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TRUNK SERVICE,
COUNTRY BRANCH.

TRANSMISSION LINE CHARACTERISTICS

PREVIOUSLY CP 203

Page.

1. INTRODUCTION.

1.1 Communication signals are transmitted over open wire lines, multi-conductor cables, coaxial cables and also by radio waves. Each method of transmission has its particular applications and all aspects of the route, such as the type of terrain, number of circuits to be "dropped off" at intermediate towns, etc, must be considered before the eventual transmission method is chosen.

1.2 With the exception of radio transmission, all the methods involve the use of metallic conductors which are broadly referred to as transmission lines. Transmission lines are mechanically simple in construction but their electrical behaviour is complex. The metallic conductors exhibit electrical characteristics which have an adverse effect on the quality of the signal being transmitted, and unless adequate compensation is made for these effects, the signal would be distorted and attenuated to such an extent that it would be of unsatisfactory quality at the receiving end of a long line.

1.3 This paper explains in simple terms some of the electrical characteristics of transmission lines, and the basis of the equipment and methods used to enable these lines to transmit signals with acceptable quality.

Issue 1, 1966.

2. TRANSMISSION LINES.

2.1 The three types of transmission lines in general use are:-

(i) Multiconductor cables.
(ii) Aerial or open wire lines.
(iii) Coaxial cables.

2.2 Multi-Conductor Cables used for the transmission of carrier signals have lead sheaths containing paper insulated conductors. Each pair of conductors are twisted together throughout the entire length of the cable, and usually two pairs are combined to form a group of four conductors called a "quad".

Multi-conductor cables are normally used on short carrier routes of up to approximately 70 miles in length. The cables are filled with gas, under pressure, and should a fault occur in the cable sheath, the gas pressure decreases and operates an alarm. Cable conductors are smaller than open wire conductors. This results in a greater signal attenuation, and therefore, a closer spacing of repeaters on cable routes, as compared to open wire routes. Fig. 1 is an example of a multi-conductor cable route of 64 miles, with repeaters spaced at approximately 16 miles.

Multi-conductor Cables are usually classified by:-

(i) The weight in lbs. per mile of single wire.
(ii) The insulation used.
(iii) The formation of the wires within the cable.

For example, a cable containing 20 lb. paper (P) insulated (I) quad (Q) conductors used for trunk (T) service is classified as 20 lb. P.I.Q.T.

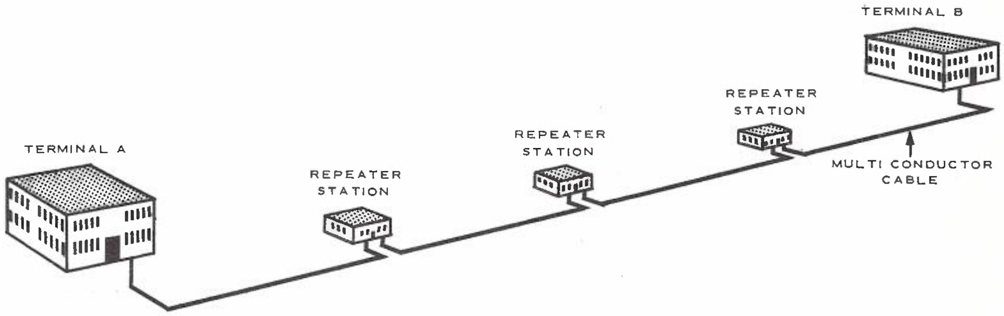


FIG. 1. MULTI-CONDUCTOR CABLE ROUTE.

2.3 Aerial or Open Wire Lines are made from hard drawn copper, cadmium copper alloy or galvanised iron. They are usually classified in terms of:-

(i) The weight in lbs. per mile of single wire.
(ii) The material from which the wires are made.
(iii) The spacing between the line conductors.

For example, a 100 lb., hard drawn copper (H.D.C.) wire line with the conductors spaced 9 inches apart is classified as - 100 lb. H.D.C. - 9" spacing.

Large groups of aerial wires are seldom connected directly to a building; they are terminated on a pole some distance away and then extended to the building by means of a "trunk entrance cable". (Fig. 2). Trunk entrance cables overcome construction and maintenance problems, and the unsightly aspects of aerial lines through the streets of cities and towns situated on the trunk route.

Due to the larger conductors and wider spacing used for aerial lines, repeaters are spaced further apart on aerial routes, as compared to cable routes. Fig. 2 is an example of two terminals connected with 140 miles of aerial transmission line, requiring one repeater station.

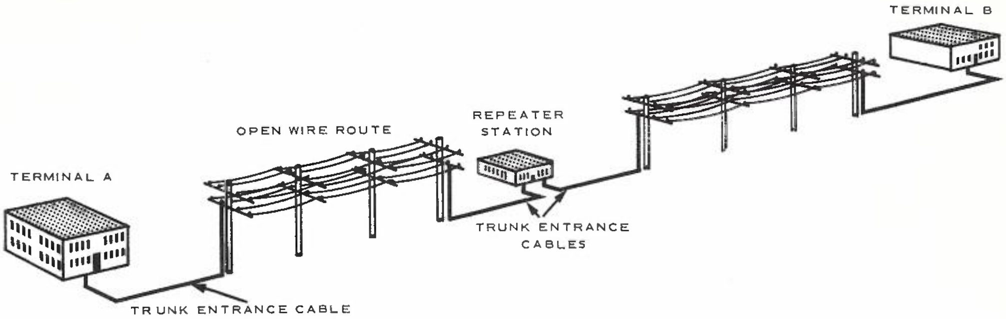


FIG. 2. OPEN WIRE LINE AND TRUNK ENTRANCE CABLES.

2.4 Electromagnetic Field. When signal voltage and current exist on a transmission line, fields or lines of force are set up about the conductors of the line. There are two types of fields, one of which is associated with the voltage and the other with the current.

The field associated with the voltage is called an electrostatic or electric field because it is produced by the potentials which exist between:-

(i) The two line conductors.

(ii) The line conductors and earth.

(iii) The line conductors and nearby lines or objects.

The field associated with the current is the magnetic field produced by the passage of current through the line conductors.

Fig. 3 shows the way in which the electric and magnetic fields orientate themselves between the conductors of a typical two wire transmission line. Both fields usually exist together and are spoken of collectively as the electromagnetic field.

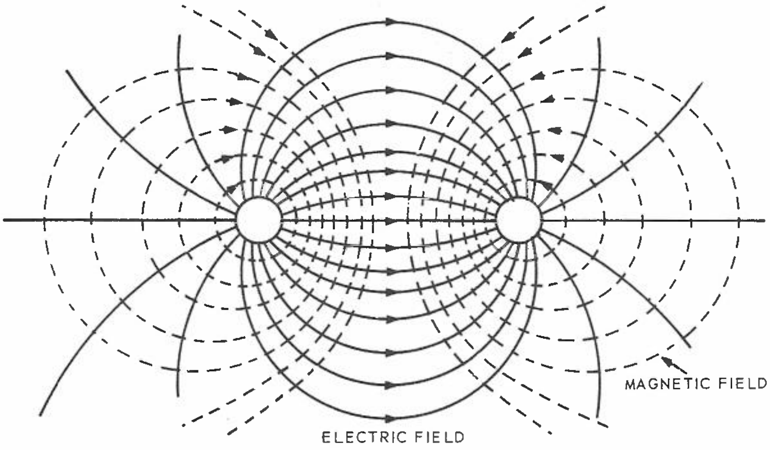


FIG. 3. ELECTROMAGNETIC FIELD.

The electromagnetic field produced by a transmission line has three main effects, all of which increase with frequency.

(i) The fields induce voltages into nearby conductors which may result in interference in the form of crosstalk.

(ii) Since the electromagnetic field contains energy, which is not all returned to the conductor when the fields collapse during each cycle of A.C., a loss of energy occurs.

(iii) The magnetic field cuts the conductor from which it is produced, causing "skin effect".

2.5 Skin Effect. At high frequencies, the current carried by a conductor is not distributed uniformly over the conductor cross-section, as is the case with direct currents, but tends to be concentrated near the surface. This action, termed "skin effect", is shown in Fig. 4 and is caused by the effects of the varying magnetic flux produced by the A.C. in the conductor. The varying flux produces a higher reactance at the conductor centre than at the outer edge of the conductor. This causes a redistribution of the current so that the major portion flows in the part of the conductor which has the least reactance, which is the outer edge.

The higher the frequency, the greater the rate of change of flux, and the more the tendency of the current to flow near the surface of the conductor. Therefore, as the frequency increases, the effective conducting area becomes less, and the effective resistance of the conductor increases. The tendency for the effective resistance of a conductor to rise with frequency is illustrated by the fact that a straight copper conductor 1 millimeter in diameter, with a resistance of 4 ohms to D.C., has an effective resistance of about 40 ohms at 1Mc/s, and 400 ohms at 100Mc/s.

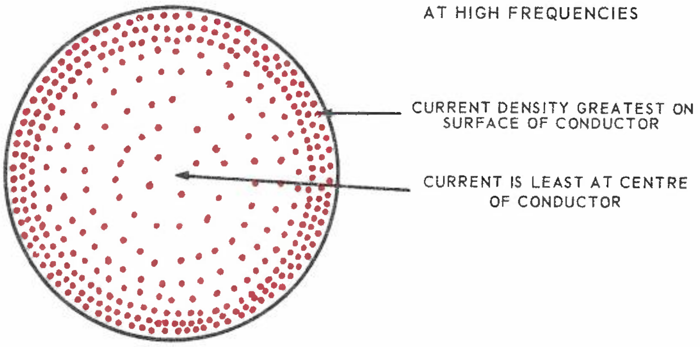


FIG. 4. SKIN EFFECT.

2.6 Coaxial Transmission Line. A coaxial transmission line consists essentially of an inner conductor of copper wire surrounded by an outer copper tube, which is the other conductor of the line. The inner conductor is held in place along the centre of the copper tube by means of thin polythene discs. Two layers of mild steel tape are wrapped around the outer tube, the second tape covering the gaps in the first. The steel tapes are covered with wrappings of insulating paper. The whole assembly is called a coaxial tube.

Usually a number of coaxial tubes are grouped together to form a coaxial cable, as shown in Fig. 5. The spaces between the coaxial tubes are filled with paper insulated quad cable wires which are used for alarm purposes, short distance bearers, etc.

Coaxial cables are classified by the number of tubes contained in the cable and are manufactured in sizes of 2, 4, 6, 8, 12 and 20 tube cables.

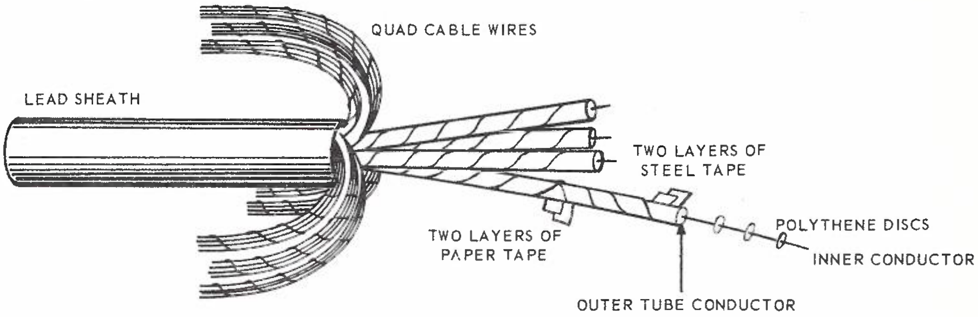


FIG. 5. 4 TUBE COAXIAL CABLE.

Coaxial cables are used on routes where it is necessary to derive many hundreds of circuits on each transmission line, and also for the relaying of television programmes. Present coaxial equipment in Australia uses a frequency bandwidth of approximately 4Mc/s for 960-channel systems and 6Mc/s for 1,260-channel systems.

It is not practical to transmit such high frequencies over multi-conductor cable lines or open wire lines because the electromagnetic fields at these frequencies produce greater electromagnetic radiation, and excessive crosstalk into nearby lines.

The coaxial tube is designed to confine the electromagnetic fields produced by these high frequencies and thus prevent them causing crosstalk.

Operation of Coaxial tube. The high frequency signal produces skin effect in both conductors. Normal skin effect causes current to flow on the outer surface of the inner conductor, but due to the potential existing between the two conductors, current flows on the inner surface of the outer tubular conductor. (Fig. 6a). The magnetic field produced by the current, and the electric field produced by the voltage arrange themselves between the inner and outer conductors as shown in Fig. 6b, and are collectively referred to as the electromagnetic field.

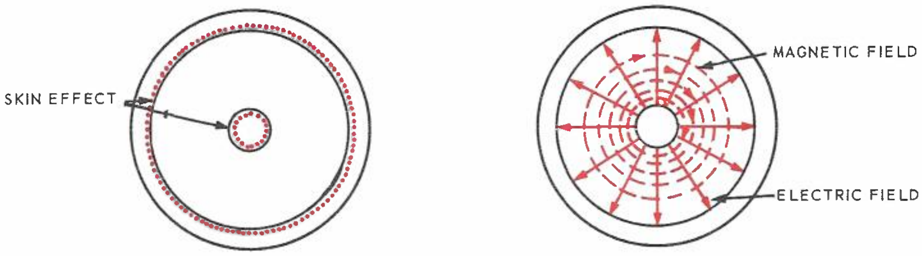


FIG. 6. SKIN EFFECT AND ELECTROMAGNETIC FIELD IN A COAXIAL CABLE.

Since the outer tube surrounds the centre conductor, it acts as an electro-static shield. The elctric field between the two conductors terminates on the inner surface of the tube, but does not penetrate it.

In addition, the changing magnetic flux induces eddy currents in the outer tube, and these have such an effect and direction as to oppose the flux producing them. At the higher frequencies (above about 300kc/s) transmitted over these cables, the effects of the eddy currents are sufficient to prevent the magnetic field penetrating through the outer tube, which therefore acts as an effective magnetic shield.

In the lower frequency range transmitted (approx. 60kc/s to 300kc/s), the magnetic shielding effect of the copper tube becomes less but crosstalk is kept within limits by the screening effect of the mild steel tapes.

