No. 169

The Institution of Post Office Electrical Engineers.

Crosstalk

H. C. S. HAYES, A.M.I.E.E., R. A. SEYMOUR
and P. R. BRAY, M.Sc. (Eng.), Grad.I.E.E.

A Paper read before the London Centre of the Institution on the
8th November, 1938

No. 169

The Institution of Post Office Electrical Engineers

Crosstalk

H. C. S. HAYES, A.M.I.E.E., R. A. SEYMOUR
and P. R. BRAY, M.Sc. (Eng.), Grad. I.E.E.

A Paper read before the London Centre of the Institution on
Tuesday, 8th November, 1938

Crosstalk

INTRODUCTION.

The subject of crosstalk has been made increasingly important by the development of multi-circuit carrier working on underground cables. While several papers have been published in this country*, including one as recently as 1935, it is felt that sufficient information has been obtained in the last two or three years to justify this additional paper. While the presentation of this information has been the primary object, the well-known principles of the subject have been included to make the paper as self-contained as possible. On the other hand, the more recent data relates almost exclusively to underground cables and associated apparatus, and therefore overhead lines are not considered.

The main portion of the paper is divided into seven parts:—

I. Principles of crosstalk measurement—on lines, apparatus and systems.
II. Measuring sets—audio and carrier types.
III. Nature of crosstalk in cables—electrostatic and electromagnetic couplings—accumulation of crosstalk within a repeater section.
IV. Crosstalk limits—crosstalk accumulation on long circuits.
V. Methods of crosstalk reduction—balance, separation, compandor.
VI. Crosstalk balancing—application to repeater section of carrier cable.
VII. Miscellaneous crosstalk considerations—effects of apparatus unbalance, cable repairs, intermediate loading, multiphone working and indirect paths.

No bibliography is attached, reference to other papers and articles appearing directly in the text.

Terms and Definitions and other relevant information are given in Appendices.

Throughout the paper the terms voltage, current and impedance, denoted by such symbols as V_A, I_A and Z_0, are intended to refer to vector quantities. If only the modulus of such a quantity is intended this is indicated by the addition of two vertical lines thus $|Z_0|$.

PART I.

PRINCIPLES OF CROSSTALK MEASUREMENT.

By definition, crosstalk[1] is the sound heard in a receiver due to telephone currents in another channel. The magnitude of such sound is a function of the electrical power in the receiver and crosstalk is usually computed by comparison of electrical powers. The decibel is a convenient unit for expressing ratios of electrical power and is the unit now most used to indicate crosstalk attenuation[2] and crosstalk volume[3].

Although crosstalk is primarily a sound, the term is in practice extended to include interference between telephone circuits at frequencies which lie outside the range audible to the human ear.

In common with all measurements of electrical power, crosstalk attenuation and crosstalk volume may be readily deduced from voltage or current measurements, providing due account is taken of impedances.

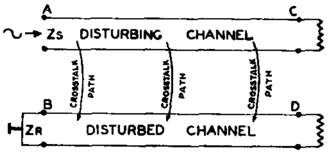


FIG. 1.

Referring to Fig. 1, if P_A, V_A and I_A are the power, voltage and current sent at A into a disturbing circuit of impedance $Z_S/\underline{\phi_1}$

and P_B, V_B and I_B are the resulting power, voltage and current received at B in the terminating impedance $Z_R/\underline{\phi_2}$

then the crosstalk attenuation between A and B is $10 \log_{10} \frac{P_A}{P_B}$ decibels.

If Z_S and Z_R are substantially non-reactive or if $_1\phi$ is equal to ϕ_2 this may also be expressed as

$$10 \log_{10} \frac{V_A^2}{Z_S} \times \frac{Z_R}{V_B^2} ;$$

$$\text{or} \quad 10 \log_{10} \frac{I_A^2}{Z_R} \times \frac{Z_S}{I_B^2} ;$$

$$\text{or} \quad 20 \log_{10} \frac{V_A}{V_B} + 10 \log_{10} \frac{Z_R}{Z_S} ;$$

$$\text{or} \quad 20 \log_{10} \frac{I_A}{I_B} + 10 \log_{10} \frac{Z_S}{Z_R} \text{ db.}$$

If Z_S and Z_R are *not* substantially non-reactive, or if ϕ_1 and ϕ_2 are *not* essentially equal, then allowance must be made for the angles of these impedances.

In practice, Z_S and Z_R and ϕ_1 and ϕ_2 are frequently equal or so nearly so that the crosstalk attenuation, or more simply " the crosstalk," in decibels is 20 times the decimal logarithm of the sent/received voltage or current ratio.

The crosstalk volume at B is the power received in the terminating impedance $Z_R/\underline{\phi_2}$. It is expressed in decibels relative to Reference Telephonic Power[8].

Up to ten years ago crosstalk attenuation was usually expressed as the received/sent current ratio in millionths. If the received current were one-tenthousandth part of the sent current, the crosstalk

---

* " Interference between Circuits in Continuously Loaded Telephone Cables "—A. Rosen, I.E.E. Journal, Vol. 64, 1926.

" Telephone Cable Circuit Interference " — A. Morris, I.P.O.E.E. Paper 126, 1929.

" Crosstalk "—S. Hanford, I.P.O.E.E. Journal, Vol. 28, 1935.

[1, 2, 3] See Appendix II.

[8] See Appendix II.

was said to be 100 units. This method of expression is still occasionally used. If Z_S and Z_R are not equal, the measured received/sent current ratio is corrected to the received/sent current ratio which would give the same received/sent power ratio if $Z_S\underline{/\phi_1}$ and $Z_R\underline{/\phi_2}$ were equal.

Thus if X = measured received/sent current ratio in the conditions shown in Fig. **1**

and X_1 = the received/sent current ratio with $Z_S\underline{/\phi_1} = Z_R\underline{/\phi_2}$.

$$\text{The received/sent power ratio} = X^2 \frac{Z_R \cos\phi_2}{Z_S \cos\phi_1}$$

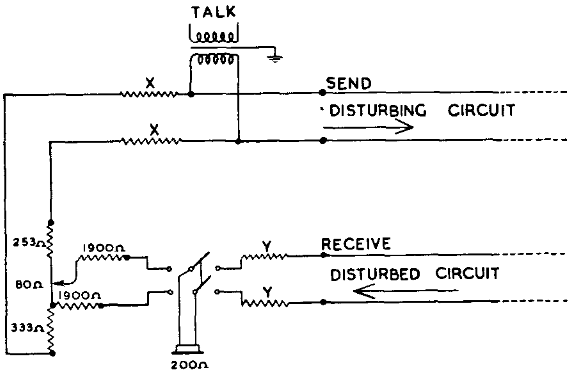
$$\left(\text{or } X_1{}^2 \frac{Z_R \cos\phi_2}{Z_R \cos\phi_2}\right)$$

and $X_1 = X\sqrt{\dfrac{Z_R \cos\phi_2}{Z_S \cos\phi_1}}$. The angular difference between the vectors Z_R and Z_S is generally small enough for the term $\dfrac{\cos\phi_2}{\cos\phi_1}$ to be neglected.

Another method occasionally used to express crosstalk attenuation is to refer to the received/sent voltage ratio in millionths and this method has sometimes been found convenient in this paper. If the impedances of the sending and receiving circuits differ, correction of the measured ratio is required. The correction factor is $\sqrt{\dfrac{Z_S \cos\phi_2}{Z_R \cos\phi_1}}$ instead of $\sqrt{\dfrac{Z_R \cos\phi_2}{Z_S \cos\phi_1}}$ which applies to the received sent current ratio in the last paragraph. (Crosstalk correction factors are given in Engineering Instruction, Tests and Inspections, Lines, H9103 (Test).)

Telephone circuits[13] are provided in a variety of ways, and a conversation between two subscribers may involve the use of overhead line, loaded or unloaded cable circuits, coaxial cable, carrier cable, internal wiring and items of internal apparatus including repeaters and transmission bridges. Crosstalk between two circuits may be due to any one or more of their constituent parts, and measurements are therefore undertaken on lines, apparatus and systems (consisting of a combination of lines and apparatus) to prove their performance from a crosstalk point of view. As a rule, in such investigations, crosstalk attenuation only is measured, as this does not entail an exact knowledge of the sent power. The only restrictions in respect of the sent power are that it should not be so great as to cause overloading of any repeaters in circuit, and not so small as to render the received power so minute as to be comparable with noise pick-up. Generally speaking a sent power of the order of 1 *m*W is desirable, but when very high attenuations are measured and there is no question of overloading repeaters, sent powers of the order of 5 watts are sometimes used to obtain the requisite sensitivity.

One method of crosstalk attenuation measurement at audio frequencies is to apply the output from an ordinary telephone, into the transmitter of which a person is talking at as constant a volume as possible, to the sending terminals of the disturbing circuit which is joined in parallel with a crosstalk meter. The latter is a type of potentiometer and is adjusted so that equal loudness is obtained in a telephone receiver connected alternately to its output terminals and to the receiving terminals of the disturbed circuit. A schematic diagram of the connections of such a set is shown in Fig. **2**. Further details of crosstalk measuring sets are discussed in Part II of this paper.



X,X = EQUAL IMPEDANCES WHICH TOGETHER WITH THE IMPEDANCE OF THE CROSSTALK METER EQUAL THE IMPEDANCE OF THE DISTURBING CIRCUIT

Y,Y = EQUAL IMPEDANCES WHICH TOGETHER WITH THE IMPEDANCE OF THE RECEIVER EQUAL THE IMPEDANCE OF THE DISTURBED CIRCUIT

Fig. 2.

If the impedances of the disturbing circuit and the crosstalk meter are equal the meter indicates directly the received/sent current ratio, and the crosstalk attenuation in decibels can be readily calculated. If these impedances are not equal, but are respectively Z_s and Z_m, the current in the meter and the current sent into the disturbing line are in the proportion $\dfrac{|Z_s|}{|Z_m|}$ and the received/sent current ratio indicated by the meter requires to be multiplied by $\dfrac{|Z_s|}{|Z_m|}$. An alternative procedure to avoid the necessity for this correction is to make Z_s and Z_m equal by means of building out impedances as indicated in Fig. **2**.

The generation of disturbing power by talking into a telephone is tedious and a complex tone is generally used as a substitute for the human voice. The tone is derived from a buzzer designed to give a complex wave form approximating to speech in energy distribution.

