile, we get miles per second, or the velocity of the signal on the transmission line:

Equation 2:

$$\text{Velocity} = \omega/\beta$$

Formulas containing complex numbers are hard to handle; Equation 1 is particularly difficult. Thus it may be helpful to start with a simplified example. Assume there are no series or shunt losses, no R or G. This is a good approximation for a transmission line between a radio transmitter and its antenna. Then

Equation 3:

$$\begin{aligned}\alpha + j\beta &= \sqrt{(j\omega L)\,(j\omega C)}\\ &= j\omega\sqrt{(LC)}\end{aligned}$$

For an equation containing complex numbers to hold, the "real" parts must be equal and the "imaginary" parts must be equal at the same time. That is, terms multiplied by j must balance independently of those not multiplied by j. In Equation 3, $\alpha = 0$ since there are no real terms on the right hand side. This tells us that there is no loss (or loss per mile) in a line that has neither R nor G. Further, β is directly proportional to frequency. This says that the velocity (Equation 2), is independent of frequency, and all frequencies entering the line at the same time will leave the distant end together at a somewhat later time. The numerical value of the velocity is $1/\sqrt{(LC)}$ and will be in miles per second if L and C are inductance and capacity per mile.

This is a lot of information from one equation. But to apply the same techniques to a telephone line, where R and C are the only important parameters, the job is a little harder. Equation 1 now becomes

Equation 4:

$$\begin{aligned}\alpha + j\beta &= \sqrt{(R)\,(j\omega C)}\\ &= \sqrt{j\omega RC}\end{aligned}$$

and this equation is much harder to handle. To get rid of the square root, we square both sides to get

Equation 5:

$$\alpha^2 - \beta^2 + 2j\alpha\beta = j\omega RC$$

By equating reals to reals and imaginaries to imaginaries, we see that $\alpha = \beta$ and

Equation 6:

$$\alpha \text{ or } \beta = \sqrt{\frac{\omega RC}{2}} = \sqrt{\pi f\, RC}$$

Equation 6 tells us that attenuation is proportional to the square root of the frequency; that is, if we multiply the frequency by 4, the attenuation per mile is doubled. This shows mathematically what Figure I suggested pictorially. If we look at velocity, we find that it, too, is no longer independent of frequency as in the lossless case, but varies as the square root of the frequency:

Equation 7:

$$\text{Velocity} = \frac{\omega}{\beta} = \frac{2\pi f}{\sqrt{\pi f\, RC}} = \sqrt{f}\sqrt{\frac{4\pi}{RC}}$$

Thus the high frequencies will get to the end of the line faster than the lower frequencies.

To attack this problem, take Equation 1, square both sides without any simplifications, set the real parts equal and the imaginary parts equal, and solve for α and β. Algebra buffs are welcome to give the problem a try. The results are as follows:

Equation 8:

$$\alpha = \sqrt{[1/2]\,[\sqrt{RG + LC\,\omega^2)^2 + (LG - RC)^2\,\omega^2} = (RG - LC\,\omega^2)]}$$

$$\beta = \sqrt{[1/2]\,[\sqrt{RG + LC\,\omega^2)^2 + (LG - RC)^2\,\omega^2} = (RG - LC\,\omega^2)]}$$

A genius, Olive Heaviside, was able to look at these equations and stop the second term under the inside square root sign. If it could be made to go to 0, the square root would be easy to take:

Equation 9:

$$\sqrt{(RG + LC\,\omega^2)^2 + 0} = RG + LC\,\omega^2$$

With Equation 9, α immediately simplifies to RG , and β becomes ω LC . This tells us that loss and velocity will be independent of frequency when LG - RC = 0, and that increasing L will decrease velocity. This condition gives us “distortionless transmission”, and is usually expressed as

Equation 10:

$$\frac{L}{R} = \frac{C}{G}$$

With the typical parameters for 24 gauge cable given above, LIR is much less than C/G. This suggests adding inductance to the line since it would be foolish to make conductance bigger and uneconomical to make R or C smaller beyond a reasonable limit.

To go beyond this point and demonstrate how the value of the loading coil is matched to the coil spacing distance, and to prove the need for spacing accuracy and uniformity, is well beyond the scope of this book. The important thing to remember is that the rules are important if good results are to be obtained and that care should be taken in locating the loading coils and building-out components (when required).

It is also important to remember that loading coils block higher frequencies and must be removed if the pairs in question are to be used for carrier systems or high-speed data. Loading also reduces the velocity of transmission, increasing echo problems on long-haul circuits. The low cost of carrier systems in the toll plant has all but eliminated loaded toll circuits; exchange carrier and remote concentrators may do the same for the exchange plant in the not too distant future.