A great advantage of the coaxial tube is that the penetration of the electromagnetic field, and therefore the effects of crosstalk induction into other lines, become less as the frequency increases.

The attenuation which occurs over transmission lines increases considerably with frequency, necessitating repeaters at approximately 6 miles spacing for 6Mc/s bandwidth coaxial routes (Fig. 7).

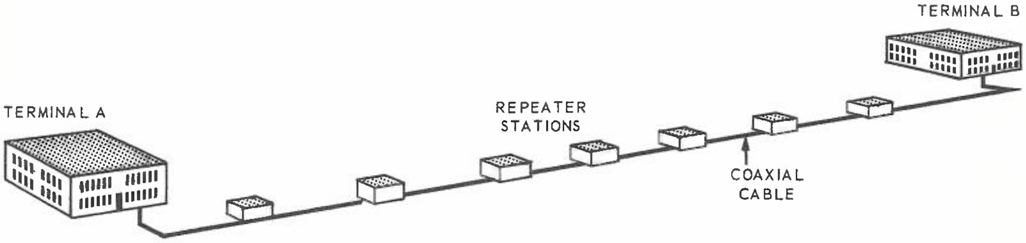


FIG. 7. COAXIAL CABLE ROUTE.

3. EFFECTS OF TRANSMISSION LINES ON SIGNALS.

3.1 In a telecommunication system, the energy transferred over a transmission line contains intelligence in the form of speech, telegraph, music or television signals. The quality of the signal transmitted over the line, and therefore the intelligibility of the signal reproduced by the receiving apparatus, is affected by the line characteristics in the following ways:-

(i) A loss of signal power occurs along the line.
(ii) The line characteristics distort the signal.
(iii) Noise and crosstalk are introduced into the line.

A brief summary only of each of these is given in this section, further explanations are given in later sections of this paper.

3.2 Loss of Signal Power. The equipment connected to the line input produces an alternating signal voltage which causes an alternating current to flow through the line to operate the receiving equipment connected at the line output. (Fig. 8).

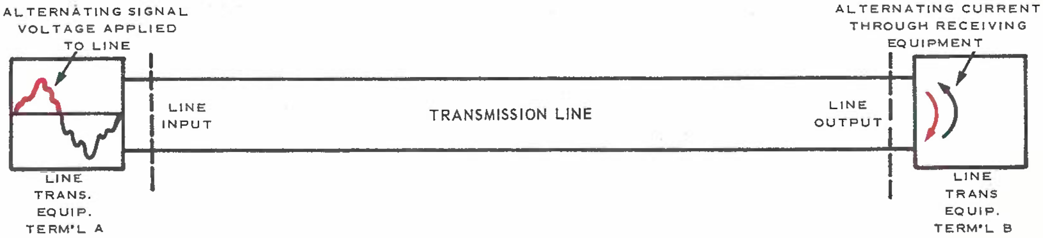


FIG. 8. ALTERNATING CURRENT SIGNAL.

The current and voltage applied to the line is called the input power and the current and voltage received at the line output is the output power.

Note that when terminal B is transmitting to terminal A, the input power and the line input is at the terminal B end of the line.

The opposition (impedance) offered by the line causes a loss of signal power along the line, thus reducing the power available at the line output. The loss of signal power along the line is called attenuation. If the attenuation of the line is excessive, the output power will be insufficient to satisfactorily operate the receiving equipment.

3.3 Signal Distortion. The signals transmitted over transmission lines have a very complex waveshape which is determined by the quality and nature of the information being conveyed.

Any complex waveshape is made up of a number of different sine wave frequencies; the complexity of the shape depending on the number of frequencies present and the amplitudes and phase relationships of these frequencies. Fig. 9 shows a simple example of a complex wave which is made up of two frequencies.

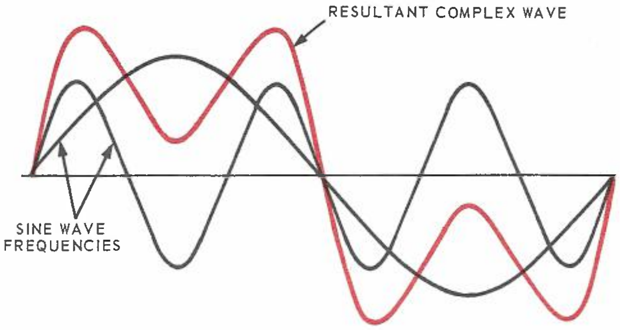


FIG. 9. ANALYSIS OF COMPLEX WAVE.

Distortion occurs if the shape of the complex wave received at the line output is different to the waveshape applied to the line input. A distorted signal is undesirable because the information reproduced by the receiving equipment is different in quality and nature to the original information.

A transmission line does not affect all frequencies to the same degree. This means that the amplitude and phase relationship of the component frequencies of a complex wave are changing as the signal progresses along the line, producing distortion in the output waveshape.

3.4 Noise and crosstalk. Noise is introduced into communication circuits from many different sources and has a tendency to distort and mask the signals being transmitted over the circuits.

To obtain good quality communication circuits the noise level is kept as low as possible, as compared to the signal level. Various methods are used to reduce the introduction of noise into circuits, and maintain the "signal to noise ratio" at a satisfactory level.

Noise can be divided into two main categories:-

(i) Noise introduced by induction from nearby lines, circuits or objects. This type of noise is usually referred to as "crosstalk".

(ii) Noise produced from within the line and the circuit components connected to the line, for example, thermal noise, tube noise, intermodulation noise, etc. This type of noise and the methods of its reduction are explained in other papers of the course.

4. WAVE MOTION ON A TRANSMISSION LINE.

4.1 The energy contained in A.C. telecommunication signals is sent over transmission lines in the form of waves. Before studying how this occurs it is necessary to have a basic understanding of the nature of waves.

4.2 Wave Motion. Waves are used to transmit many forms of energy, such as light, sound, radio signals, electrical signals, etc., from one point to another through various types of mediums.

Two important factors concerning the passage of a wave through a medium are:-

(i) A wave takes time to travel through a medium; that is, it has a particular velocity which depends on the type of energy, and the medium through which the energy is being transmitted.

(ii) As a wave travels, it disturbs the particles in the medium, causing them to oscillate backwards and forwards about their original position. When the wave passes, the particles resume their original position.

These two points can be illustrated by placing a cork on the smooth surface of water and then dropping a stone into the water. The stone creates waves which travel outwards in ever widening circles. It is important to note that the water does not move outwards, only the wave. The water merely moves up and down as the wave passes by, as indicated by the cork bobbing up and down.

Another example of wave motion is the transmission of sound waves through air, as described in Telephony 1. The sound waves, as they travel through the air, cause the air molecules to vibrate back and forth about the positions they occupied before the sound waves arrived. The sound wave progresses away from the sound source causing successive layers of air molecules to vibrate as the wave passes through them.

4.3 Wave Motion on Transmission Lines. The alternating signal voltage produced at the line input causes a movement of electrons, which in turn produces an electromagnetic field about the conductors. Electrical energy takes time to travel over a transmission line and is transferred to the distant end in the form of an electrical wave. The wave progresses along the conductors causing the electrons, and the subsequent electromagnetic field, to move as the wave passes. The electrical wave is actually transferring the electrical energy via the movement of electrons and the associated electromagnetic field.

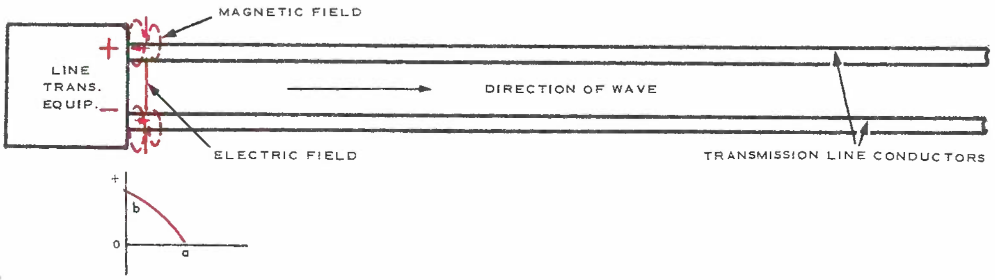


FIG. 10. WAVE PRODUCED BY FIRST PORTION OF A.C. SIGNAL.

Fig. 10 shows the first portion of an A.C. signal voltage applied to a transmission line causing a +ve and -ve potential at the line input. This potential causes electron movement and an electromagnetic field which are the start of an electromagnetic wave. As discussed in sub-para. 4.2(i) this wave will have a definite velocity for a given line.

As the signal voltage further rises towards its maximum value, the first part of the wave (a-b) has moved along the conductor, as shown in Fig. 11. The higher potential produced at the line input causes a larger electron movement and a larger electromagnetic field near the line input.

Note that the direction and value of the current (electron movement) are represented by the length and direction of the arrows in the figures.

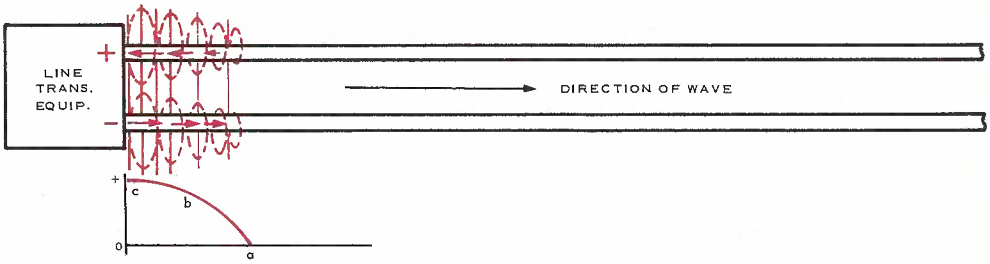


FIG. 11. WAVE PRODUCED BY THE FIRST QUARTER CYCLE OF SIGNAL.

The second quarter cycle (c-d) causes the line input voltage to reduce to zero, as shown in Fig. 12. The first quarter cycle of the wave (a-c) has moved along the line.

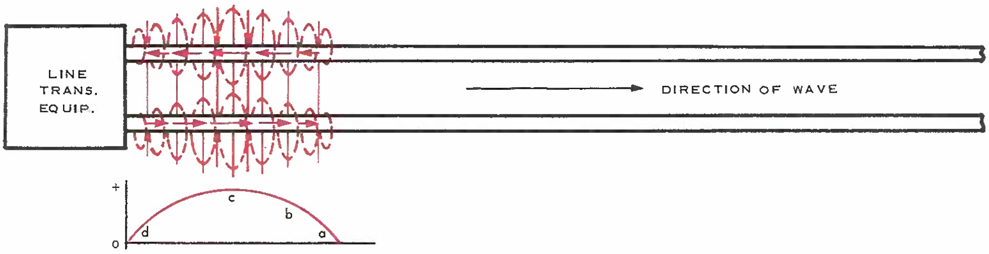


FIG. 12. WAVE PRODUCED BY FIRST HALF CYCLE OF SIGNAL.

The first half cycle of the wave keeps travelling down the line followed by the next half cycle (d-e), as shown in Fig. 13. Note that the potentials produced by the second half cycle are opposite to the first half cycle and the electrons near the line input are moving in the opposite direction.

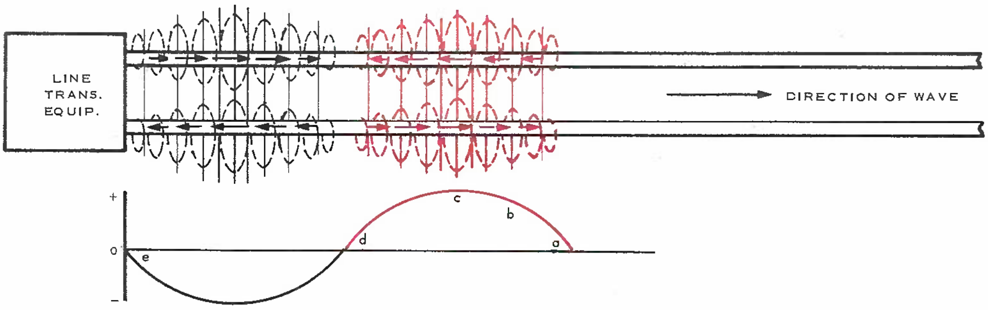


FIG. 13. WAVE PRODUCED BY BOTH HALF CYCLES OF SIGNAL.

The cycle of A.C. travels down the line, causing the electrons to move back and forth and the electromagnetic field to rise and fall as each half cycle passes, as shown in Fig. 14. Other cycles produced by the signal source follow on in a similar manner.

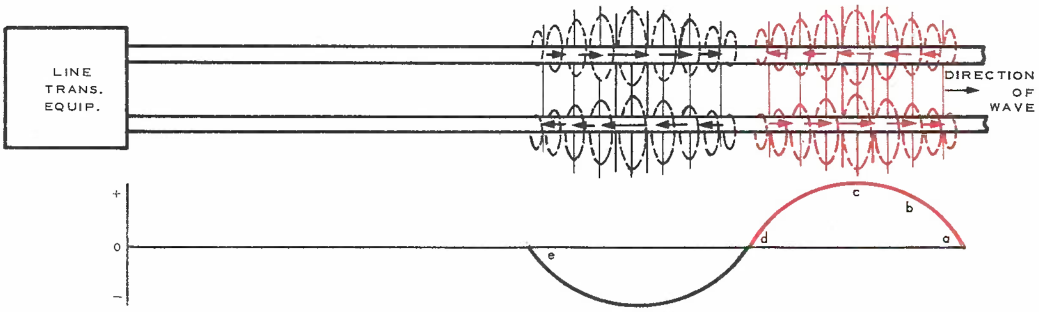


FIG. 14. WAVE PRODUCED BY ONE CYCLE OF SIGNAL PROGRESSING ALONG THE LINE.

4.4 Velocity of Propagation. The velocity at which a wave travels along a transmission line is called the "velocity of propagation".

The maximum velocity of propagation that could be obtained over a purely resistive line is approx. 186,000 miles per second, but this velocity is never reached in practice because a transmission line contains inductance and capacitance as well as resistance.

In practice, the actual velocity of a signal over a transmission line depends on:-

(i) The frequency of the signal. The velocity increases as the frequency increases until a particular frequency is reached where the velocity becomes constant.