Considerable experience is necessary to judge correctly the equality of two volumes of sound heard in a receiver, and as an alternative to the aural method of comparison a visual method is often preferable. In this method tone is applied as before to the sending terminals of the disturbing circuit and to a potentiometer in parallel. Adjustment of the potentiometer allows any fraction of the voltage applied to the disturbing circuit to be tapped off for comparison with that received across an impedance terminating the disturbed circuit. By means of a two-way switch the voltage obtained from the output terminals of the potentiometer or the voltage received from the disturbed circuit can be connected in turn across the

---

[13] See Appendix II.

high impedance input of an amplifier-rectifier. The potentiometer is adjusted until a sensitive D.C. reflecting galvanometer in the rectifier circuit shows the same deflection in both positions of the two-way switch and thus indicates equality between the voltages being compared. The potentiometer is calibrated to read directly the received/sent voltage ratio or the corresponding attenuation in decibels.

Crosstalk attenuation measured by a visual method is generally 1 or 2 dbs. less than that measured by aural comparison. This is due to the fact that crosstalk attenuation between audio circuits is as a rule rather less at the top end of the audio range than at the lower end, and while the amplifier-rectifier has practically the same sensitivity over the whole audio range and attaches the same relative importance to all frequencies, the combination of the receiver with the ear is less sensitive to the high frequency crosstalk components and tends to under-rate them. Differences between the two methods of measurement are small and do not in practice give rise to difficulty. No difference would occur if pure tone were used for the disturbing power. Measurement with pure tone often suffices and is usually made at a frequency of 800 or 1000 c/s.

Measurements of crosstalk attenuation between carrier systems are of two kinds, those made at high frequency between the lines used for the systems, and those made at low frequency at the terminals of the systems.

The high frequency measurements are invariably carried out with a single frequency source of disturbance as the change of crosstalk attenuation between lines is comparatively small for a change of frequency within the limited range of a sideband, and there is no virtue in the use of a complex wave. Measurements at frequencies corresponding to those of the sidebands are valuable, because the amplitude of the audio frequency produced on demodulation is directly proportional to the amplitude of the sideband frequency by which it is set up. The principle of measurement is the same as in ordinary visual crosstalk tests at audio frequencies. Power at the required frequency is applied (through a balanced transformer) to the disturbing circuit and an attenuator is connected to one end of the circuit. Adjustment of the attenuator allows any required fraction of the voltage at this end of the disturbing circuit to be compared with that received across an impedance terminating the same end of the disturbed circuit. The comparison is made by means of a high impedance amplifier-detector with a mirror galvanometer in the detector circuit. When the attenuator is adjusted so that both voltages are equal its reading indicates directly the crosstalk attenuation in decibels.

Measurement of overall crosstalk at audio frequency between any two circuits derived from different carrier systems but utilizing the same high frequency channels[12] over the carrier portions of the circuits presents no difficulty and is carried out by either the aural or visual methods already indicated. The method of measuring crosstalk between two circuits derived from the same (or different) carrier groups and utilizing different high frequency bands over the line is, however, rather different. This latter type of crosstalk is not audible between circuits associated with channels having carriers of widely different frequencies, but it is audible, although unintelligible, between circuits on adjacent channels, *i.e.*, channels with carriers separated by 4 kc/s.

The way in which audible but unintelligible crosstalk is produced will be clear from a consideration of an example of interference between two channels with carriers of 40 and 36 kc/s respectively on the same pair. When two frequencies of 1000 and 3000 c/s are passed into the circuit associated with the 40 kc/s carrier, corresponding frequencies of 39 kc/s (40-1) and 37 kc/s (40-3) are transmitted to line. These frequencies are in the upper sideband of the 36 kc/s channel and if the 36 kc/s channel filter does not discriminate sufficiently between the upper and lower sidebands, frequencies of 3 kc/s and 1 kc/s appear after demodulation. Frequencies of 1 kc/s and 3 kc/s are thus transformed respectively into frequencies of 3 kc/s and 1 kc/s. Crosstalk produced in the circuit associated with the 36 kc/s carrier, as a result of speech in the circuit associated with the 40 kc/s carrier, has the same rhythm as speech, but the frequencies are inverted. This question has been more fully discussed in I.P.O.E.E. Paper 157 (" Recent Advances in Carrier Telephony ") by R. J. Halsey, 1935.

Inter-channel crosstalk is generally measured with a circuit noise-meter (Psophometer) (see " The Circuit Noise-Meter (Psophometer) and its Applications," by H. R. Harbottle, I.E.E. Journal, Vol. 83, August, 1938). This instrument, as its name implies, is designed for measuring noise. It is essentially a sensitive amplifier-detector capable of giving an indication on a D.C. micro-ammeter when an A.C. voltage at audio frequency is applied to its input terminals. At any particular frequency the deflection is proportional to the input voltage. Between the input terminals and the amplifier-detector, however, a filter network is incorporated which attenuates the incoming voltages differently at different frequencies so that they affect the micro-ammeter deflection to a greater or less degree in the same way as they would affect an average human ear listening to an average receiver. The combination of a receiver with a human ear has much greater sensitivity between 600 and 1400 c/s than at other frequencies, the frequency of greatest sensitivity lying between 1000 and 1100 c/s, and the psophometer is therefore designed to give greatest weight to frequencies which lie between these limits. A weighting curve for a typical psophometer is given in Fig. **3**. The ordinates of this curve represent the relative effects of equal voltages at frequencies between 50 and 4000 c/s, in terms of the effect of the same voltage at 800 c/s.

Inter-channel crosstalk is not usually expressed as an attenuation but is measured as the voltage received across an impedance terminating the disturbed circuit

---

[12] See Appendix II.

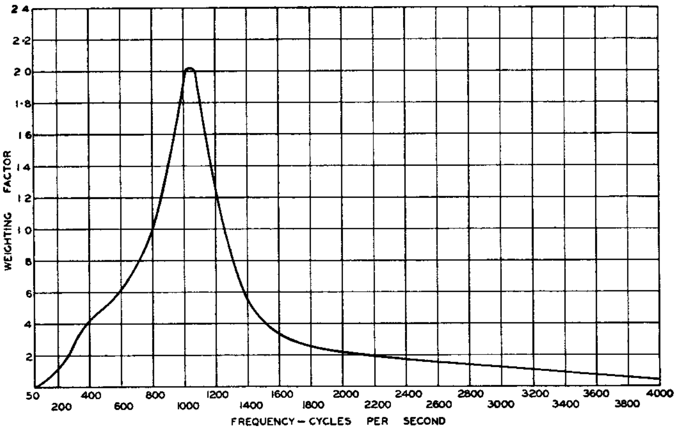


FIG. 3.—TYPICAL WEIGHTING CURVE FOR PSOPHOMETER.

in terms of the voltage at 800 c/s which would give the same deflection on the psophometer micro-ammeter.

Near-end and Far-end (or Distant-end) Crosstalk.[4,5]

When crosstalk energy is transferred from one circuit to another it may usually be detected at both ends of the disturbed circuit. In Fig. **4** the crosstalk at B is referred to as near-end crosstalk, and that at D at the far-end of the circuit as far-end crosstalk.

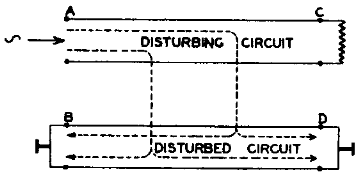


FIG. **4**.

If P_A is the power sent at A, and P_B and P_D are the powers received at B and D respectively, the near-end crosstalk attenuation $= 10 \log_{10} \frac{P_A}{P_B}$ and the far-end crosstalk attenuation $= 10 \log_{10} \frac{P_A}{P_D}$ db.

With unidirectional circuits near-end crosstalk only is of importance between circuits transmitting in opposite directions and far-end crosstalk only is of importance between circuits transmitting in the same direction.

The principles of near-end and far-end crosstalk measurement are identical, but with far-end crosstalk the receiving end of the disturbed circuit is generally far removed from the sending end of the disturbing circuit, and direct comparison of the sent and received currents or voltages from one point by means of some form of potentiometer or attenuator is not possible. Usually, however, both the disturbing and disturbed circuits terminate at the same point and the ratio of power received on the disturbing circuit to that received on the disturbed circuit is readily obtained by comparison of the currents or voltages at C and D. This ratio is referred to as Signal-to-Noise Ratio[7] (S/N) Crosstalk.

When both disturbing and disturbed circuits are of similar composition and follow the same route, the power levels under working conditions at points C and D are generally alike, and the signal-to-noise measurement of crosstalk, therefore, not only supplies information as to the relative strengths of the signal power at C and the crosstalk power at D, but also of the relative strengths of the normal speech and crosstalk powers received at D.

To convert values of far-end crosstalk measured as signal-to-noise ratios into crosstalk attenuation in the sense of its definition it is necessary to take the attenuation of the disturbing line into account.

Far-end crosstalk (S/N)

(where P_C is power received at C)

$$= 10 \log_{10} \frac{P_C}{P_D} \text{ db.}$$

Far-end crosstalk attenuation as per definition

$$= 10 \log_{10} \frac{P_A}{P_D} \text{ db.}$$

$$= 10 \log_{10} \frac{P_A}{P_C} \times \frac{P_C}{P_D} \text{ db.}$$

$$= 10 \log_{10} \frac{P_A}{P_C} + 10 \log_{10} \frac{P_C}{P_D} \text{ db.}$$

= Attenuation of circuit AC (db.)
+ far-end crosstalk (S/N) (db.).

If crosstalk measurements between two circuits, the ends of which all terminate at different points, are desired, actual measurements of the sent and received powers are necessary because comparison of the sent and received voltages or currents by means of a potentiometer or other similar device is not possible.

Crosstalk Measurement on Lines.

Crosstalk attenuation between lines is affected by the value of the impedances with which they are terminated.

For example if, as shown in Fig. **5**(*a*), a single source of crosstalk exists between two lines AC and BD terminated at C and D so that no reflection of power takes place from these points, the path of the near-end crosstalk between A and B is as indicated by the single dotted line. If, however, reflection takes place from C and D two additional crosstalk paths are introduced as indicated in Fig. **5**(*b*). To obviate effects of this

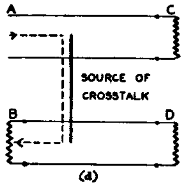


FIG. **5**(*a*).

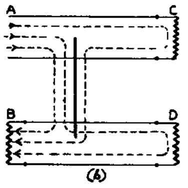


FIG. **5**(*b*).