(ii) The type of transmission line. The same frequency will travel at different velocities over different transmission lines.

The graphs in Fig. 15 show how the velocity varies with frequency for two typical transmission lines.

Referring to the graphs, note how the velocity over 200 lb. open wire increases with frequency until at 3kc/s it becomes constant at approximately 183,000 miles per second. Also note, how the same frequency travels at different velocities through the two different lines. For example, 10kc/s travels at 183,000 miles per second through the 200 lb. open wire line and at 110,000 miles per second through the 40 lb. cable conductors.

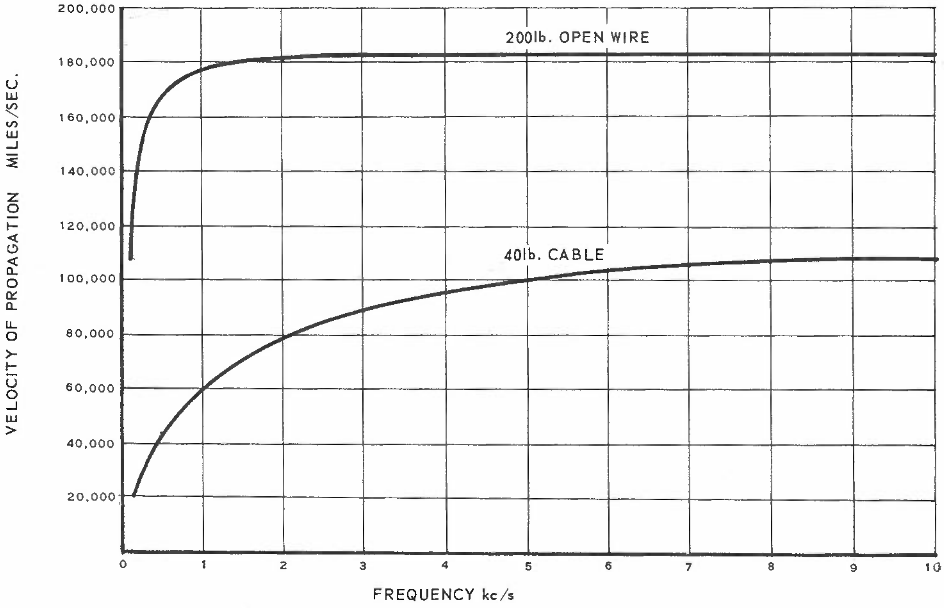


FIG. 15. VELOCITY OF PROPAGATION.

4.5 Delay Distortion. Delay distortion occurs when the sine wave frequencies which make up a complex wave travel at different velocities over a transmission line.

Fig. 16 shows two sine wave frequencies of a complex wave applied to the input of a transmission line. As the lower frequency travels at a lower velocity, it will reach the line output later than the higher frequency, thus altering the phase relationship between the two sine wave frequencies. Altering the phase relationship between the two sine wave frequencies alters the shape of the complex wave, resulting in distortion of the complex wave.

This distortion has been caused by the lower frequency being delayed for a longer period during its transmission over the line. The effects of delay distortion are not particularly noticeable in the frequency ranges normally used over open wire and multiconductor cables, but it becomes a serious problem in coaxial cable operation.

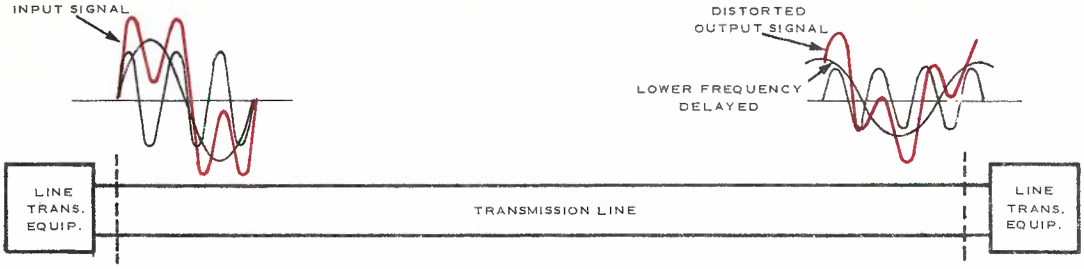


FIG. 16. DELAY DISTORTION.

Delay Equalisers. In cases where the effects of delay distortion deteriorate the quality of the signal, it is normal practice to install delay equalisers in the line transmission equipment at the receiving station, as shown in Fig. 17. The delay equaliser is composed of components which have the function of reducing the velocity of the higher frequencies, and thus delaying them until they are once again in the correct phase relationship with the lower frequencies which were delayed by the line.

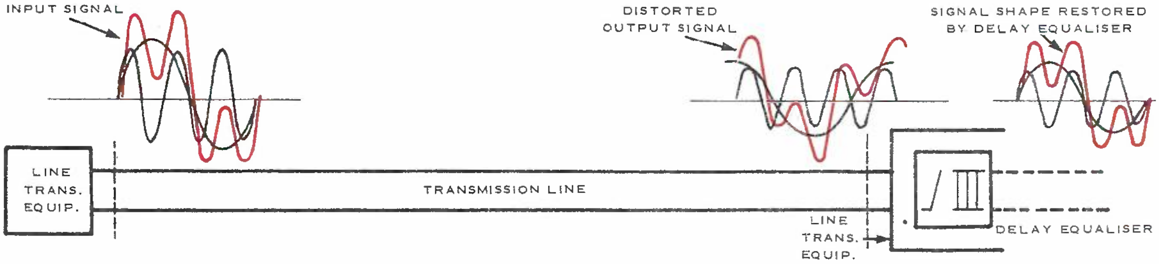


FIG. 17. DELAY EQUALISER.

4.6 Wave Length. The length of line occupied by one complete cycle of current or voltage is termed the "wavelength" and is represented by the Greek letter λ (Fig. 18).

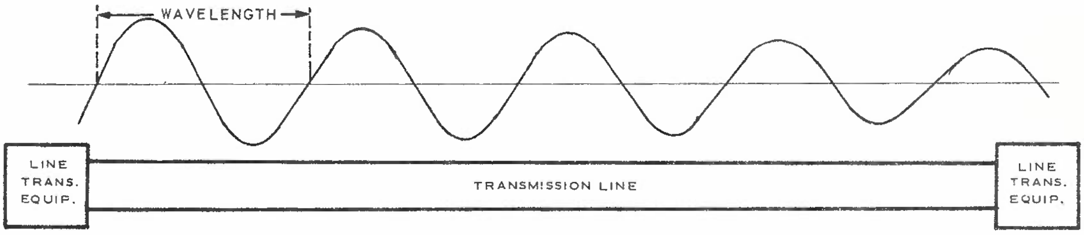


FIG. 18. WAVELENGTH.

The wavelength of a signal over a particular line is calculated by:-

$$\text{Wavelength } (\lambda) = \frac{\text{Velocity}}{\text{Frequency}}$$

Example:- Calculate the wavelength of a 3Mc/s signal transmitted over a coaxial line at a velocity of 150,000 miles per second.

$$\text{Wavelength } (\lambda) = \frac{\text{Velocity}}{\text{Frequency}} = \frac{150,000}{3,000,000}$$

Answer: Wavelength (λ) = 0.05 miles.

4.7 Since the velocity of propagation varies for different types of lines, the same frequency will have a different wave length on different lines. For example, a 1000c/s signal travels at a velocity of 170,000 miles per second over a 200 lb. open wire line and has a wavelength of 170 miles. When the same signal (1000c/s) is transmitted over a 40 lb. cable line, the velocity becomes 60,000 miles per second and the wavelength changes to 60 miles.

5. PRIMARY CONSTANTS.

5.1 A transmission line has four electrical properties, which are evenly distributed over the entire length of the line and determine the effects that the line has on A.C. signals transmitted over it. These properties are:-

(i) Series Resistance (R).
(ii) Series Inductance (L).
(iii) Shunt Capacitance (C).
(iv) Shunt Conductance (G).

The values of R, L, C and G expressed for one mile of line, are termed the "primary constants" of the line. The primary constants depend on the construction of the line, and the material used for the wires. Typical values of the four primary constants of some different types of transmission lines are given in Table 1.

Type of Line	Series Resistance (R) (Ohms/Loop Mile)	Series Inductance (L) mH/Loop Mile	Shunt Capacitance (C) μF/Mile	Shunt Conductance (G) μMhos/Mile
200 lb. H.D.C. open wire	8.8	3.3	.0090	.5 (at 3kc/s
100 lb. H.D.C. open wire	17.6	3.6	.0085	.5 (at 3kc/s
40 lb. P.I.Q. cable	44	1	.065	4 (at 3kc/s
20 lb. P.I.Q. cable	88	1	.065	4 (at 3kc/s
Coaxial cable	8.47	.4	.075	13 (at 1Mc/s

TABLE 1.

5.2 Series Resistance (R). A transmission line has resistance all along its length, as shown in Fig. 19. This resistance, which is in series with the signal being transmitted, is termed series resistance and is expressed in ohms per loop mile.

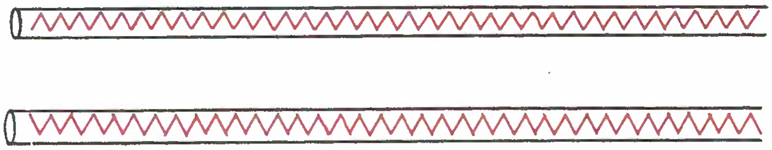


FIG. 19. SERIES RESISTANCE.

When the resistance per loop mile of line is known, the resistance of any length of the line can be calculated. For example, a 200 lb. H.D.C. open wire line 100 miles long will have a loop resistance of 880 ohms.

Due to skin effect, the resistance of a transmission line increases with frequency; for this reason the values of series resistance are given for D.C. in Table 1. The resistance of a line to A.C. is called "effective resistance" and the correct value of effective resistance for the particular frequency must be used for calculations.

5.3 Series Inductance (L). An alternating current flowing through a transmission line produces a rising and falling flux which cuts the conductors and induces an e.m.f. of self induction. The "series inductance" producing this effect is evenly distributed along the entire length of the line, as shown in Fig. 20.

The amount of series inductance possessed by a line depends on the diameter of the wires and their spacing and is expressed in millhenries per loop mile.

The inductance of cables lines is less than open wire lines, because the cable conductors are closer together. The flux of one cable conductor tends to cancel the flux of the other, reducing the value of the induced e.m.f. and thus the inductance of the conductors.

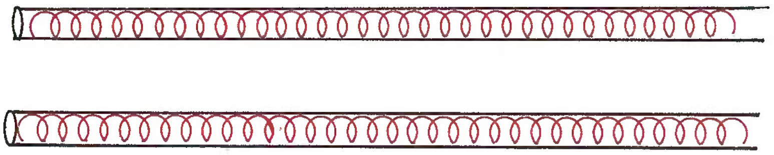


FIG. 20. SERIES INDUCTANCE.

5.4 Shunt Capacitance (C). A transmission line consists of two conductors separated by an insulating material such as air, paper, or plastic. The two conductors form the plates of a capacitor and the insulation material the dielectric, as shown in Fig. 21. The distributed capacitance appearing between the two line conductors is called "shunt capacitance" and is expressed in microfarads per mile.

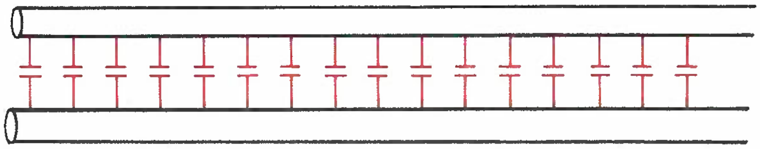


FIG. 21. SHUNT CAPACITANCE.

Shunt capacitance increases as the size of the conductors increase and as the distance between them decreases. The capacitance between cable conductors is greater than that between open wire conductors because of the very close proximity of the cable conductors.

5.5 Shunt Conductance. The insulating materials used between the conductors of transmission lines are not perfect insulators, and as a result, leakage paths exist over the entire length of the line (Fig. 22). Line leakage can be expressed in terms of the insulation resistance in ohms per mile, but the normal practice is to express it in terms of the reciprocal of the insulation resistance, called "shunt conductance" which is expressed in micromhos per mile.

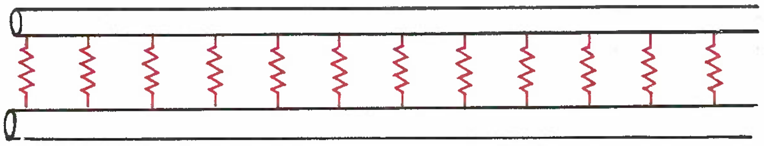


FIG. 22. SHUNT CONDUCTANCE.

The value of shunt conductance varies considerably with changing weather and temperature conditions, and with frequency. The main variation in frequency is due to dielectric losses and for this reason a particular frequency is quoted in Table 1.

5.6 Equivalent Line Circuits. Even though the four primary constants are evenly distributed over a transmission line, it is common practice to represent than as "lumped" components for each mile of line so that the characteristics of the line can be expressed more clearly. Fig. 23 shows the network of lumped components which represents the primary constants of one mile of 100 lb. H.D.C. open wire line.

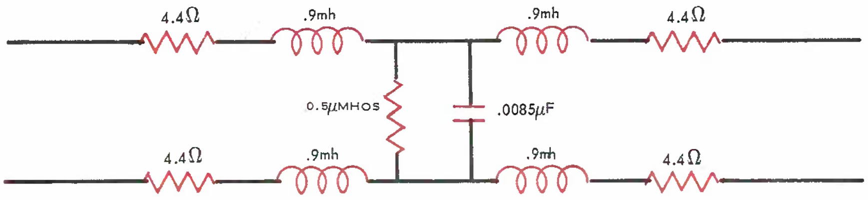


FIG. 23. EQUIVALENT CIRCUIT OF TRANSMISSION LINE.

6. ATTENUATION.

6.1 The gradual reduction in amplitude of signal power as it progresses along a line is called attenuation. The amplitude of signal power is proportional to the product of the current and voltage ($P \propto E \times I$), therefore, these gradually diminish along the line, as shown in Fig. 24.