[4, 5, 7] See Appendix II.

nature crosstalk attenuation measurements on lines are generally carried out with terminations B, C and D all made equal to the characteristic impedances of the lines they terminate. It is convenient to refer to such terminations as perfect terminations. No particular value of terminating impedance is as a rule necessary at A.

In the technique of line crosstalk measurement true crosstalk attenuation is considered as that obtained by comparing sent power with power received in a perfect termination. In crosstalk investigations one (or more) of the terminating impedances B, C and D is sometimes intentionally set to a value which is other than its perfect value, and if the termination at the receiving end of the disturbed line is so treated a correction to the measured current or voltage figure is necessary.

Referring to Fig. **6**, if Z_R represents an impedance terminating a line of characteristic impedance Z_0, by Thevenin's theorem* any incoming crosstalk power may be considered as being due to a generator of internal impedance Z_0 which replaces the line. Assume the open-circuit voltage of this generator is E. Then

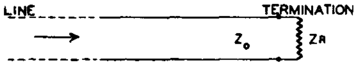


Fig. **6**.

The current received in a perfect termination Z_0

$$= \frac{E}{Z_0 + Z_0} = \frac{E}{2Z_0}$$

The voltage received across a perfect termination

$$= \frac{E}{2Z_0} \times Z_0 = \frac{E}{2}$$

The current received in an imperfect termination Z_R

$$= \frac{E}{Z_0 + Z_R}$$

The voltage received across an imperfect termination Z_R

$$= \frac{E}{Z_0 + Z_R} \times Z_R$$

To convert current or voltage measured in an imperfect termination Z_R into the corresponding current or voltage which would be received in a perfect termination Z_0, it is therefore necessary to multiply the measured current by $\frac{Z_0 + Z_R}{2Z_0}$ and the measured voltage by $\frac{Z_0 + Z_R}{2Z_R}$

For example, if when measuring near-end crosstalk between A and B (Fig. **7**) I_A and V_A are the current and voltage sent at A into the disturbing line of characteristic impedance Z_S, and I_B and V_B are the resulting current and voltage measured at B in Z_R which terminates the disturbed line of characteristic impedance Z_0, the current and voltage which would be measured at B in a perfect termination Z_0 are—

$$I_B \times \frac{Z_0 + Z_R}{2Z_0} \text{ and } V_B \times \frac{Z_0 + Z_R}{2Z_R}$$

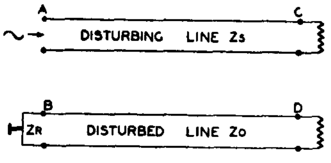


Fig. **7**.

Assuming Z_S, Z_R and Z_0 are substantially non-reactive the true near-end crosstalk is—

$$20 \log_{10} \frac{I_A}{I_B \times \frac{Z_0 + Z_R}{2Z_0}} + 10 \log_{10} \frac{Z_S}{Z_0}$$

$$= 20 \log_{10} \frac{I_A}{I_B} + 20 \log_{10} \frac{2Z_0}{Z_0 + Z_R} + 10 \log_{10} \frac{Z_S}{Z_0} \text{ db.}$$

or

$$20 \log_{10} \frac{V_A}{V_B \times \frac{Z_0 + Z_R}{2Z_R}} + 10 \log_{10} \frac{Z_0}{Z_S}$$

$$= 20 \log_{10} \frac{V_A}{V_B} + 20 \log_{10} \frac{2Z_R}{Z_0 + Z_R} + 10 \log_{10} \frac{Z_0}{Z_S} \text{ db.}$$

The two last terms are correction terms. The first of these is due to the imperfect termination and the second to the difference in impedance of the disturbed and disturbing circuits. Exactly similar corrections apply to far-end crosstalk measurements.

Crosstalk Measurement on Apparatus.

The crosstalk introduced between two circuits by items of apparatus, such as cord circuits or repeaters, depends on the impedances of the circuits into which they are connected. Crosstalk between apparatus should therefore be measured with the input and output terminals closed with impedances equal to the impedances of the lines (as viewed through any terminating transformers in circuit) to which they are normally connected. These impedances vary considerably but have a mean value at audio frequencies in the neighbourhood of 600 ohms, and this value is generally used for terminating apparatus in audio measurements.

Referring to Fig. **8**, the disturbing voltage V_1 is compared with the voltage V_2 received across termination B or voltage V_3 received across termination D. The crosstalk is taken as $20 \log_{10} \frac{V_1}{V_2}$ or $20 \log_{10} \frac{V_1}{V_3}$ db., the former being a near-end and the latter a far-

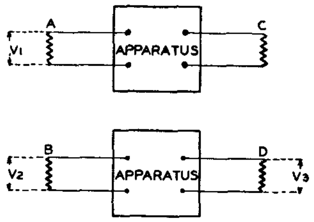


Fig. **8**.

---

* See Appendix III.

end measurement. Termination A may be omitted if desired without vitiating the measured values.

Between audio repeaters crosstalk is measured between the input of one repeater and the output of another, both repeaters being set to maximum gain. The frequency used is 800 c/s, and the measurements are taken from the repeater distribution frame (R.D.F.) so as to include the wiring between the R.D.F. and the repeater tag blocks.

4-Wire repeaters.

With 4-wire repeaters the volume of the disturbing power is adjusted so that the output from the disturbing repeater is 10 *m*W. Measurements are taken between adjacent repeaters and also between the halves of the same repeater units.

Referring to Fig. **9**, the voltage at C is 40 db. greater than the voltage at A, and any crosstalk voltage present at D causes a 40 db. greater voltage at B. Hence to meet a requirement that the crosstalk attenuation between A and B shall not be worse than say 20 db., the near-end crosstalk attenuation between C and D must at least be equal to 20 + 40 + 40 = 100 db.

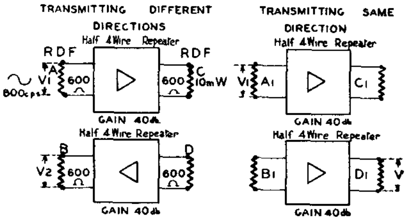


Fig. **9**.

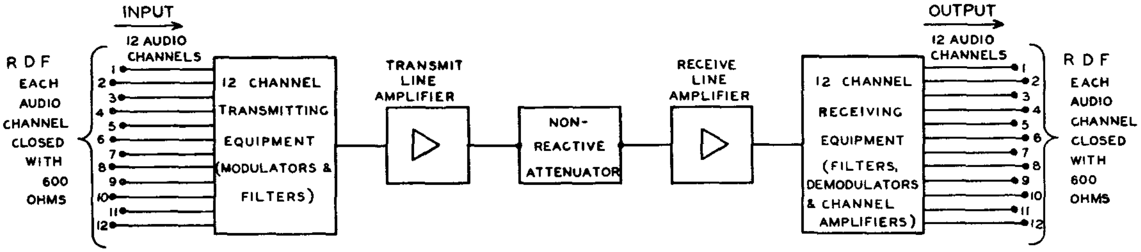


Fig. **11**.—Terminal Apparatus joined Back-to-Back for Crosstalk Measurement.

Again any voltage at A_1 produces a voltage at C_1 which is greater by 40 db. Therefore, if the crosstalk attenuation between A_1 and D_1 is say 38 db., the far-end crosstalk attenuation (S/N) between C_1 and D_1 is 78 db.

2-Wire repeaters.

For 2-wire repeaters the volume of the disturbing power is adjusted so that the output power from the disturbing repeater is 4 *m*W.

Referring to Fig. **10**, any signal voltage at A produces a voltage at C which is greater by 20 db., also any crosstalk voltage input at D produces a 20 db. greater voltage at B. It therefore follows that if the crosstalk attenuation between input A and output B is say 48 db., the near-end crosstalk attenuation in the wiring to the repeaters between C and D must be at least 48 + 20 + 20 = 88 db. Again any signal voltage at C produces a voltage at A which is greater by 20 db., also any crosstalk voltage input at B gives a 20 db. greater voltage at D, thus if the near-end crosstalk attenuation between input C and output D is 48 db., the crosstalk attenuation in the wiring to the repeaters between A and B must at least be 48 + 20 + 20 = 88 db.

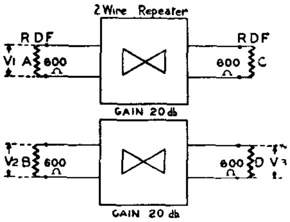


Fig. **10**.

Twelve-circuit carrier terminal station apparatus.

Crosstalk between the apparatus at a station at which one or more twelve-circuit carrier groups terminate is tested by joining the output of the common amplifier associated with the transmitting side of one group, *via* a non-reactive attenuator, to the input of the common amplifier on the receive side of the group as indicated in Fig. **11**. All groups are treated in the same way.

Under these conditions the audio transmitting channels of a group are joined through to the corresponding audio receiving channels and provide twelve unidirectional circuits. These are terminated with 600 ohms at the R.D.F. The modulator level adjustment pads are set as for zero overall equivalent without 2-wire extensions and the level gains are adjusted to give correct operation levels. The measurements are carried out chiefly to test the efficiency of the filters and are made at audio frequency between the input of any one channel and the output of any other channel. As the crosstalk between channels in one group is unintelligible a psophometer is generally used.

Crosstalk Measurement on Systems.

Crosstalk between channels of a carrier group, or between channels of different carrier groups, can be divided into three classes.

(1) Crosstalk between channels in the same group.
(2) Crosstalk between channels in different groups which do not use the same frequency band over the line.
(3) Crosstalk between channels in different groups which use the same frequency band over the line.

Class (1) is dependent upon the efficiency of the channel filters and on non-linearity in loading coils, amplifiers, etc., and such crosstalk is either (*a*) inaudible, (*b*) of such high frequency as to be scarcely audible or (*c*) audible but inverted. In a twelve-circuit carrier system it is measured in the following way. After the system has been lined up to give zero overall equivalent two persons read continuously into two Telephones No. 162 and their speech output is fed into two channels of a group. The speech input is maintained as closely as possible to a volume which is 4 dbs. below Reference Telephonic Power (R.T.P.) as indicated on calibration meters. This level is the level which would obtain if the channels were terminated with 2-wire/4-wire equipment, and R.T.P. were applied at the 2-wire end. The resulting noise voltage across a 600 ohm termination is measured at the receiving end of the disengaged channels with a psophometer.

Crosstalk of class (2) is as a rule negligibly small, but can be measured if necessary in the same way as class (1).