The reduction in voltage amplitude is caused by the series impedance (consisting of R and X_L) opposing the current and producing a voltage drop over the line. The reduction in current amplitude is caused by the shunt impedance (consisting of G and X_C) which provides leakage paths to shunt some of the current.

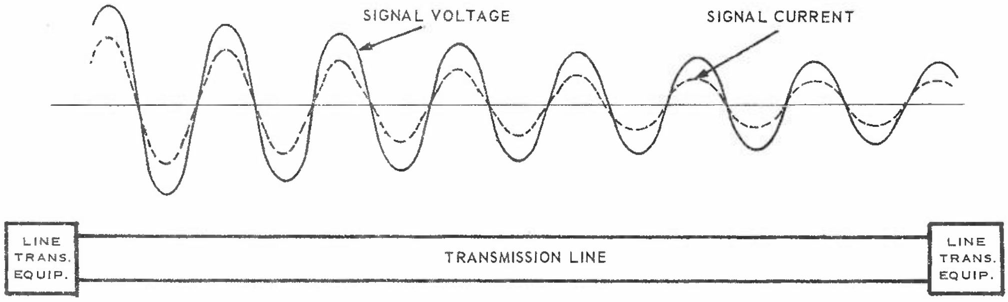


FIG. 24. ATTENUATION OF SIGNAL VOLTAGE AND CURRENT.

6.2 Power level diagrams. It was shown in the paper "Transmission Units", that a loss or gain of power is expressed in db and a power level is expressed in dbm. A transmission line has an input and an output power level expressed in dbm, and since the output level is less than the input level, the loss produced by attenuation over the line is expressed in db.

The levels and losses of transmission lines (at a particular frequency) are often represented graphically by "power level" diagrams. The power level diagram in Fig. 25 shows a transmission line with an input power level of +17 dbm and an output power level of -5dbm. The difference between the input and output power levels indicates that the line has a loss of 22db.

Power level diagrams clearly show the gradual loss of power over the line, and it is possible on these diagrams to determine the level at any point on the line.

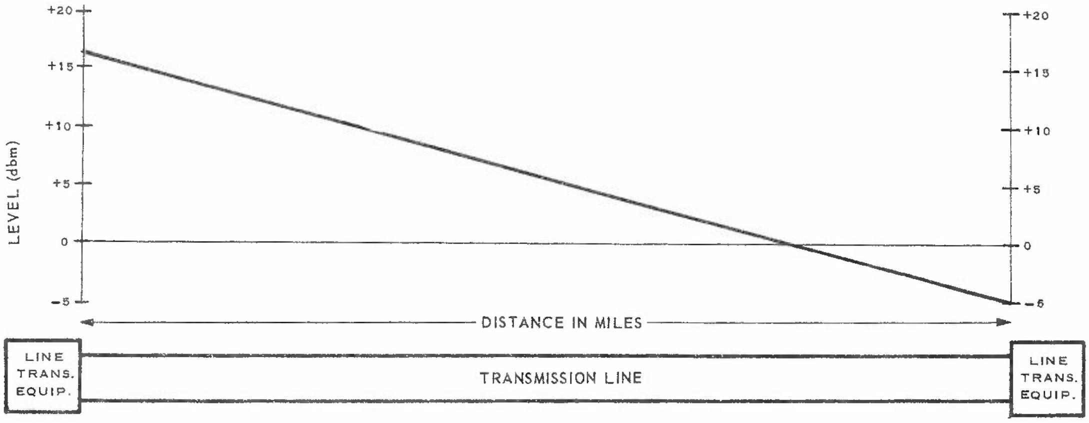


FIG. 25. POWER LEVEL DIAGRAM.

6.3 Attenuation Constant. The loss which occurs over a transmission line of uniform construction is the same for each mile, that is, if the loss of the first mile of line is 0.1db, then the loss of the second mile is 0.1db, the third mile 0.1db and so on. The loss per mile of line, when expressed in db, is called the "attenuation constant". Fig. 26 shows a length of transmission line with an attenuation constant of 0.5db per mile.

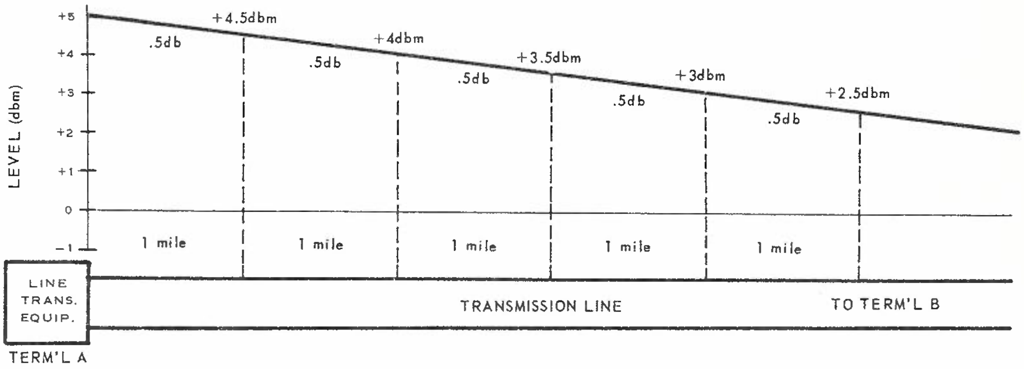


FIG. 26. ATTENUATION CONSTANT.

6.4 When the attenuation constant of a particular type of line is known, the loss of any length of that line can be calculated by:-

LOSS OF LINE = ATTENUATION CONSTANT x LENGTH OF LINE

For example, the loss of 20 miles of line with an attenuation constant of 0.2db/mile is 4db.

6.5 Amplifiers. When the length of the line is such that it would produce excessive attenuation, amplifiers are included in the terminal equipment, and repeaters are installed at intervals along the line. The amplifiers and repeaters restore the signal level which has been decreased by attenuation. Fig. 27 shows the power level diagrams for the attenuation and amplification which occurs in the A-B, and B-A direction, on a typical multi-conductor cable transmission line equipped with repeaters.

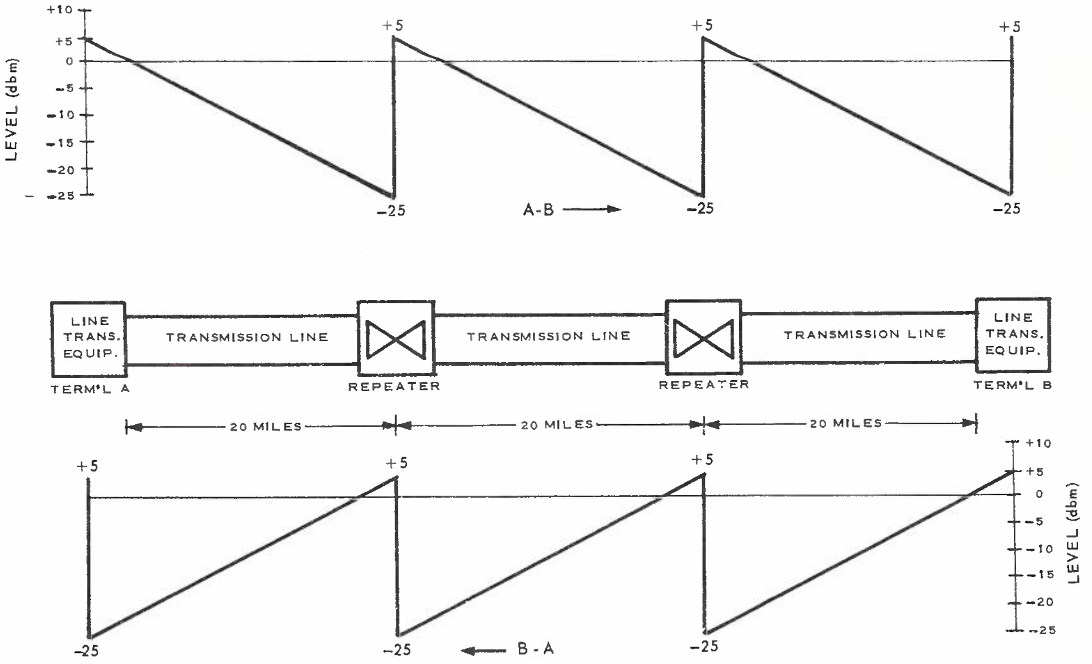


FIG. 27. AMPLIFIERS COMPENSATE FOR ATTENUATION.

6.6 Variation of attenuation with frequency. Attenuation constant increases with frequency, therefore, the loss which occurs over a transmission line increases with frequency.

The reasons for this are:-

(i) Series impedance increases with frequency, producing a greater voltage drop over the line.

(ii) Shunt impedance decreases with frequency, causing a larger leakage current.

Graphs showing the effect of frequency on the attenuation constant for three types of transmission lines are shown in Fig. 28.

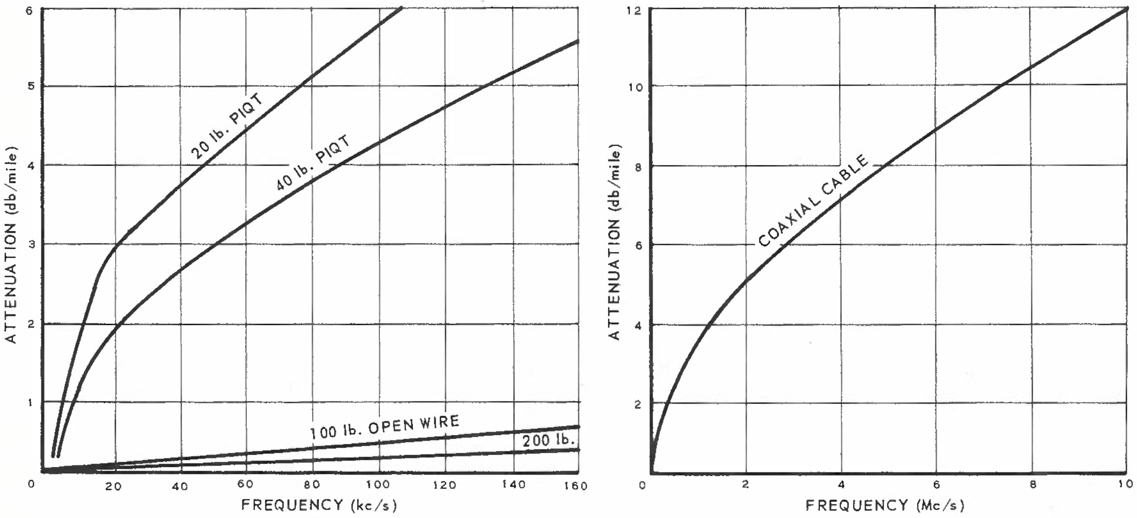


FIG. 28. EFFECT OF FREQUENCY ON ATTENUATION CONSTANT.

Fig. 29 is a power level diagram showing two frequencies, 3kc/s and 9kc/s, applied at the same level to a line input. As the two frequencies progress along the line, the 9kc/s frequency is attenuated more than the 3kc/s frequency and reaches the line output at a lower power level than the 3kc/s frequency.

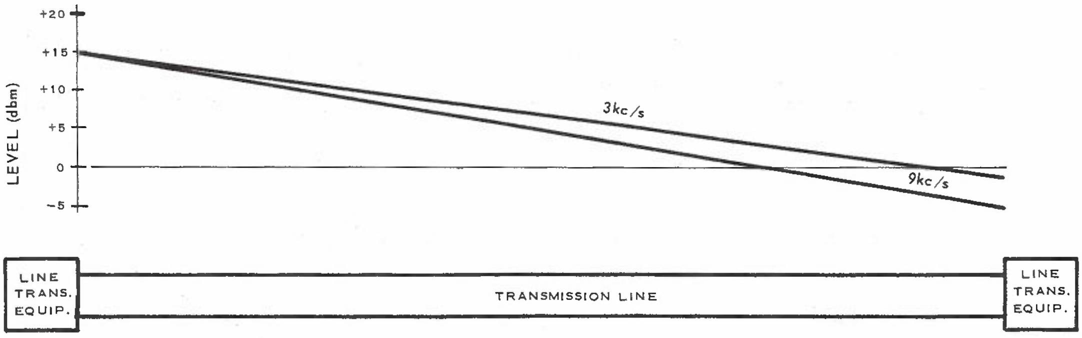


FIG. 29. ATTENUATION INCREASES WITH FREQUENCY.

6.7 Frequency Distortion. Due to the unequal attenuation of different frequencies by a transmission line, the sine wave frequency components of a complex wave reach the line output with different relative amplitudes, as compared with the amplitudes at the line input. (Fig. 30). The higher frequencies are attenuated more than the lower frequencies and the waveshape at the line output is different to the input waveshape. This form of distortion, known as "frequency distortion", is shown in Fig. 30.

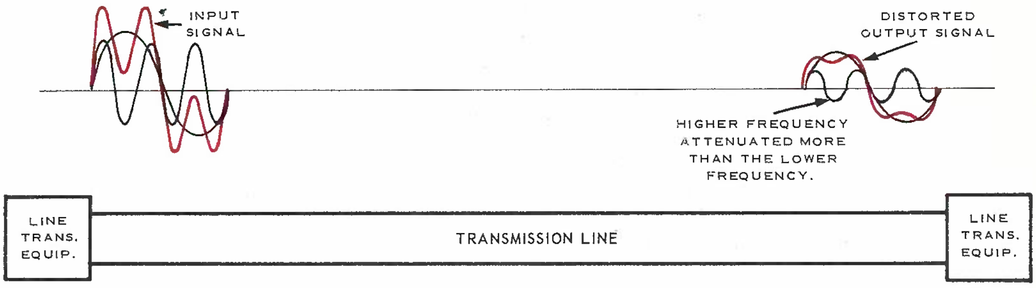


FIG. 30. FREQUENCY DISTORTION.

6.8 Attenuation Equalisers are a network of resistive, capacitive and inductive components, which are placed at the receiving end of a transmission line to correct for the unequal attenuation of frequencies caused by the line, and thus reduce frequency distortion.

The attenuation equaliser introduces additional attenuation to the circuit and has an attenuation versus frequency characteristic which is opposite to that of the line; therefore, the lower frequencies are attenuated more than the higher frequencies and all frequencies at the equaliser output will have been attenuated by the same amount.