Crosstalk of class (3) is intelligible and is chiefly due to the line. In twelve-circuit carrier working the cable pairs for different groups run together in close proximity for many miles and there is therefore a good chance of this class of crosstalk occurring, and in practice it is the most troublesome. It is measured by either the aural or visual method, the necessary connections being made to the audio transmitting and receiving channels at the R.D.F.s at the terminal stations, after the circuits have been lined up to zero overall equivalent with 2-wire/4-wire terminations included. Near-end and far-end measurements are made, 600 ohm terminations being used.

PART II.

MEASURING SETS FOR AUDIO AND CARRIER FREQUENCIES.

This part of the paper deals firstly with the design and operation of two types of crosstalk measuring sets, which are termed the " balanced " and " unbalanced " type respectively.

The " balanced " crosstalk set.

This set is used at both audio and carrier frequencies, the only difference being in the values of the transformer inductance and the amplifier design. The basic circuit is given in Fig. **12**.

The principle of operation is to obtain from the potentiometer, by adjustment of R, a voltage equal to that obtained from the disturbed circuit. This is indicated by an amplifier-rectifier and galvanometer. At equality the ratio of R, the variable resistance, to the total resistance of the potentiometer, is the same as the ratio of the voltage on the disturbed circuit to the voltage on the disturbing circuit. In this type of set it is extremely difficult to maintain exact symmetry of the voltage applied to the potentiometer with respect to earth. Unless the resistance R is tapped off at exactly the electrical centre of the circuit formed by the secondary winding of the input transformer, the potentiometer resistances, and the primary winding of the amplifier input transformer, the voltage appearing at the secondary winding of this latter transformer will consist of that derived from R, added to potential differences due to unbalance currents flowing to earth in the primary. Thus a false reading on the potentiometer may be obtained.

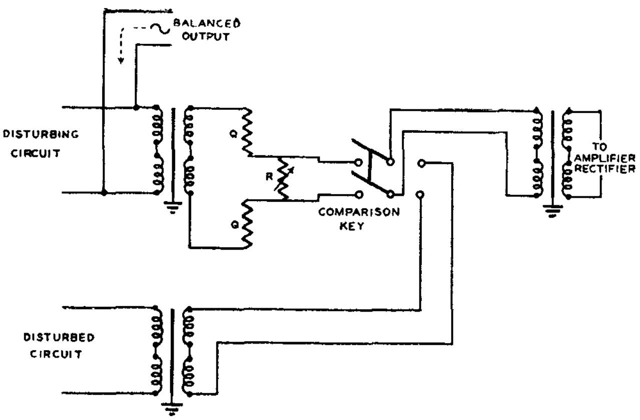


FIG. **12**.—BALANCED TYPE CROSSTALK SET

As a result of this difficulty the " unbalanced " type of set was designed.

The " unbalanced " crosstalk set.

The circuit of this type of set is given in Fig. **13**.

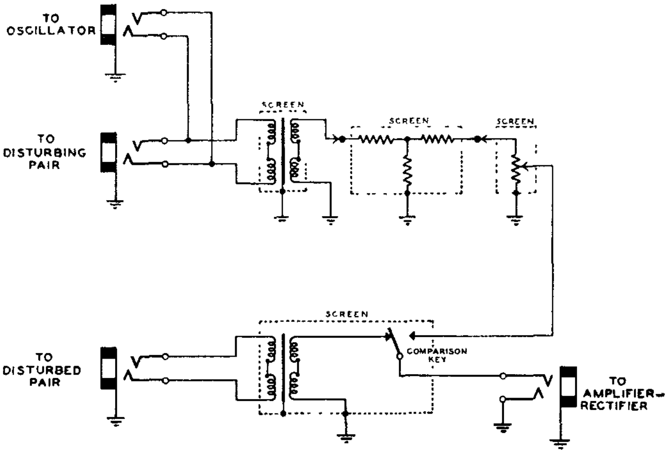


FIG. **13**.—UNBALANCED TYPE CROSSTALK SET.

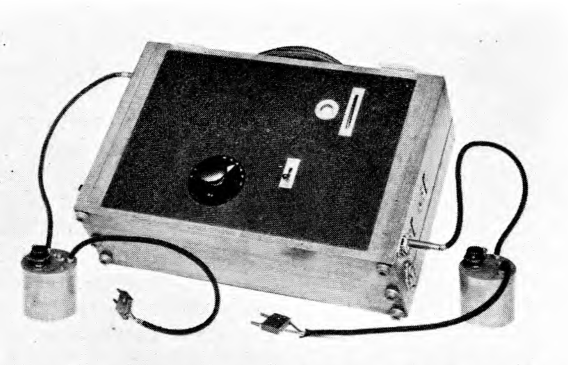
The method of operation in this set is the same as that for the " balanced " type already described, but in this case the possibility of obtaining spurious voltages at the amplifier input is eliminated by the simple process of arranging that one side of the potentiometer and amplifier input are at earth potential, so that the amplifier records potential differences with respect to earth, which can be obtained only from the potentiometer. The potentiometer in this set consists of a T network of paste resistances which are variable in steps of 20 db. from 40-140. This network is closed with a ten ohm resistance tapped in steps of 2 db. from 0-20. The chief difficulty experienced in the construction of this type of set is in the manufacture of the balanced and screened transformers, since it is essential that they introduce but a very small unbalance to earth on the line winding, even though there is a full earth on one end of the set winding. With the transformers at present in use the capacity unbalance to earth does not exceed 2 $\mu\mu$F. under this condition. In addition they must have a reasonable no-load impedance, not less than 3000 ohms say, and a loss as low as possible (not greater than 1 db.). If the two transformers have similar loss characteristics their effect on the set measurements is negligible, since only the difference of their losses is measured.

The set is capable of measurements from 40 to 130 db. below one milliwatt in 200 ohms at frequencies from 10 to 200 kc/s.

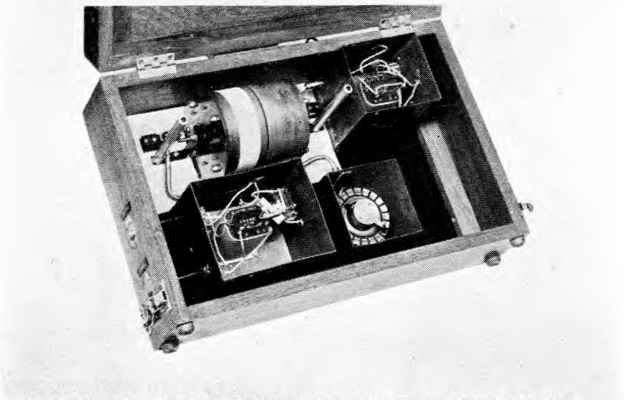
Photographs showing constructional details of the unbalanced crosstalk set, a complete set of testing equipment and details of the screened terminations used for terminating cable pairs are given in Figs. **13**(*a*), **13**(*b*) and **13**(*c*).

The admittance-unbalance set.

While the crosstalk set is an exceedingly useful measuring instrument it only gives information as to the level of the crosstalk voltage, and gives no information as to the phase of this voltage relative to that of the voltage in the disturbing circuit. This



CARRIER FREQUENCY CROSSTALK MEASURING SET & TERMINATIONS.



CARRIER FREQUENCY CROSSTALK SET. (INTERNAL CONSTRUCTION)

FIG. **13**(*a*).

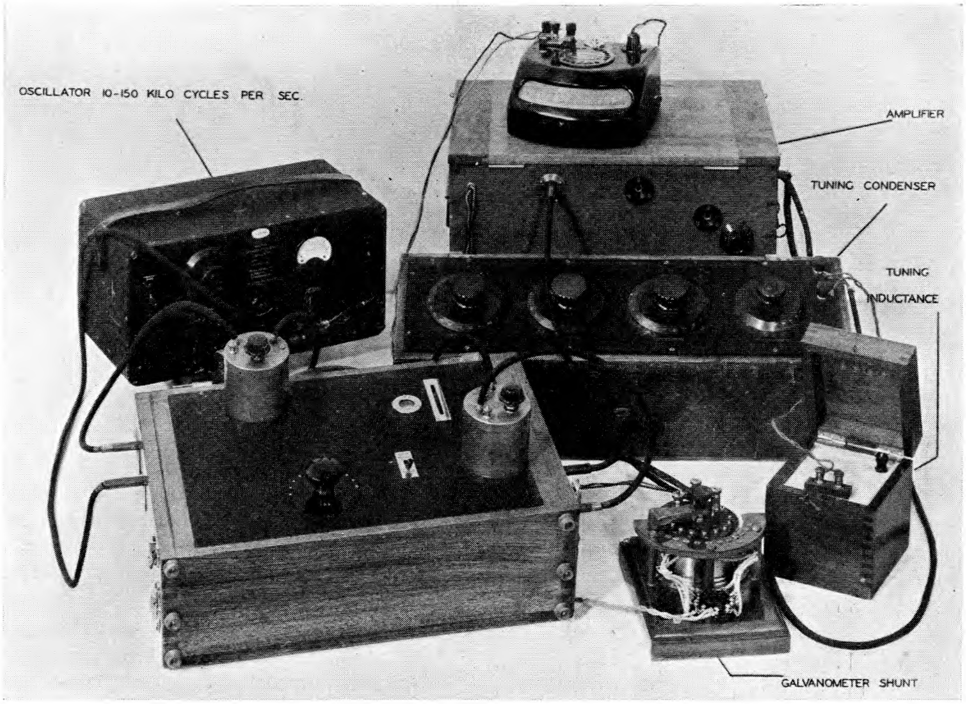


FIG. **13**(*b*).—CARRIER FREQUENCY CROSSTALK SET AND ASSOCIATED EQUIPMENT.