In Fig. 31, a power level diagram and a graphical diagram show how an attenuation equaliser compensates for the unequal attenuation of frequencies on a transmission line. Note how the wave shape at the output of the attenuation equaliser is the same as the waveshape of the signal at the line input, although attenuated due to the effects of the line and the equaliser.

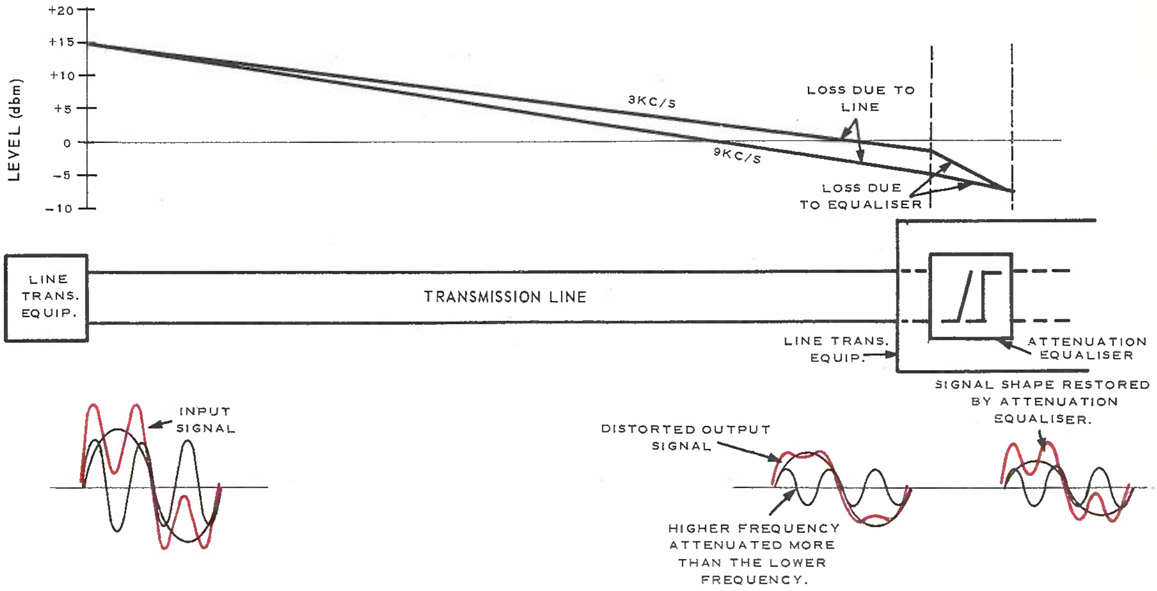


FIG. 31. ATTENUATION EQUALISER.

7. REFLECTION.

7.1 A transmission line is a means of transferring power from the line input equipment (source) to the line output equipment (load).

The transfer of power takes place in two stages:-

(i) Signal power is transferred from the input equipment to the transmission line.

(ii) The signal has a velocity of propagation and takes time to travel down the line. At the end of the line, the power which remains after attenuation has occurred is transferred to the output equipment.

Since the transmission line is between the input and output equipment, and has an impedance which is determined by its primary constants, the impedance of the input and output equipment is designed, during manufacture, to match the nominal impedance of the line concerned. That is, the impedance of the input equipment matches the impedance of the line, and the impedance of the output equipment matches the impedance of the line.

The nominal impedance of a line is called its "characteristic impedance" and is explained in section 8 of this paper.

7.2 If the impedance of the input or output equipment does not match the characteristic impedance of the line, maximum transfer of power will not take place and "reflection" occurs at the point of "mismatch".

Reflection can be likened to an echo which occurs when sound waves, travelling through air, suddenly strike a solid object such as a brick wall. All the sound energy cannot pass through the wall and some of it is reflected back towards the sound source in the form of an echo.

Fig. 32 shows a transmission line which is terminated in output equipment having an incorrect impedance, that is, a mismatch has occurred because the impedance of the output equipment does not match the line characteristic impedance. All of the power reaching the mismatch is not accepted by the output equipment, and some is reflected back along the line. Since power consists of voltage and current waves, the line contains signal voltage and current waves moving towards the output equipment, and reflected voltage and current waves travelling back towards the input equipment. (only the current waves are shown in Figs. 32 and 33).

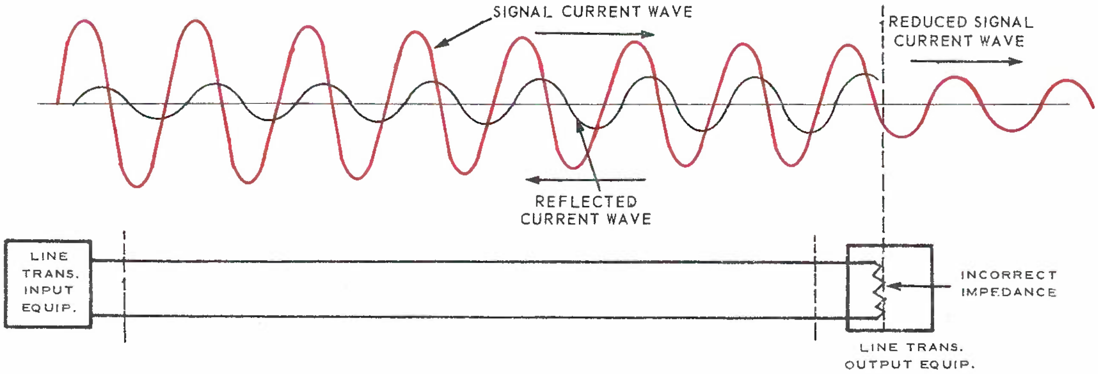


FIG. 32. REFLECTION DUE TO INCORRECT IMPEDANCE OF OUTPUT EQUIPMENT.

7.3 Reflection on a transmission line has the following main disadvantages:-

(i) The power delivered to the terminal equipment is reduced,

(ii) the reflected waves distort the waveshape of the transmitted signal, thereby degrading the quality of the signal and

(iii) in some circumstances, the reflected wave may be heard as an echo in the transmitting equipment.

7.4 Reflection also occurs at any point in a transmission line where impedance irregularities exist due to faulty lines and line construction, and where lines having different characteristic impedances are joined without special matching precautions.

Fig. 33 shows reflection at the junction of an open wire and cable transmission line due to the mismatch caused by their different characteristic impedances.

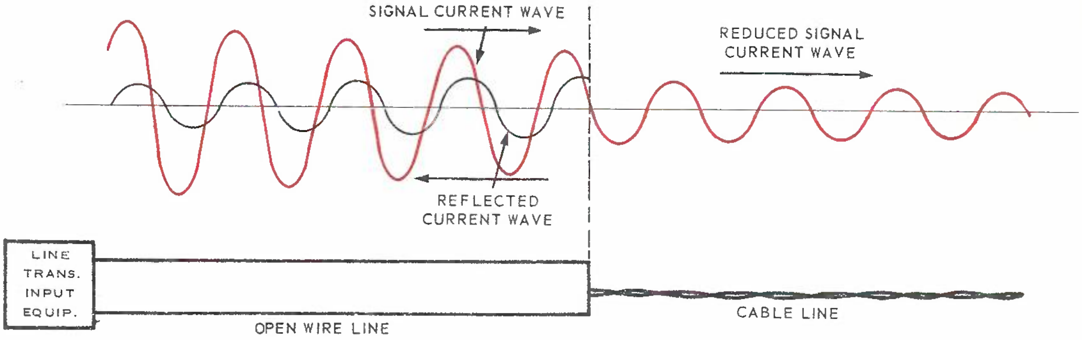


FIG. 33. REFLECTION DUE TO MISMATCH ON TRANSMISSION LINE.

7.5 Reflection is reduced on transmission lines by the following methods:-

(i) The equipment at each end of the line is matched to the line. This is achieved by using equipment having the same impedance as the characteristic impedance of the line, or by using transformers to match the line to the equipment.

(ii) The line construction is made uniform, and either transformers or loaded cables are used when open wire lines are joined to cable lines. Loaded cables are explained in Section 9 of this paper.

7.6 Line faults such as short circuited or open conductors, earthed conductors, high resistance joints, etc., cause reflection of transmitted signals. The principle of reflection is used in "pulse echo" type instruments to accurately locate the distance to line faults from a testing station.

A pulse echo type instrument produces electrical pulses which are transmitted along the line under test. When a pulse reaches the fault (point of mismatch) a portion of it is reflected back to the transmitting end, where it is applied to a cathode ray oscilloscope circuit. The time taken for the pulse to reach the fault and be reflected back to the testing station is indicated in microseconds on the oscilloscope screen. Since the velocity of propagation of the particular line is known, the distance to the fault can be readily calculated.

8. CHARACTERISTIC IMPEDANCE (Zo).

8.1 For every type of transmission line, irrespective of length, there is a particular value of impedance, which when used to terminate the line, results in a maximum transfer of power from the signal source to the terminating equipment, and a minimum reflection of energy. This value of impedance is individual to the particular type of line construction and is termed the "characteristic impedance" (Zo) of the line.

The value of characteristic impedance is determined by the primary constants of the line, particularly the series inductance and shunt capacitance, and is entirely independent of the length of the line. That is, one mile of a particular type of transmission line has the same characteristic impedance as two miles, three miles or any other length of that type of line. Typical values of the characteristic impedance for various types of line are shown in para. 8.3.

8.2 The characteristic impedance of a line can be calculated by various mathematical formulas, most of which use the primary constants or dimensions of the line, or by practical measurements in conjunction with the following formula:-

$$Z_o = \sqrt{Z_{oc}\ Z_{sc}}$$

Where:-

Zoc is the input impedance of the line when the output end is open circuit.

Zsc is the input impedance of the line when the output end is short circuit.

This formula can be applied to any length of line in the following manner. With the output end of the line open circuited the input impedance (Zoc) is measured as shown in Fig. 34a. The output end of the line is then short circuited at the same point and the input impedance (Zsc) measured, as shown in Fig. 34b.

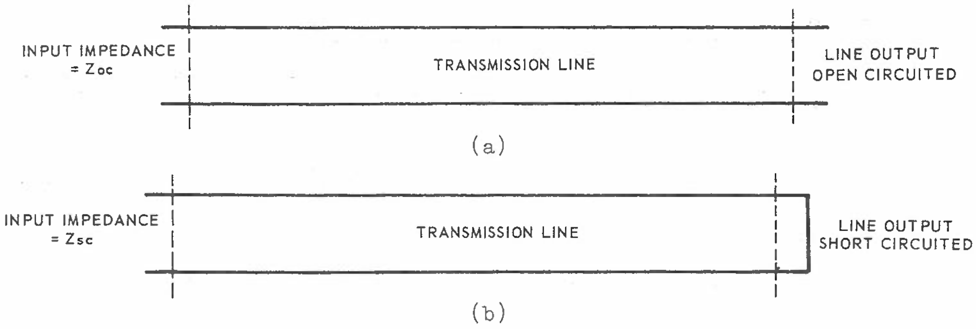


FIG. 34. MEASURING Zoc AND Zsc.

When the measured values of Zoc and Zsc are applied to the formula, the value of the characteristic impedance for that particular line is obtained. The same numerical value of characteristic impedance will be obtained for the line regardless of whether the measurements are taken over one mile, two miles, or any other length of the line.

8.3 Typical values of the characteristic impedance for various types of line are:-

Open wire lines..................	600 ohms
Multiconductor cable line........	135 ohms
Coaxial line.....................	75 ohms

These values are the nominal values used in practice, but are only average values, because lines of a similar type vary slightly due to constructional details and the frequency used over the line. For example, a 100 lb H.D.C. open wire line with 6" spacing has a Zo of about 620 ohms, where as, a 200 lb. H.D.C. with the same spacing has a Zo of 580 ohms.

8.4 Terminating a line in an impedance equal to its characteristic impedance. When a line is terminated in an impedance equal to its characteristic impedance, the input impedance of the line becomes equal to the characteristic impedance. For example, when the open wire line in Fig. 35 is terminated in an impedance of 600 ohms, the input impedance is 600 ohms also.

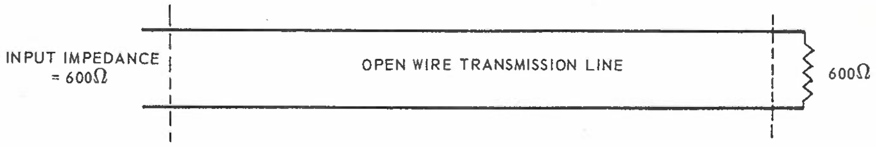


FIG. 35. TERMINATING A LINE IN IT'S CHARACTERISTIC IMPEDANCE.

The input impedance equals the characterstic impedance of the line regardless of the length of the line terminated. For example, Fig. 36a shows a short length of multiconductor cable line and Fig. 36b a long length of multiconductor cable line, both terminated in their characteristic impedance of 135 ohms. In both cases the input impedance is equal to the characteristic impedance.

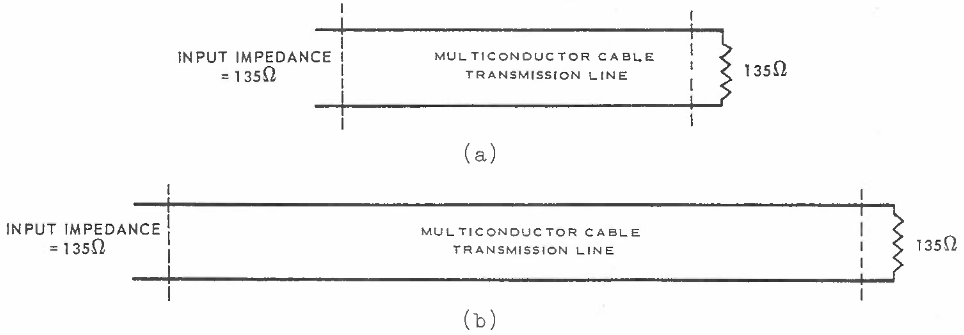


FIG. 36. TERMINATING DIFFERENT LENGTHS OF A LINE IN ITS CHARACTERISTIC IMPEDANCE.