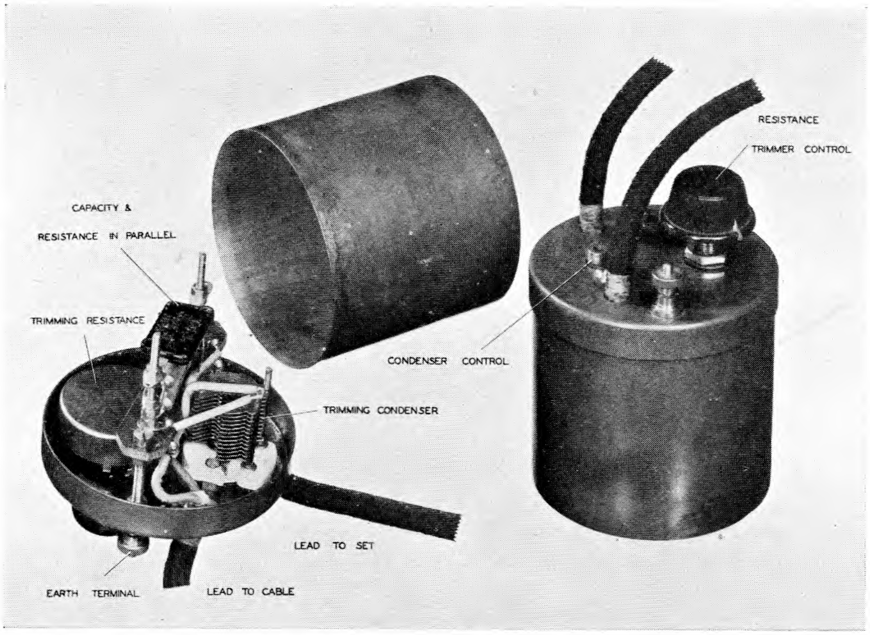


FIG. 13(*c*).—SCREENED TERMINATION.

knowledge is very necessary when investigating the possible reduction of far-end crosstalk by the use of networks. Consequently a set has been designed, which will give the additional information in the form of the admittance required to neutralise the crosstalk voltage, when joined between the wires of the disturbing and disturbed circuits. The circuit arrangements of this set, which is termed an admittance-unbalance set, are given in Fig. **14** and a photograph of the apparatus is shown in Fig. **14**(*a*).

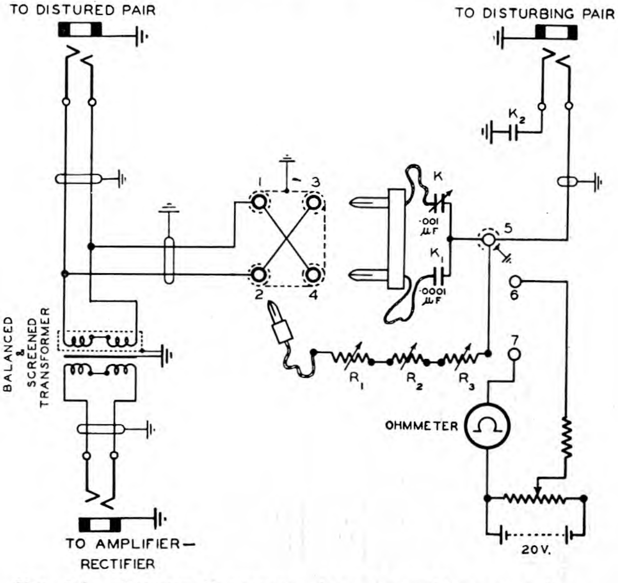


FIG. **14**.—CARRIER-FREQUENCY ADMITTANCE-UNBALANCE SET.

From this circuit diagram it will be seen that the reactive portion of the admittance is provided by the .001 μF. variable air condenser K, which has its residual capacity neutralized by the .0001 μF. trimmer. The real part of the admittance is obtained with three chemical type volume controls, R_1, R_2, and R_3, continuously variable from 10,000 ohms to 1 megohm.

One end of the resistance chain and the condenser common are connected to the A-wire of the disturbing pair, while the opposite ends of the condensers and the resistances can be connected as required to the A or B wires of the disturbed circuit by the use of screened plugs and sockets. An amplifier-rectifier-galvanometer set, connected *via* a balanced and screened transformer to the disturbed pair, indicates by a minimum galvanometer deflection when a balance has been obtained and the crosstalk voltage neutralised. The ohmmeter is provided to enable the value of the balancing paste resistances R_1, R_2 and R_3 to be accurately ascertained. To perform this measurement the sockets 5 and 6 are joined with a U-link and the plug at the free end of the resistance chain is inserted in socket 7. The fixed condenser K_2 connected between the B-wire of the disturbing pair and earth is equal in value to the earth capacity of the set wiring and apparatus connected to the A-wire. Thus any earth unbalance at this terminal of the set is eliminated.

The convention adopted for indicating the positions of the resistance and capacity when a balance has been obtained, is that the resistance and capacity are termed positive when connected between the A-wire of the disturbing pair and the A-wire of the disturbed pair, and negative when they are connected between the A- and B-wires of the respective pairs.

This set is suitable for measurements in cases of crosstalk giving signal-to-noise values between 40 and 80 db. at frequencies from 10 to 200 kc/s.

In the construction of future sets the switching of the condensers and resistances will be performed by means of low capacity keys, and the variable resistances will be calibrated, the ohmmeter being required

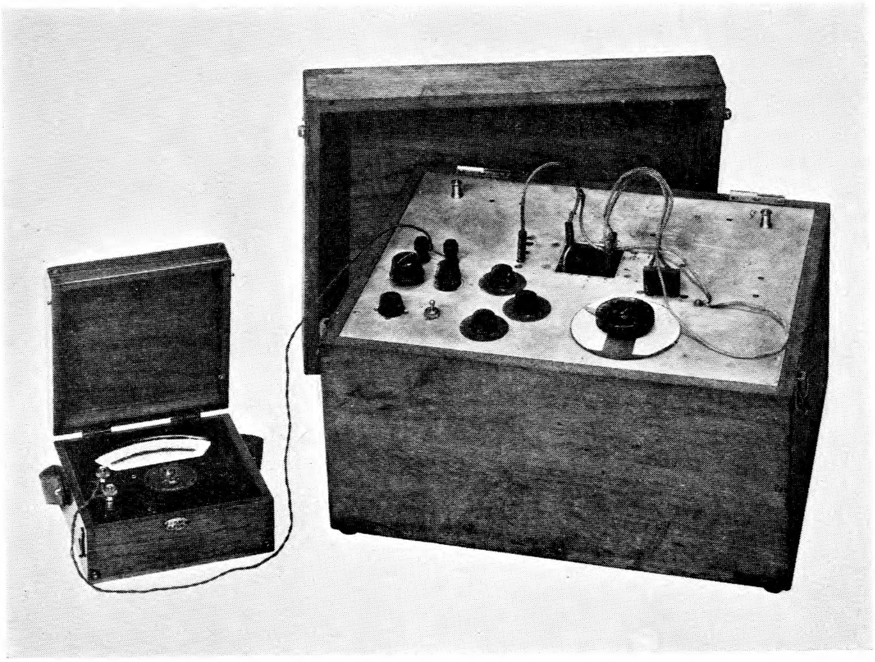


Fig. **14**(*a*).—Carrier Frequency Admittance Unbalance Set.

for occasional check measurements only. This should result in the speed of testing being increased.

The type of cable termination network shown in Fig. **13**(*c*) and employed in conjunction with the admittance unbalance, and carrier frequency crosstalk sets is constructed as follows. The resistance element consists of a paste resistance trimmed with a 5000 ohms chemical type volume control, while the parallel capacity is obtained with M type fixed value mica condensers mounted on studding. The trimmer is a small 100 $\mu\mu$F. variable air condenser. All these elements are mounted on the lid of a 3″ diameter copper can, and can thus be entirely screened from external fields. The connections consist of two 18″ screened V.I.R. leads connected in parallel with each other and in parallel with the resistance and capacity of the network. One lead is used for joining the network to the cable under test, and the other connects to the measuring set.

Measurement of Electrostatic Couplings.

To study the nature of crosstalk in cables it is necessary to take short cable lengths of say 176 yards or less for in such lengths it is possible to distinguish between the crosstalk voltages set up by electrostatic and electromagnetic couplings by the simple device of opening and short circuiting the pairs at the end of the cable remote from the testing end. Of the circuits employed for the measurement of the phase and magnitude of these two types of crosstalk couplings, that for the electrostatic type of coupling will be described first. Fig. **15** shows the circuit arrangements. The cable is open circuited at the far end.

The set operates on the principle of neutralisation of the crosstalk voltage set up in the disturbed circuit *via* the electrostatic coupling or capacity unbalance in the cable. The neutralisation is performed by the agency of a capacity K represented by $K_1 - K_2$ placed between the A-wire of the disturbing circuit, and the A- or B-wire of the disturbed circuit as required. To secure accurate measurement it is essential that the B & S transformers employed should have very small earth capacity unbalances and that the variable condensers should have small earth capacities. The variable condensers employed have been of the ultra short wave type with a variation from 5—40 $\mu\mu$F. and the balanced and screened transformers have had unbalances of less than 2 $\mu\mu$F. on their line windings under working conditions.

It has so far not been found necessary to provide any means of changing the phase of the neutralising voltage from that given by a simple capacity, as the

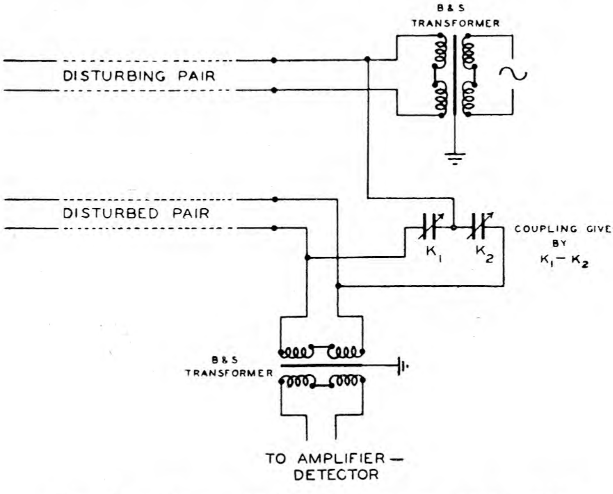


Fig. 15.—Method of Measurement of Electrostatic Couplings.

power factor of high grade cable dielectric is very small.

Measurement of Electromagnetic Couplings.

The next circuit described is that evolved for the measurement of the phase and magnitude of the electromagnetic couplings in a short length of cable. Fig. **16** shows the connections. The cable is short-circuited at the far end.

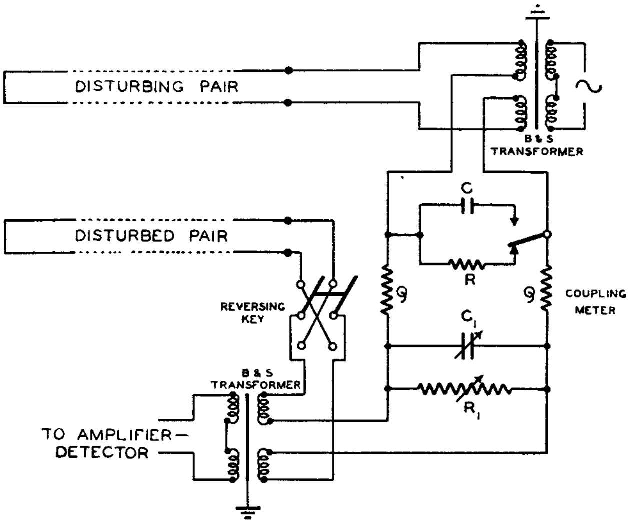


Fig. **16**.—Method of Measurement of Electromagnetic Couplings.

The general principle in this set, as in the electrostatic measuring set, is one of neutralisation of the voltage induced in the disturbed circuit. This induced voltage is produced magnetically by the current in the disturbing circuit. The method of derivation of the neutralising voltage is as follows. The current I in the disturbing circuit also flows through R or C, selected by means of the change-over key, according to whether a voltage in phase or lagging by 90° is required. The magnitude of this voltage will be RI or $\frac{I}{\omega C}$. The impedance of R or C is of the order of a few ohms only. A potentiometer is formed by the resistances Q and the parallel combination of R_1 and C_1. The neutralising voltage is that developed across R_1 and C_1 and is applied to the inner ends of the primary winding of the balanced and screened transformer connected to the amplifier-detector. When a neutralising voltage, equal in phase and magnitude to the voltage from the disturbed circuit, is applied to the inner ends of the primary winding no current flows in this winding and consequently no voltage is induced in the secondary winding connected to the amplifier input. Incidentally at balance no current is taken from the disturbed circuit, and therefore the neutralising voltage will equal the true open circuit E.M.F. The reversing key is included so that it is only necessary to cater for phase changes between 0 and 180° on the potentiometer assembly. Selection of R and adjustment of R_1 and C_1 covers the range 0—90°, and selection of C and adjustment of R_1 and C_1 covers the range 90—180°. To simplify calculations the total impedance of the potentiometer is made high compared with the impedance of R and C. 2Q is also high compared with the impedance of R_1 and C_1 in parallel, so that the angle of the total impedance of the potentiometer is not materially changed by variations of R_1 and C_1 during balancing.

The calculation of the mutual inductance M, when a balance has been obtained, is performed in the following manner. Firstly assume that the angle of the coupling is such that the resistance R is used.

Then the voltage ωMI in the disturbed circuit will equal the neutralising voltage whose magnitude will be $\frac{RI|Z_\beta|}{2Q}$, where $|Z_\beta|$ is the modulus of the impedance formed by R_1 and C_1 in parallel.

Hence M will equal $\frac{R|Z_\beta|}{2\omega Q}$ Henrys.

The phase angle of the coupling relative to the phase of the current in the disturbing circuit will be + or − $\phi_\beta{}^0$ the sign depending on the position of the reversing key. $\phi_\beta{}^0$ is the angle of the impedance formed by R_1 and C_1.

If the angle of the coupling necessitates the use of capacity C in order to obtain a balance then the calculation will be altered to the following form:—

$$\omega MI = \frac{I}{\omega C}\,\frac{|Z_\beta|}{2Q}$$

$$\therefore \quad M = \frac{|Z_\beta|}{2\omega^2 CQ} \text{ Henrys.}$$

The phase angle will be + or − $(90 + \phi_\beta)$ degrees.

The present set is suitable for measuring down to 10^{-8} henrys at frequencies from 10 to 200 kc/s.

PART III.

THE NATURE OF CROSSTALK IN CABLES.

Crosstalk between cable pairs can be divided into two main categories—

(1) that due to electrostatically induced potential differences between the wires of the disturbed pair, and

(2) that caused by electromagnetically induced potentials along the wires of the disturbed pair.

Electrostatic Crosstalk.

Consider first the representation of a single electrostatic coupling in the form of capacity unbalance between two circuits in a short length.

Fig. **17** gives the complete system of capacity

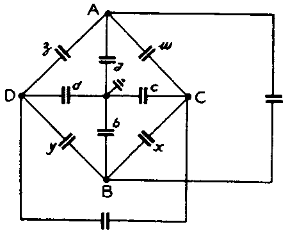


Fig. **17**.

couplings between two circuits in a cable. This can be simplified by the elimination of the earth point to the form given in Fig. **18** ("A New Network Theorem" by A. Rosen. I.E.E. Journal, Vol. 62, 1924, and "Direct Capacity Measurement" by G. A. Campbell. Bell System Technical Journal, Vol. 1, 1922).

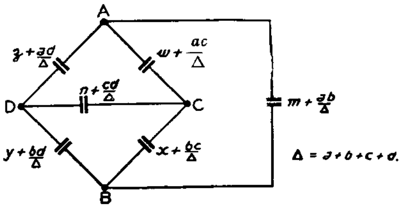


FIG. **18.**

The network can be expressed in the form shown in Fig. **19** since the capacities $w + \frac{ac}{\Delta}$, $x + \frac{bc}{\Delta}$, $y + \frac{bd}{\Delta}$ and $z + \frac{ad}{\Delta}$ are nearly equal to each other. The impedances of these capacities are represented in Fig. **19** by $x + \delta_1 x, x + \delta_2 x, x + \delta_3 x$ and $x + \delta_4 x$ respectively where $\delta_1 x$, $\delta_2 x$, $\delta_3 x$ and $\delta_4 x$ are small.

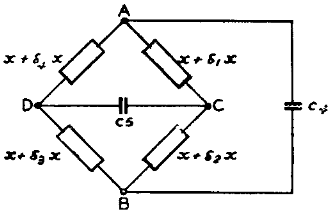


FIG. **19.**

Again because the four arms of the network differ only by small amounts from one another, the diagram can be simplified to that given in Fig. **20**, where K is the capacity unbalance equivalent to the value of $(\delta_1 x - \delta_2 x) - (\delta_4 x - \delta_3 x)$ which is shown in Appendix I to determine the magnitude of the voltage developed across CD when a voltage is applied to AB.

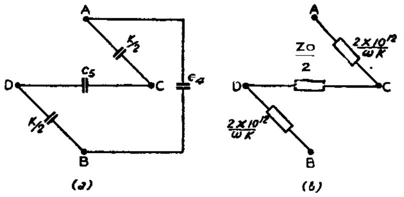


FIG. **20.**

From Fig. **20**(*b*) it can be seen that if a voltage V is impressed across AB the voltage across CD will be given by $\frac{V \times |Z_0| \times \omega K}{2 \times 4 \times 10^{12}}$ $\left(\text{because } \frac{|Z_0|}{2} \text{ is small compared with } \frac{2 \times 10^{12}}{\omega K}\right)$. Hence the crosstalk ratio N in decibels will be $N = 20 \log_{10} \frac{8 \times 10^{12}}{\omega K |Z_0|}$, where K is given in micro-micro farads.

This type of coupling is found to be most severe between circuits which are close together in the cable cross-section, since small irregularities in spacing then produce relatively large capacity unbalance, or resultant K, and hence a proportionally greater crosstalk. Also there are no intervening conductors to produce a screening effect. Thus side-to-side capacity unbalance is found to be greatest, adjacent pair-to-pair capacity unbalance next in order, and the capacity unbalance between pairs separated by other pairs is negligible.

Electromagnetic Crosstalk.

The second category is that of electromagnetic crosstalk. This type of crosstalk is the result of potentials induced longitudinally in the disturbed circuit through the agency of the magnetic field set up by the current in the disturbing circuit. The couplings can be represented in the simple case of direct couplings between pairs as simple mutual inductances. This method of representation is demonstrated in Fig. **21**(*a*).

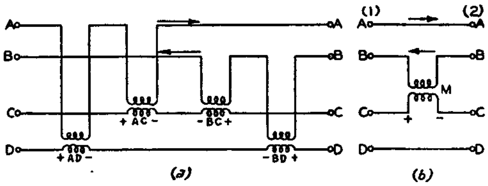


FIG. **21.**

With the pair-to-pair couplings given in Fig. **21**(*a*) the voltages induced at AC and BC will be in opposition, and so will those induced at AD and BD.

The relative magnitudes of these four induced voltages will be determined solely by the relative geometrical positions of the four wires of the pairs. Thus the resultant voltage, which will normally be much smaller than the individual voltages, can be represented as being due to a single mutual inductance M as shown in Fig. **21**(*b*). With the simple direct coupling the induced voltage ωMI will be in phase quadrature with the current in the disturbing pair. It will be observed that if the generator is moved from end 1 to end 2 the disturbing current will be reversed in direction while at the same time the disturbing circuit voltage will not be reversed, therefore the magnetically induced voltage will be reversed with respect to the electrostatically induced voltage. Thus with two pairs possessing both electrostatic and electromagnetic couplings the crosstalk measured at end 1 on the disturbed pair, with the generator at end 1 on the disturbing pair, will differ from that measured at end 1 on the disturbed pair, with the generator at end 2 on the disturbing pair. This effect is most noticeable in side-to-side crosstalk where the two types of coupling are most nearly equal in magnitude. In side-to-side crosstalk the relative signs of the electrostatic and electromagnetic induced voltages are not independent and consequently with short lengths of cable the crosstalk measured at the end remote from the generator is always found to be less than that measured at the same end as the generator. It is the difference of the two types of induced voltage which is measured in the first case, and the sum in the latter case.

Now, in cables, owing to the presence of the metallic mass of the sheath and other conductors in which eddy currents are induced by the field set up by the disturbing current, the voltage induced in the disturbed pair will not necessarily be in phase quadrature with the disturbing current, but will have an angle differing from 90°. The resultant coupling can be represented as shown in Fig. **22**.

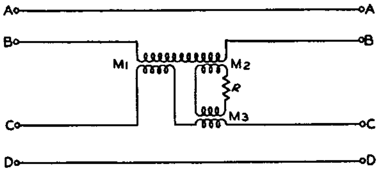


Fig. 22.

This type of coupling is termed a complex magnetic coupling, since the effective resistance R is likely to change in value with frequency, thus causing the resultant voltage induced in the disturbed circuit to vary in angle and magnitude in an erratic manner with frequency.

The calculation of the crosstalk voltage produced by a simple magnetic coupling is performed in the following manner:—

The voltage on the disturbing circuit is $I|Z_0|$ if I is the current in the disturbing circuit and $|Z_0|$ is the characteristic impedance. The induced voltage measured at one end of the disturbed circuit is $\frac{\omega MI}{2 \times 10^6}$, where ω is $2\pi \times$ frequency.