8.5 Since a transmission line is a two way device, the input end of the line is also terminated in an impedance equal to its characteristic impedance. The impedance at the output end of the line now equals the characteristic impedance, as shown in the example of an open wire line in Fig. 37.

FIG. 37. TERMINATING THE INPUT OF A LINE IN ITS CHARACTERISTIC IMPEDANCE.

In practice, both ends of a transmission line are terminated in impedances equal to its characteristic impedance (Fig. 38). This ensures that the input and output impedances of all lines of the same type are the same value, and are equal to the characteristic impedance of the line for each direction of transmission.

FIG. 38. TERMINATING THE INPUT AND OUTPUT OF A LINE IN ITS CHARACTERISTIC IMPEDANCE.

8.6 Advantages of terminating a line in its characteristic impedance. These are:-

(i) The impedance of the input equipment equals the input impedance of the line, therefore maximum transfer of power takes place from the input equipment to the line.

(ii) The impedance of the output equipment equals the output impedance of the line, therefore, maximum transfer of power takes place from the line to the output equipment.

(iii) As explained in Section 7 of this paper, when a line is correctly terminated and maximum transfer of energy takes place, no reflection occurs on the line.

(iv) The equipment which operates over transmission lines is manufactured to standard specifications, and matches the characteristic impedance of the line over which it is designed to operate. This means that flexibility is obtained, because the equipment can be connected to a line of any length, provided of course it is the type of line for which it was designed.

8.7 Effect of frequency on characteristic impedance. The characteristic impedance of a line varies at the lower frequencies, but becomes fairly constant as the frequency increases. This is illustrated in Fig. 39, which shows graphs of the effect of frequency on the characteristic impedance for a typical open wire and multiconductor cable transmission line.

As shown by the graphs, the variation in characteristic impedance with frequency takes place mainly in the voice frequency range, but becomes constant above this range. This higher frequency range is the frequency range used for carrier system.

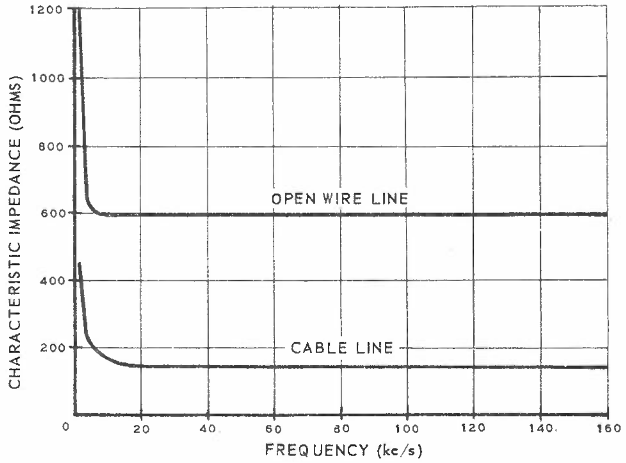


FIG. 39. EFFECT OF FREQUENCY ON Zo - MULTICONDUCTOR & OPEN WIRE LINES.

The variation in characteristic impedance with frequency for a coaxial transmission line is shown in Fig. 40.

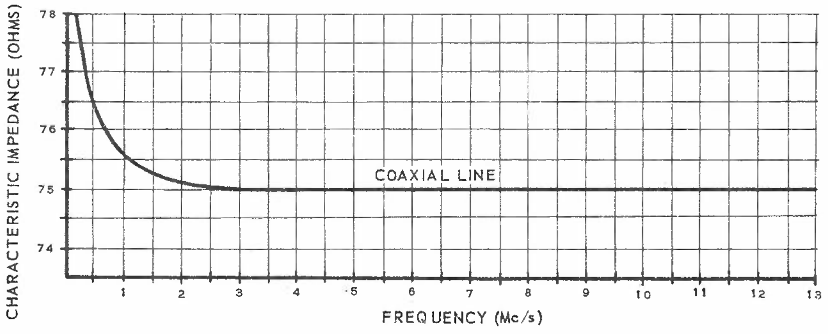


FIG. 40. EFFECT OF FREQUENCY ON Zo - COAXIAL LINES.

9. LOADING.

9.1 The close proximity of the twisted pair of wires in a multiconductor cable transmission line produces a large shunt capacitance between them. The effect of this large shunt capacitance is much greater than the effect of series inductance and the line is capacitive (or reactive). The capacitive line causes the signal current to lead the signal voltage by a fairly large phase angle (in some cases up to 45°).

The disadvantages of this large capacitance are:-

(i) A high attenuation constant results, thus restricting the length of cable over which the required transmission standards can be obtained without amplification.

(ii) The attenuation constant varies considerably with frequency, causing frequency distortion.

(iii) The velocity of propagation varies considerably with frequency, causing delay distortion.

(iv) The characteristic impedance varies in the lower frequency range in such a manner that the matching of multiconductor cable lines to open wire lines is difficult.

9.2 The adverse effects produced by the high shunt capacitance are reduced by connecting additional inductance in series with each side of the line. The additional inductance tends to neutralise the effect of the shunt capacitance and reduces the phase angle to zero (or as near as possible to zero).

The insertion of additional inductance in series with a line is called "loading".

Loading is not necessary on open wire lines because the wider spacing reduces the shunt capacitance, and the phase angle is almost zero.

9.3 Two methods of inductance loading are used in practice, they are:-

(i) Continuous loading.

(ii) Lumped loading.

Continuous loading involves wrapping a continuous tape of magnetic material around the entire length of the line. This method is expensive but is used on submarine cables where a smooth external cable construction simplifies handling.

Lumped Loading. In this method, inductance is added to each side of the line by placing "loading coils" at regular intervals along the line, as shown in Fig. 41. Lumped loading is used on underground cables because it is cheaper than continuous loading and can be applied easily to previously unloaded cables. While it is not as effective as continuous loading, the results are quite satisfactory for trunk and junction cables.

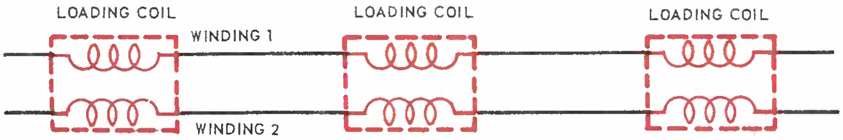


FIG. 41. LUMPED LOADING.

9.4 Loading Coil Construction. A loading coil consists of two equal windings wound on a circular shaped magnetic core (Fig. 42). The coils are wound to be electrically balanced so that each has the same electrical effect (inductance, resistance, etc.) when inserted into each side of the line.

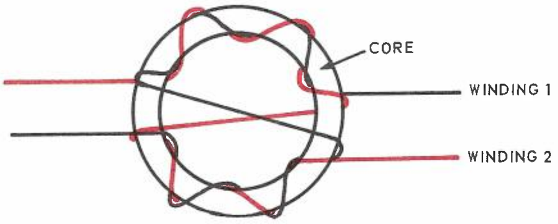


FIG. 42. WINDINGS OF A LOADING COIL.

Since it is usual to load more than one pair of wires in a cable, a number of loading coils are mounted in a container which is filled with an impregnating material and sealed, the complete unit being called a "loading pot".

Connections are made to the coils by means of wires in short lengths of cable, called cable "stubs". The cable stub wires are terminated on the loading coils before the container is impregnated and sealed. The loading pots are placed in cable pits, or buried in the ground, and the loading coils are connected in series with the lines to be loaded by selecting the correct wires in the cable "stub" and jointing then into the multiconductor cable (Fig. 43).

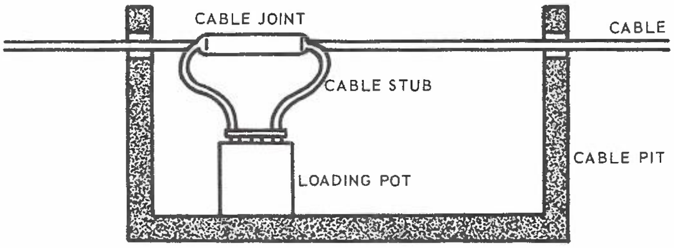


FIG. 43. LOADING POTS.

Loading coils are designed to have the following characteristics:-

(i) A high insulation resistance between windings.
(ii) A low capacity between windings.
(iii) Effective shielding to prevent interference into neighbouring coils.
(iv) Accurate inductive and resistive balance between the windings.
(v) Low resistance of windings.
(vi) Small construction.

9.5 Cut-off frequency. The addition of loading coils in series with a transmission line has the effect of limiting the frequency range which can be satisfactorily transmitted over the line. Therefore, the advantages gained by loading are only effective in the frequency range for which the loading is designed. The maximum frequency which can effectively be transmitted over a loaded cable pair is called the "cut-off" frequency, because the frequencies above "cut-off" receive increased attenuation, as shown in the graph in Fig. 44. The addition of the extra series inductance causes the pair to behave as a low pass filter, in which the attenuation increases rapidly above the cut-off frequency. The reason for this is explained in the course paper on filters.

9.6 The most economical form of loading is one involving the minimum number of loading coils with maximum spacing, but this gives a fairly low cut-off frequency. In order to transmit higher frequencies on loaded pairs, lower value inductance coils are used at more frequent intervals. The value of the loading coils and their spacing is, therefore, determined by the range of frequencies to be transmitted on the cable pair. The most common forms of loading are "voice frequency", "radio programme frequency" and "carrier frequency", and details of coil values and spacing for each are listed in Table 2.

Type of loading	Coil Value	Coil Spacing	Cut-off Frequency
Voice Frequency	88mH	6000 ft.	3.5 - 4kc/s
Programme	14mH	3000 ft.	12kc/s
Carrier	2.44mH	600 ft.	30.40kc/s

TABLE 2.

9.7 Advantages of loading. Correct loading produces the following results in all types of transmission lines.

(i) The attenuation constant is reduced considerably over the frequency range for which the cable pair is loaded. For example, the graph in Fig. 44 shows the attenuation constant of 20 lb. cable with and without loading, for the transmission of voice frequencies.

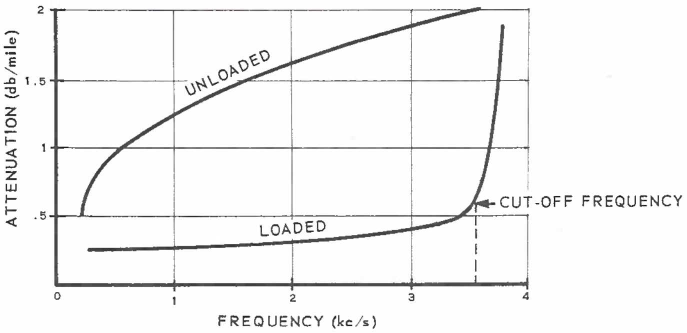


FIG. 44. ATTENUATION CONSTANT FOR LOADED AND UNLOADED CABLE PAIRS.

(ii) Since the attenuation becomes fairly constant over the frequency range for which the cable is loaded (Fig. 44) frequency distortion is reduced.

(iii) The velocity of propagation is reduced, but it becomes more constant for all frequencies in the frequency range for which the loading is designed, therefore reducing delay distortion. For example, the graph in Fig. 45 shows the velocity of propagation of a 20 lb. cable with and without loading, for the transmission of radio programme frequencies.

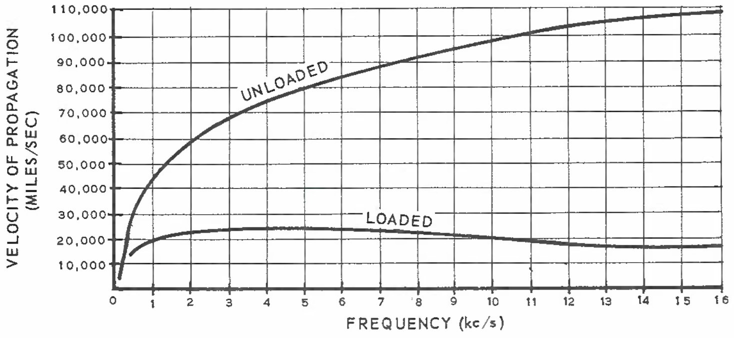


FIG. 45. VELOCITY OF PROPAGATION FOR LOADED AND UNLOADED CABLE PAIRS.

(iv) The characteristic impedance is increased, but becomes more constant for the frequencies within the band to be transmitted. This is a most important consideration for matching trunk cables to open wire lines. The graph in Fig. 46 shows the characteristic impedance for a cable with and without loading for carrier frequencies.

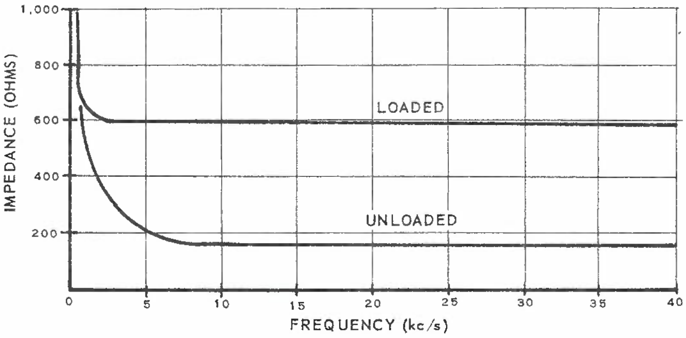


FIG. 46. CHARACTERISTIC IMPEDANCE FOR LOADED AND UNLOADED CABLE PAIRS.

The advantages of loading listed in para. 9.7, are obtained for all types of loaded pairs, but each type of circuit is loaded for specific reasons, which are explained in paras. 9.8 to 9.10.

9.8 Voice frequency loading is used on junction cables and voice frequency trunk cables. The main purposes of loading these cables is to reduce their attenuation, but a reduction in distortion is also obtained. The reduction in attenuation constant and the improvement in distortion enables the required transmission standards to be obtained over much longer lengths of cable, without the aid of repeaters.

9.9 Radio programme frequency loading. The main reason for loading radio programme cable pairs is to reduce distortion and attenuation. The coils have a smaller inductance and are spaced at closer intervals than those used for VF loading. This gives the radio programme channel a higher cut-off frequency and, therefore, the wider frequency range required for reasonable quality radio programme transmission.