Therefore the crosstalk voltage ratio in decibels is given by

$$20 \log_{10} \frac{\text{Voltage in disturbing circuit}}{\text{Voltage in disturbed circuit}}$$

$$= 20 \log_{10} \frac{I|Z_0| \times 2 \times 10^6}{\omega MI}$$

$$= 20 \log_{10} \frac{2 \times 10^6 \times |Z_0|}{\omega M}$$

The value M is the mutual inductance measured in μH, microhenrys. The crosstalk due to a complex magnetic coupling can be evaluated in the same way, if the angle is neglected and an equivalent value for ωMI is substituted giving the total induced voltage.

Circuits with different impedances.

The foregoing formulæ have been derived on a voltage basis. Where the circuit impedances differ from one another, the relevant power ratio is obtained as follows:—

Assume that the disturbing circuit has an impedance of $Z_S/\underline{\phi_1}$ ohms, the disturbed circuit an impedance of $Z_R/\underline{\phi_2}$, and that a voltage V is applied to the disturbing circuit. The power in the disturbing circuit is $\frac{V^2}{Z_S}\cos\phi_1$. With an electrostatic coupling K micro farads the power in the disturbed circuit is

$$\frac{V^2 \times (\omega K)^2 \times Z^2_R \cos\phi_2}{64 \times 10^{24} \times Z_R} = \frac{V^2 (\omega K)^2 Z_R \cos\phi_2}{64 \times 10^{24}}$$

$$\text{Hence the power ratio} = \frac{\dfrac{V^2}{Z_S}\cos\phi_1}{\dfrac{V^2(\omega K)^2 Z_R \cos\phi_2}{64 \times 10^{24}}}$$

$$= \frac{V^2 \times 64 \times 10^{24} \cos\phi_1}{Z_S \times V^2 (\omega K)^2 Z_R \cos\phi_2}$$

$$= \left(\frac{8 \times 10^{12}}{\omega K}\right)^2 \cdot \frac{1}{Z_S Z_R} \cdot \frac{\cos\phi_1}{\cos\phi_2}$$

If ϕ_1 and ϕ_2 are substantially equal this ratio expressed in db. becomes

$$N \text{ db.} = 10 \log_{10}\left\{\left(\frac{8 \times 10^{12}}{\omega K}\right)^2 \times \frac{1}{|Z_S|\,|Z_R|}\right\}$$

With an electromagnetic coupling M microhenries the power in the disturbed circuit is

$$\frac{\left(\dfrac{\omega M}{2 \times 10^6}\right)^2 \dfrac{V^2}{Z_S{}^2}\cos\phi_2}{Z_R}$$

$$\text{Hence the power ratio} = \frac{\dfrac{V^2\cos\phi_1}{Z_S}}{\dfrac{(\omega M)^2 V^2 \cos\phi_2}{4 \times 10^{12} \times Z_S{}^2 Z_R}}$$

$$= \frac{4 \times 10^{12} \times V^2 \,.\, Z_S{}^2 \,.\, Z_R \,.\, \cos\phi_1}{Z_S(\omega M)^2 V^2 \cos\phi_2}$$

$$= \left(\frac{2 \times 10^6}{\omega M}\right)^2 Z_S Z_R \frac{\cos\phi_1}{\cos\phi_2}$$

If ϕ_1 and ϕ_2 are substantially equal this ratio expressed in db. becomes

$$N \text{ db.} = 10 \log_{10}\left(\left(\frac{2 \times 10^6}{\omega M}\right)^2 |Z_S|\,|Z_R|\right)$$

Crosstalk/frequency characteristics of electrostatic and electromagnetic couplings.

From measurements on factory lengths of cable it is found that the value of K, capacity unbalance, does not change with frequency up to at least 150 kc/s. Thus, providing there are no other factors, the crosstalk voltage due to an electrostatic coupling is directly proportional to frequency. This, however, is only true in the carrier frequency range above 10 kc/s where the characteristic impedance of unloaded cable becomes substantially constant with frequency because the crosstalk voltage from electrostatic couplings is directly proportional to the characteristic impedance of the disturbed circuit.

The crosstalk voltage produced by a simple magnetic coupling is directly proportional to frequency providing the characteristic impedance of the disturbing circuit remains constant with frequency. This is reasonably true above 10 kc/s on unloaded cables, but at lower frequencies the impedance must be taken into account because the crosstalk voltage is inversely proportional to the characteristic impedance of the disturbing circuit.

A complex magnetic coupling gives a crosstalk/frequency characteristic similar to that produced by a simple magnetic coupling with the addition of the effect of the indirect path, which may give an induced voltage which varies with frequency in such a manner as to have a varying phase relationship with the induced voltage *via* the direct path, which is proportional to frequency. The resultant crosstalk voltage will then not be proportional to frequency, but will still be inversely proportional to the characteristic impedance of the disturbing circuit.

The fact that the electrostatic crosstalk voltage is directly proportional to the characteristic impedance, while the electromagnetic crosstalk voltage is inversely proportional, explains why the electromagnetic crosstalk is negligible at audio frequencies, the characteristic impedance being several times greater at audio than at carrier frequencies.

Electromagnetic and electrostatic couplings in audio and carrier type trunk cables.

Values of electrostatic and electromagnetic couplings measured on a 90 yard length of ordinary trunk type quad cable, as used for audio circuits, are given in Table 1. Typical values for carrier type cable are given in Table 2. The superiority of the carrier type cable as regards magnetic couplings between pairs in non-adjacent quads will be noted. This is due to the use of different lays for all quads in carrier type cable whilst the same lay is used for alternate quads in audio type cable.

TABLE 1.

PAIR-TO-PAIR CAPACITY UNBALANCES ON 90 YDS. OF 38/40 P.C.Q.T. CABLE AT 60 KC/S.

Combination	Mean $\mu\mu$F.	Max. $\mu\mu$F.
Side-to-side	9	27
Adjacent quads in first layer	4	15
Separated by one or more quads	1	2
Adjacent quads in second layer	5	15
Separated by one or more quads in second layer	0	0
Centre quad to quads in first layer	5	15
Centre quads to quads in second layer	0	0
Quads in first layer to quads in second layer	3	15

MODULI OF MAGNETIC COUPLINGS IN 90 YARDS OF 38/40 P.C.Q.T. CABLE AT 60 KC/S.

Combination	Mean μH.	Max. μH.
Side-to-side	0.03	0.1
Adjacent quads of different lay, first layer	0.004	0.012
Alternate quads of same lay, first layer	0.18	0.3
Adjacent quads of different lay, second layer	0.012	0.025
Alternate quads of same lay, second layer	0.15	0.53
Centre quad to first layer quads, different lay	0.025	0.074
Centre quads to second layer quads, different lay	0.012	0.025
Quads in first layer to quads in second layer, different lays	0.015	0.054

TABLE 2.

ELECTRICAL CHARACTERISTICS OF TWELVE-CHANNEL CARRIER P.C.Q. CABLE.

Factory Lengths.

1. Mutual capacity at audio frequency and capacity unbalance (lengths 176 to 200 yards).

	Typical Values			
	Max/ mean	Max/ max	Mean/ mean	Mean/ Max
Mutual capacity μF per mile	—	—	0.056	—
Deviation from mean mutual capacity	2.0	6.3	1.0	2.7
Unbalance in $\mu\mu$F between pairs in—				
(1) Same quad	31	120	13	37
(2) Adjacent quads	8	55	4	15
(3) Non-adjct. quads	3	10	—	1
(4) Centre and first layer quads	7	60	3	20
Unbalance between any pair and earth	97	340	35	120

2. Moduli of magnetic couplings (lengths 176 to 200 yards).

	Typical Values at 60 kc/s			
	Max/ Mean	Max/ max	Mean/ mean	Mean/ max
Moduli of magnetic couplings in micro henries, μH, between pairs in —				
(1) Same quad	0.12	0.525	0.060	0.150
(2) Adjacent quads	0.04	0.31	0.015	0.065
(3) Non-adjacent quads	0.025	0.2	0.008	0.04
(4) Centre and first layer quads	0.05	0.37	0.025	0.12

Overall Repeater Section Results (lengths 16—22 *miles).*

3. Far-end crosstalk without networks.

Frequency range 12—60 kc/s	Typical Values	
	Average	Worst
Crosstalk db.	75	60

4. Far-end crosstalk with networks.

Frequency range 12—60 kc/s	Typical Values	
	Average	Worst
Crosstalk db.	85	75

5. Near-end crosstalk within cable.

Frequency range kc/s		Typical Values		
		30	40	60
Crosstalk db.	Average	81	79	75
	Worst	68	66	62

6. Near-end crosstalk between cables.

Frequency 60 kc/s	Typical Values	
	Average	Worst
Crosstalk db.	145	135

7. Characteristic impedance.

Frequency range kc/s	Typical Values		
	10	30	60
Impedance (ohms)	160/$\overline{16}$	148/$\overline{8}$	142/$\overline{5}$

8. Attenuation.

Frequency range kc/s	Typical Values 10	 30	 60
Attenuation per mile db	1.3	1.8	2.6

All the values shown in Table 2 do not refer to any one cable, but have been deduced as typical after examination of test results on a number of cables.

In order to make comparison between the values of crosstalk in different types of cable it is usual to plot a probability curve from the measurements made on a representative number of combinations in the cable. The method is to plot the proportion of cases at each interval of magnitude, say every two decibels. If the crosstalk is entirely random then the curve will have only one peak, which indicates the most probable value of crosstalk in the length of cable at the frequency of measurement. It is this value which is employed for purposes of comparison, since it is a very stable value.

At carrier frequencies the high values for alternate quads of the same lay in the audio type of cable give rise to a second most probable value of crosstalk for these combinations of pairs alone. This second most probable value occurs because the combinations of this type have crosstalk values which are grouped at random about a worse level of crosstalk than that for the rest of the couplings in the cable. Fig. **23** gives the probability curve for 90 yards of P.C.Q.T. type cable and Fig. **24** that for 176 yards of carrier type cable.

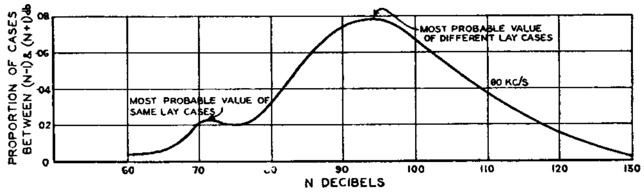


Fig. **23**.—Distribution of Far-end Crosstalk in 90 yard length of 38/40 P.C.Q.T. Audio Type Cable.