9.10 Carrier frequency loading. Where trunk entrance cables and short lengths of intermediate cables are connected to open wire lines, it is not always practical to use transformers to match over the wide range of frequencies transmitted, (say from 300c/s to say 30kc/s) because the impedance of the open wire line and the unloaded cable pair vary in a different manner in the lower frequency range, as shown in Fig. 47. For example, the impedance ratio between the open wire line and unloaded cable pair is approx. 4:1 at 10kc/s and 2:1 at 300c/s.

Carrier frequency loading is applied to trunk entrance cables, and short lengths of intermediate trunk cables, primarily for the purpose of increasing the characteristic impedance of the cable to a value which more evenly matches the characteristic impedance of the open wire line for the complete range of frequencies to be transmitted, (Fig. 47). Carrier frequency loading also provides a reduction in attenuation and distortion in the cable pair.

The characteristic impedance of the open wire line is used as a basis for calculating the inductance and spacing of the loading coils applied to the cable connected to it. The characteristic impedance of open wire lines is generally regarded as being 600Ω, so the trunk entrance cable connected to it would be loaded to have the same characteristic impedance. The size of the coils and the spacing required to match a multiconductor cable pair to an open wireline, for carrier frequency loading, limits the cut-off frequency of the cable pair to 30-40kc/s.

Loaded disc insulated star quad (D.I.S.Q.) cable of a special design is used for the higher frequency range required for twelve channel systems and is explained in the course paper on twelve channel open wire systems.

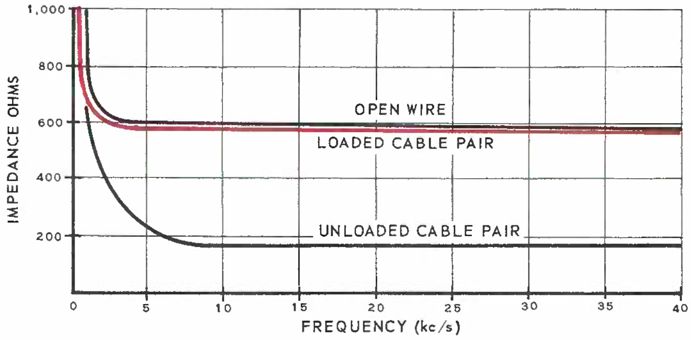


FIG. 47. CHARACTERISTIC IMPEDANCE OF LOADED CABLE PAIR AND OPEN WIRE LINE.

10. CROSSTALK.

10.1 Crosstalk is intelligible or unintelligible noise that is induced into a circuit from another circuit situated nearby. The inducing circuit is known as the disturbing circuit and the circuit in which the crosstalk occurs is the disturbed circuit.

Due to their length, and the distances they run parallel to other telecom. and power circuits, transmission lines would have a high level of crosstalk noise induced into them unless suitable precautions are taken in the design and construction of the lines and routes.

As explained in para. 2.4, a signal sets up magnetic and electric fields in the space around the line conductors. These fields vary in strength according to the amplitude of the signal producing them. When the fields cut nearby conductors, e.m.fs. are induced into them causing current to flow and crosstalk to result. The waveshape of the crosstalk induced in the disturbed circuit is the same as the waveshape of the signals in the disturbing circuit. The cutting of other conductors by the fields is referred to as "magnetic coupling" and "electrostatic coupling".

10.2 Magnetic coupling. In Fig. 48, A and B are the conductors of a disturbing transmission line which is running parallel to C and D, the conductors of a disturbed transmission line. Assume that an A.C. signal is being transmitted over A and B, and at one instant it produces a magnetic field which couples the conductors C and D, as shown. The flux density at C is greater than at D, therefore, the e.m.f. induced in C will be greater than that induced in D, as shown by the dotted arrows. The resultant e.m.f. between C and D causes current to flow in the disturbed circuit, producing crosstalk.

During the other half cycle, the same conditions exist, but all the currents and voltages are reversed.

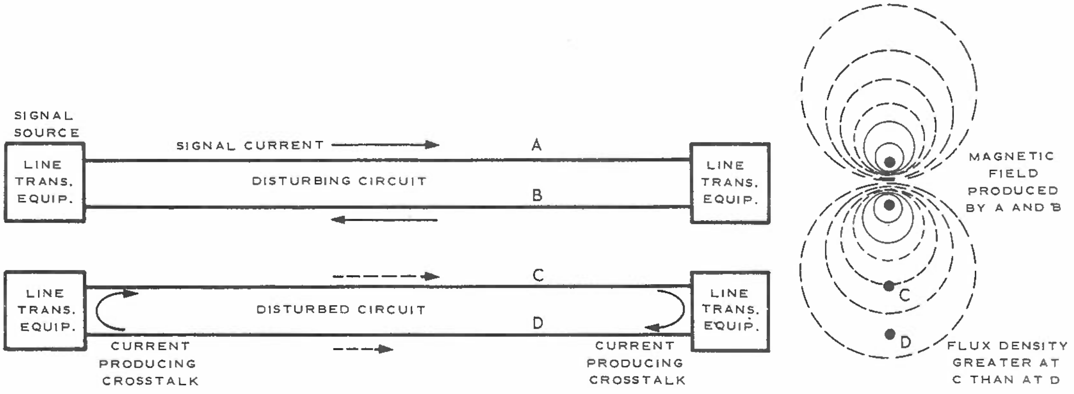


FIG. 48. MAGNETIC COUPLING.

10.3 Electrostatic coupling. The electric field produced by the signal in the disturbing circuit, A and B, produces electrostatic coupling to the disturbed circuit C and D. The electrostatic coupling can be represented by lumped capacitors C1, C2, C3 and C4, as shown in Fig. 49. Assume that at one instant the direction of A.C. signal current in A and B is as shown.

The capacitors C1 and C2 in series and C3 and C4 in series provide shunting paths for the signal current across A and B.

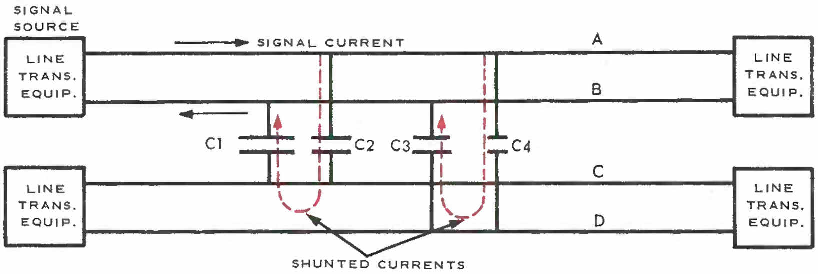


FIG. 49. ELECTROSTATIC COUPLING.

The four capacitances which exist between the conductors can be represented in simplified form by an arrangement of the wheatstone bridge, as shown in Fig. 50. The signal voltage is applied across A and B, and the shunting paths for signal current are shown by the arrows.

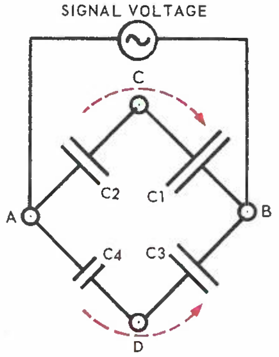


FIG. 50. EQUIVALENT CIRCUIT - ELECTROSTATIC COUPLING.

The size of the capacitances will vary due to the different spacing between the conductors. As the ratio of C1 to C3 is not the same as that of C2 to C4, the bridge is not balanced and there will be a potential difference across C and D.

This potential difference causes current to flow and, therefore, crosstalk in the disturbed circuit C and D, as shown in Fig. 51. During the other half cycle, the same conditions exist but the currents and voltages are reversed.

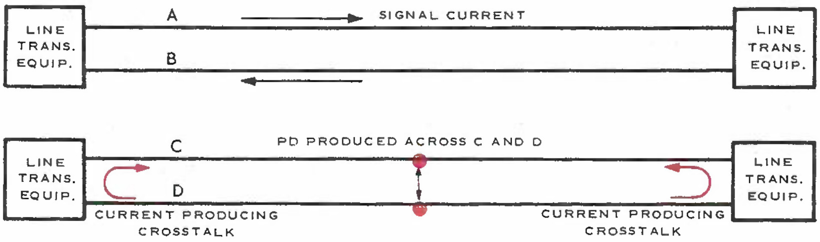


FIG. 51. CROSSTALK PRODUCED BY ELECTROSTATIC COUPLING.

10.4 Combined effects of electrostatic and Magnetic coupling. The effects of magnetic and electrostatic coupling should be combined and considered together, because the signal in the disturbing circuit produces both fields together in the form of an electromagnetic wave, which cuts the conductors of the disturbed circuit.

Fig. 52 shows the induced currents in the disturbed circuit due to magnetic and electrostatic coupling. The effects of these currents is to combine and produce:-

(i) A high level of crosstalk at one end of the disturbed circuit, because the currents at that end are in the same direction and additive.

(ii) A lower level of crosstalk at the other end of the disturbed circuit, because the currents are in opposition and only the difference between them produces the crosstalk.

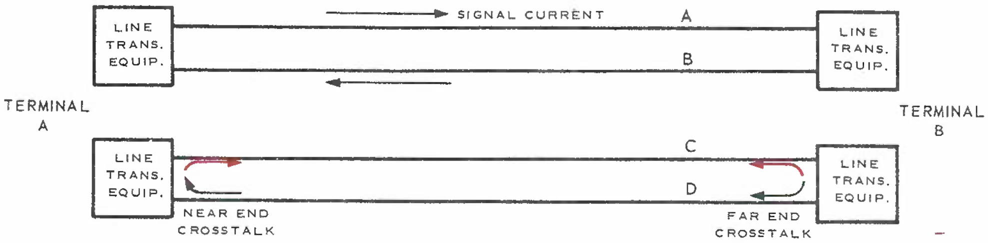


FIG. 52. NEAR END AND FAR END CROSSTALK - TERMINAL A TRANSMITTING.

10.5 Near end and Far end crosstalk. Crosstalk is referred to as "near-end" and "far-end" crosstalk, with reference to the signal source of the disturbing circuit. For example, if terminal "A" is transmitting, as shown in Fig. 52, then the crosstalk produced at terminal A end of the line is near-end crosstalk, and that produced at terminal B end of the line is far-end crosstalk.

Fig. 53 shows the location of near-end and far-end crosstalk in the disturbed circuit when terminal B is transmitting over the disturbing circuit.

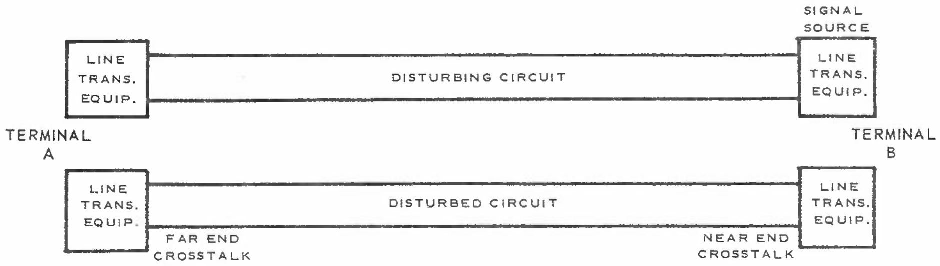


FIG. 53. NEAR END AND FAR END CROSSTALK - WHEN TERMINAL B IS TRANSMITTING.

10.6 The amount of crosstalk induced by magnetic and electrostatic coupling varies with the frequencies transmitted over the disturbing circuit, and the spacings between the conductors of the disturbed and disturbing circuits.

Because crosstalk increases with frequency, more elaborate precautions have to be taken to reduce crosstalk as the frequency range transmitted is increased. Transmission lines, therefore, are designed and constructed for the particular frequency range to be transmitted over them.

10.7 The effects of crosstalk between transmission lines is reduced by suitable equipment design and line construction design.

Equipment design methods of reducing crosstalk include, sending different frequencies ranges over lines on the same route, ensuring correct signal levels are used on the lines, correct spacing of repeaters, etc. All of these methods are explained in other papers of the course.

The general principle employed in line construction methods to reduce crosstalk, is to arrange the lines in such a manner that the induced voltages in each side of the disturbed circuit are equal and opposite and produce a zero resultant voltage.

11. CROSSTALK REDUCTION BETWEEN OPEN WIRE LINES.

11.1 Two methods are used in open wire line construction to reduce crosstalk, they are:-

(i) Correct spacing of the line conductors.

(ii) Transpositions of the line conductors.

11.2 Spacing of line conductors. If the two conductors of a line are spaced very close to each other and separated by large distances from the conductors of other lines, crosstalk between the lines would be reduced to a minimum. For example, if the spacing between A and B is small and they are spaced a large distance from C and D, as shown in Fig. 54, the effects of the fields produced from A and B will be practically the same on C as on D, and little crosstalk will result.

FIG. 54. SPACING OF OPEN WIRE LINE CONDUCTORS.

In practice, the limit to closeness between the two conductors of a line is set by the possibility of them contacting in the span, and the maximum distance between lines is determined by the width of the polearms and the number of pairs to be carried on them. The actual spacing used varies on different routes, according to the frequencies transmitted over the lines etc. An example of spacing used for carrier systems operation up to 140kc/s is shown in Fig. 55.

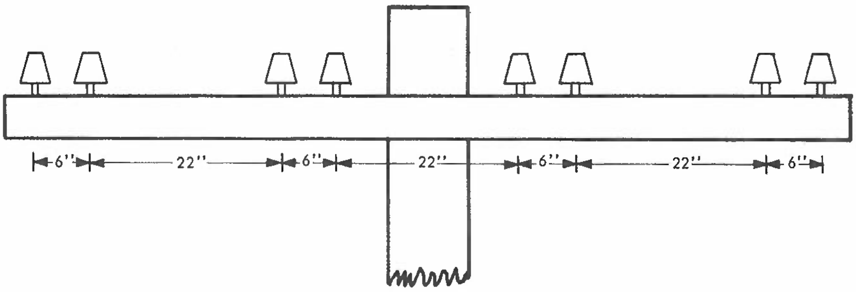


FIG. 55. SPACING OF OPEN WIRE LINES FOR FREQUENCIES UP TO 140kc/s.

11.3 Transpositions. Spacing of line conductors only reduces crosstalk but does not eliminate it, because both conductors of one line are not equidistant from the conductors of the other line, therefore, resultant voltages are still induced in the disturbed circuit.

Transpositions are a method of further reducing crosstalk, by interchanging the positions of the two conductors of a line at specific intervals along the line. Fig. 56 shows the wires of C and D transposed in the centre of the line.

Magnetic Coupling. (Fig. 56). Considering the magnetic coupling, a large and a small e.m.f., (shown by the dotted arrows) are induced in C conductor and also in D conductor, so the resultant e.m.f. will be very small and crosstalk is further reduced.

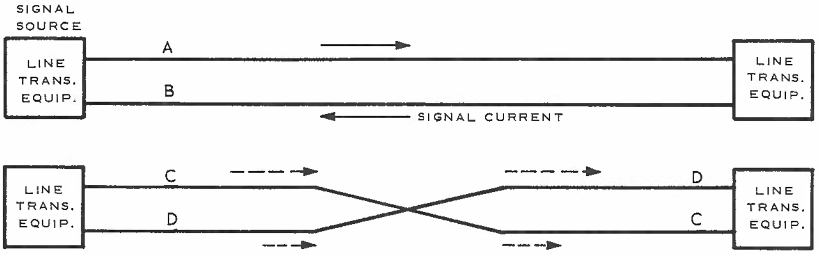


FIG. 56. EFFECT OF TRANSPOSITIONS ON MAGNETIC COUPLING.

Capacitive Coupling. The capacitive coupling existing between the transposed conductors is shown in Fig. 57 (for simplicity only the capacitances between B and C and between B and D conductors are shown).

The total capacity between B and C equals $C1_a$ and $C1_b$ and the total capacity between B and D equals $C3_a$ and $C3_b$.

Since $C1_a = C3_a$ and $C1_b = C3_b$, the capacitances C1 and C3 in Fig. 50 are equal. Similarly, the capacitances C2 and C4 are equal. The bridge is now balanced, resulting in negligible crosstalk due to capacitive coupling.

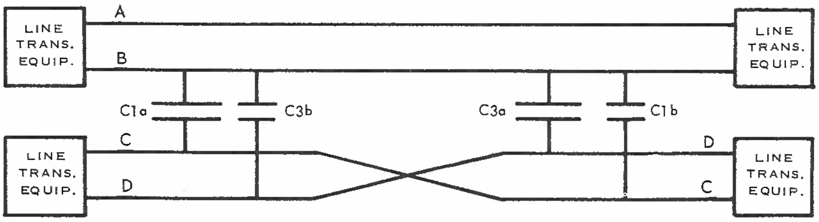


FIG. 57. EFFECT OF TRANSPOSITIONS ON ELECTROSTATIC COUPLING.

11.4 Practical Transpositions. A single transposition is not satisfactory on a transmission line for the following reasons:-

(i) The amplitude of the signal in the disturbing circuit is larger at the line input than at the line output, due to attenuation, therefore larger e.m.fs. are induced into the near end of the disturbed circuit than at the far end. (Fig. 58). The induced voltages on each side of the transposition would not be equal and a resultant voltage would exist to produce crosstalk.

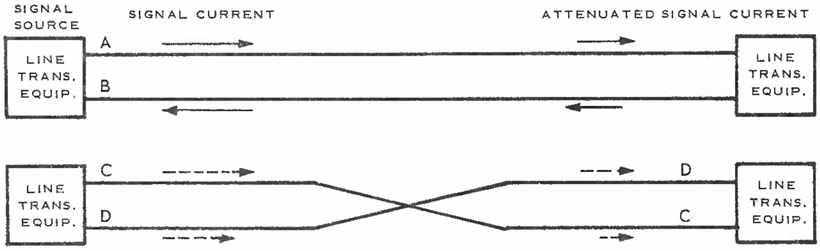


FIG. 58. EFFECT OF ATTENUATION ON A SINGLE TRANSPOSITION.

(ii) At higher frequencies a line may have one or more wavelengths of a signal travelling over it at the same time. If for example the line was one wavelength long, as shown in Fig. 59, the induced voltages, produced by the opposite potentials of the signal on each side of the transposition, would not cancel out. At the instant shown in Fig. 59, the two larger e.m.fs. induced into the C and D conductors are actually in phase, therefore, a resultant voltage exists to produce crosstalk.

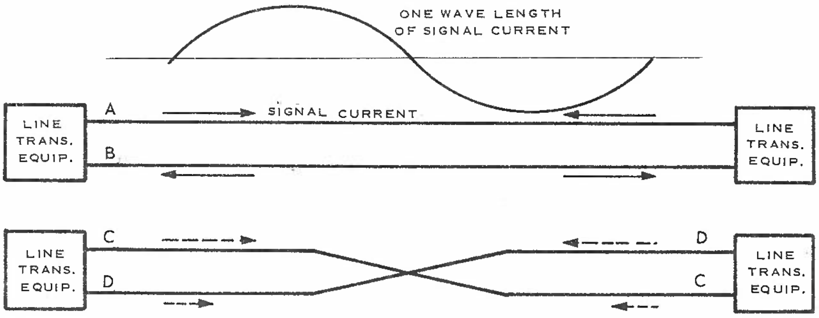


FIG. 59. EFFECT OF WAVELENGTH ON CROSSTALK.

For these reasons a number of transpositions are made in all the lines of a trunk route. The number and spacings of the transpositions are carefully calculated with reference to frequency, wavelength, distance of route.

Fig. 60 shows an example of a transposition scheme applied to four lines on section of a route designed for carrier systems operating up to approximately 30kc/s.

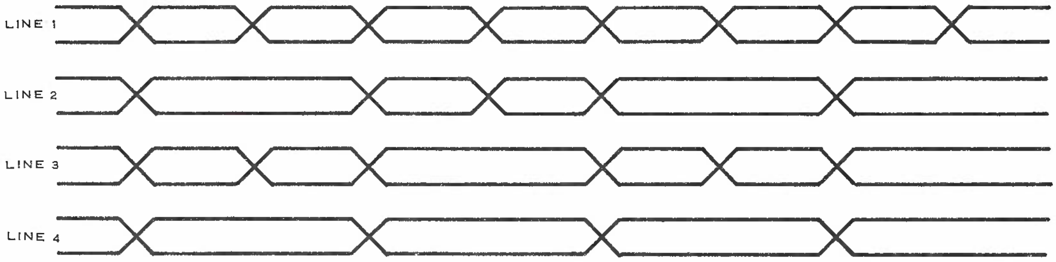


FIG. 60. TYPICAL TRANSPOSITION SCHEME.

12. CROSSTALK REDUCTION IN MULTICONDUCTOR CABLES.

12.1 The perfect arrangement of conductors for the reduction of crosstalk is to arrange the wires in the "square four" configuration shown in Fig. 61. In this arrangement, both wires of transmission line A and B are equidistant from the C and D wires of the other line. It is not possible, due to practical difficulties, to construct open wire lines in the square four arrangement, but multiconductor cables are manufactured with each two pairs of conductors arranged in this manner. The two pairs of cable conductors are called a "star quad"or "quad".

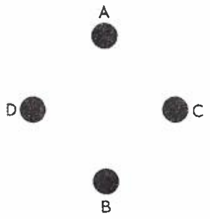
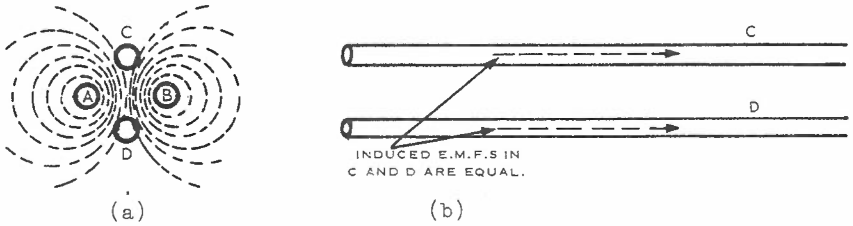


FIG. 61. SQUARE FOUR OR STAR QUAD ARRANGEMENT.

12.2 Magnetic Coupling. In a correctly manufactured quad, conductors A and B are each equidistant from C and D. Therefore, a signal in A and B will induce e.m.fs. of equal value into C and D, because the flux densities at C and D are the same. (Fig. 62a). Since the induced e.m.fs. in C and D are equal and opposite, no crosstalk is induced into them by the signal. (Fig. 62b).



(a) (b)

FIG. 62. MAGNETIC COUPLING BETWEEN QUAD CONDUCTORS.

12.3 Capacitive Coupling. If a quad is perfect in its manufacture, the spacing between the conductors is equal, and the capacities C1, C2, C3 and C4 are equal. The bridge in Fig. 63 is balanced and no potential difference exists between C and D to cause crosstalk.

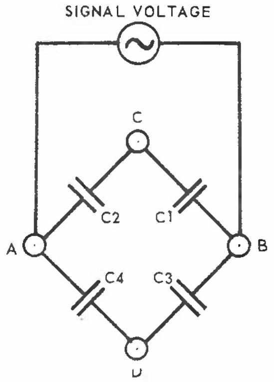


FIG. 63. ELECTROSTATIC COUPLING BETWEEN QUAD CONDUCTORS.

12.4 A multiconductor cable contains many pairs of conductors arranged in star quad form. Transpositions are provided to reduce crosstalk between neighbouring quads, by continuously rolling together the four wires of each quad throughout the entire length of the cable (Fig. 64a). To further reduce crosstalk, each layer of quads are spiralled in opposite directions around the core of the cable, as shown in Fig. 64c.

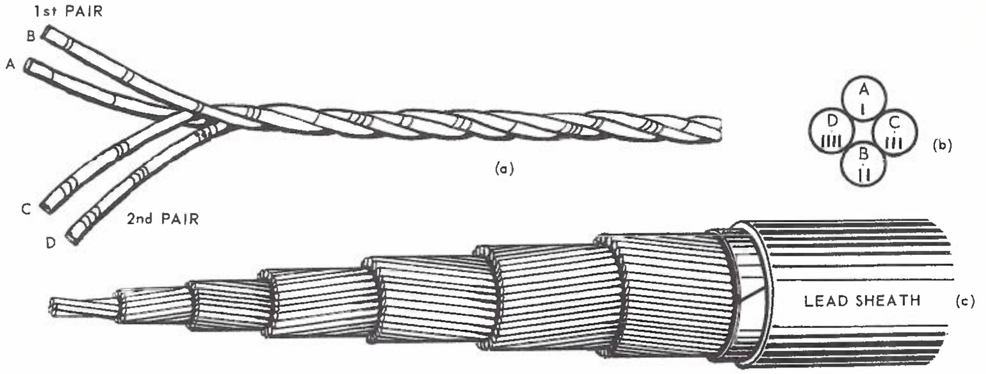


FIG. 64. STAR QUAD CABLE.

12.5 Capacity unbalance. The capacities existing between the conductors in a quad are only equal in a perfect length of cable. In practice, it is impossible to manufacture a length of perfect cable, because:-

(i) The diameter of the soft copper conductors may vary slightly.

(ii) The thickness of the insulation paper may vary.

(iii) Some conductors may be longer than others, due to the twisting of quad conductors and spiralling of layers.

(iv) Irregularities may occur in the application of the paper insulation around the conductors.

(v) The formation of the quads may not be regular throughout the length of the cable.

Since cable conductors are situated in close proximity to each other, the capacitances between them is high, therefore, any defects in cable construction causes capacity unbalance between the conductors. Capacity unbalance can exist between conductors within the same quad and also between conductors in neighbouring quads.

12.6 Capacity unbalance in cables is compensated for by:-

(i) Selective jointing, and

(ii) Capacity balancing.

In selective jointing, all quads in each length of cable in a route are tested for capacity unbalance, which may exist within the quads, or between neighbouring quads. Quads in each of the cable lengths are then chosen and jointed together so that capacity unbalance of quads in one length of cable are compensated for by the capacity unbalance which exists in the quads chosen in the other lengths of cable.

Capacity balancing. Any capacity unbalance remaining, after selective jointing has been completed, is compensated for by connecting capacitors between the conductors until a satisfactory balance is obtained. The capacitors are connected in cable joints, or in "capacity balancing bays" situated in terminal or repeater installations. The size of the capacitors, and conductors between which they are connected, can only be determined after capacity unbalance tests have been completed over the entire cable route.

NOTES

11. *TEST QUESTIONS.*

1. *Sketch the electromagnetic field existing around the two conductors of a transmission line.*
2. *What is "skin effect" and how is it affected by frequency?*
3. *Describe the construction of a coaxial cable.*
4. *Sketch the electromagnetic field existing in a coaxial cable.*
5. *What are "trunk entrance" cables and why are they used?*
6. *Explain with the aid of sketches how a signal travels in the form of waves over a transmission line.*
7. *What is "velocity of propagation"?*
8. *Calculate the wavelength of a 4Mc/s signal transmitted over a coaxial line at a velocity of propagation of 150,000 miles per sec.*
9. *Briefly explain how delay distortion is produced in a signal being transmitted over a transmission line.*
10. *Name the four primary constants and state the units in which they are expressed.*
11. *Sketch an equivalent circuit of a transmission line.*
12. *What is "attenuation constant"?*
13. *Draw a "power-level" diagram which illustrates attenuation occuring over a transmission line.*
14. *Explain, with the aid of sketches, how frequency distortion is produced over a transmission line.*
15. *What is the function of an "attenuation equaliser"?*
16. *What is "reflection" and how is it produced on a transmission line?*
17. *State the formula used for calculating the characteristic impedance of a transmission line.*
18. *What are the advantages of terminating lines in an impedance equal to their characteristic impedance?*
19. *What are the advantages of loading multiconductor cables?*
20. *Explain the main reasons for loading.*
    - *(a) Voice frequency cables.*
    - *(b) Radio programme cables.*
    - *(c) Carrier frequency trunk entrance cables.*
21. *Explain how magnetic coupling produces crosstalk.*
22. *Explain how electrostatic coupling produces crosstalk.*
23. *What is "near end" and "far end" crosstalk?*
24. *Explain how transpositions reduce crosstalk in open wire lines.*
25. *Explain how crosstalk is reduced by the star quad arrangement of multiconductor cable pairs.*
26. *What produces capacity unbalance in star quad cables and state two methods of compensating for it.*

END.