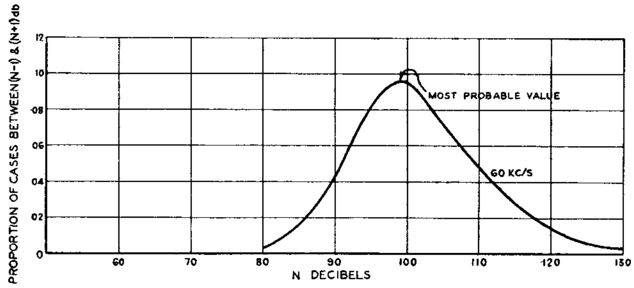


Fig. **24**.—Distribution of Far-end Crosstalk in 176 yard length of 24/40 P.C.Q. Carrier Type Cable.

It is found that if two factory lengths of the same type of cable are measured and the results plotted in the form of a probability curve the agreement between the two curves is good, although the individual measurements on a few combinations in the two lengths may differ widely.

Crosstalk at carrier frequencies is found to have a most probable value which is directly proportional to frequency. This indicates that the most probable coupling has a constant value with frequency.

Accumulation of far-end crosstalk within a repeater section.

The increase in magnitude of far-end crosstalk with distance along a cable from the sending end may be either direct or random. In the former case a pair which is inherently unbalanced owing to its form of construction, will accumulate crosstalk uniformly along its length. Thus if a length *l* gives rise to a crosstalk of N millionths, a length 2*l* will give rise to 2N millionths.

We are however usually more concerned with random accumulation, due to admittance unbalance between pairs which are supposed to be balanced.

In the manufacture of cable, one of the objects of the design is to preserve the balance of a pair to all the other pairs. The reason why this object is not precisely obtained is due to the limitations of the materials and the machinery, and it would therefore be expected that deviations from the ideal would follow a normal error law.

Assuming that the admittance unbalances in individual lengths follow the normal error law (Gaussian error function) it has been demonstrated that the crosstalk due to the resultant unbalances increases according to the square root of the number of lengths, when these are connected in series without any attempt at making the joints advantageously from the point of view of unbalance (see article by T. Laurent, Ericsson Technics No. 1, 1938).

While it is outside the scope of this general paper to investigate this problem deeply, a particular example is given which may be of interest. It is convenient here to refer to the crosstalk in terms of millionths of the disturbing voltage, this unit of measurement being directly proportional to admittance unbalance. While the unbalances have a phase angle as well as magnitude, the great majority, whether due to electromagnetic or electrostatic causes, can be neutralized almost completely with a capacity. This means that any unbalance can be said to have one of two opposite phases, indicated by the prefix + or −. This was assumed in the paper by T. Laurent already referred to.

The principle of the accumulation of far-end cross-

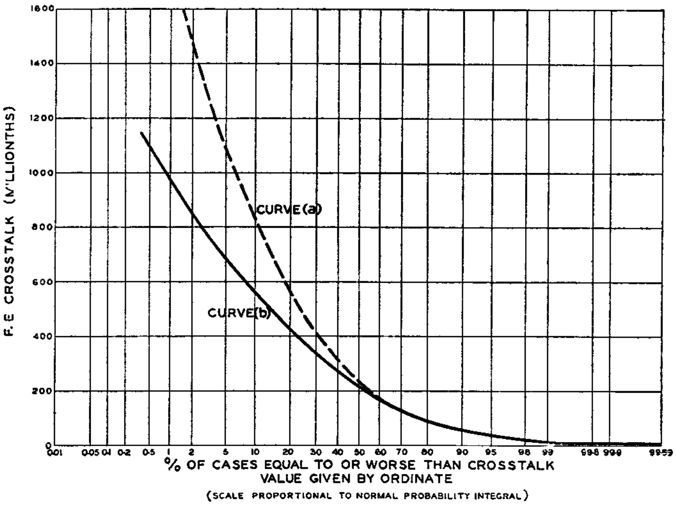


Fig. **25**.—Accumulation of Far-end Crosstalk in a Repeater Section. Statistical Test of Significance.

talk being directly proportional to the square root of the length refers to the modulus of the crosstalk vector.

Fig. **25**, curve (a), gives an illustration of the application of the principle of random accumulation. Far-end crosstalk measurements were made on a 173 yard length of 24/40 P.C.Q. carrier cable, and the magnitudes increased by a factor proportional to the square root of the length to give an estimate of the far-end crosstalk for 9 miles of cable. The ordinate of the curve gives the crosstalk value in millionths, and the abcissa gives the percentage of cases having a value equal to or worse than the crosstalk value given by the ordinate. This scale is proportional to the normal probability integral on which the normal error law is based. This means that if the crosstalk distribution followed this curve, a straight line would be obtained on the chart. It is seen that this is not the case, showing that the original assumption made about random accumulation is not true. In other words the statistical frequency distribution is skew and not normal as is generally assumed.

Curve (b) gives the crosstalk measured on a 9 mile length of the same cable, in which the joints were selected with a view to reducing crosstalk. The effect of the selection on the bad values of crosstalk is marked, but it is interesting to see that the reasonable values, down to 50% of the total, have not been affected. The most probable value of crosstalk falls in this region, and it follows that the most probable value and the cases better than the most probable value can be calculated from measurements made on a single length, with a sufficient degree of accuracy for most purposes.

An interesting point is that selection of joints makes the curve on the probability chart straighter, implying that the distribution approaches statistical normality. This means that even the distribution of the worse cases can be anticipated to a certain extent, when long lengths with selected joints (*e.g.*, repeater sections) are considered.

PART IV.

CROSSTALK LIMITS.

A telephone call which is satisfactory in every way as regards volume and articulation may yet be marred

TABLE 3.—MINIMUM CROSSTALK REQUIREMENTS OF CABLES, REPEATERS AND TWELVE-CIRCUIT CARRIER SYSTEMS.

			Possible combinations †		
			100% db.	95% db.	90% db.
Main underground cables (audio-frequency)	Between 20/88/1.136 loaded pairs (side-to-side and and pair-to-pair) in same group.	Near-end	76	—	78
		Far-end	78	—	80
		Far-end (S/N)	62	—	64
	Between 20/88/1.136 loaded pairs in different groups which are (*a*) completely segregated by other pairs (*b*) not completely segregated by other pairs	(*a*) Near-end	100	—	—
		(*a*) Far-end	100	—	—
		(*b*) Near-end	80	—	—
		(*b*) Far-end	82	—	—
	Between 40/16/1.136 screened pairs . .	Near-end .	104	—	—
		Far-end	104	—	—
Cables not carrying long distance traffic (audio-frequency)	Between 20/88/1.136 loaded pairs, side-to-side	Near-end	62	—	68
		Far-end	62	—	68
	Between 20/88/1.136 loaded pairs, pair-to-pair	Near-end	70	—	76
		Far-end	70	—	76
Subscribers' cables (audio frequency)	Between unloaded pairs, side-to-side and pair-to-pair	Near-end	65*	(Termi	nated)
		Far-end	—	—	—
Twelve-channel carrier cables 24/40 P.C.Q. (frequency 60kc/s) Repeater section crosstalk	Between pairs in same cable .	Near-end .	52*	57*	—
	Between pairs in different cables	Near-end .	125	135	—
	Between pairs in same cable without networks .	Far-end .	52*	—	—
	Between pairs in same cable with networks	Far-end .	70*	—	75*
4-wire repeaters (double stage No. 25A) frequency 800 c/s.	Between input of one repeater and output of any other at the R.D F.	Repeaters set to maximum gain (40 db.)	33	—	38
	Between input of one half and output of other half of same unit at the R.D.F.		15	—	20
2-wire repeaters (single stage No. 27A) frequency 800 c/s.	Between input of one repeater and output of any other at the R.D.F.	Repeaters set to maximum gain (20 db.)	48	—	—
Twelve-circuit carrier. Terminal apparatus	Between one audio channel and another as in Fig. 11	Far-end .	70	—	—
Twelve-circuit carrier. Complete systems	Between audio channels using same frequency band in different groups	Near-end	60	—	65
		Far-end	60	—	65
	Between audio channels (without 2-wire/4-wire terminations) in the same group	Far-end	Psophometric E.M.F. not to exceed 2mV on any channel when two other channels are disturbed with speech from Telephones No. 162 at 4 db. below Reference Volume.		

* Provisional limit.

† *Note.*—By a combination is meant the crosstalk between one pair and another. Thus between two groups of 10 cable pairs, each pair may crosstalk to 10 pairs in the other group and the total possible combinations is thus 10 × 10 = 100

by the overhearing of other telephone users' conversations during those periods of the call when conversation is not actually in progress. To prevent such overhearing it has been necessary to specify crosstalk limits between cable pairs, repeaters, and channels in twelve-circuit carrier systems, and these are given in Table 3 for classes of plant in common use.

These limits have been fixed largely as the result of experience and are far more exacting than would be necessary if only the disturbing effect of crosstalk on transmitted speech had to be considered.

Between items of exchange apparatus level differences are generally small and the crosstalk is as a rule so good, compared with that between lines, that it can be neglected. A recent measurement at a large exchange between two circuits which ran adjacent in switchboard cable for 300 yards and in addition passed through bank multiples, first code selectors and first, second and final numerical selectors, gave a near-end crosstalk value of 86 db. The measurement was made at audio frequency with an ordinary crosstalk set and with both circuits terminated with 600 ohms.

It has not hitherto been the practice to specify crosstalk limits for exchanges, but as impedance unbalance between the two wires of a circuit and earth in an exchange may give rise to crosstalk when a circuit is extended, particularly in a cable, the introduction of crosstalk limits under specified conditions of test is contemplated for both exchanges and P.B.X.s.

Long distance circuits are almost invariably worked on a 4-wire basis, utilising repeaters and cable pairs. Crosstalk between 4-wire repeaters should be quite small and any crosstalk experienced on 4-wire circuits will in the main be due to near-end and far-end crosstalk between the pairs in the repeater sections. The effects of near-end and far-end repeater section crosstalk on the near-end and far-end crosstalk between the 2-wire terminals of 4-wire circuits is considered in the following paragraphs with reference to Fig. **26**, which indicates the level differences existing between two typical long distance circuits.

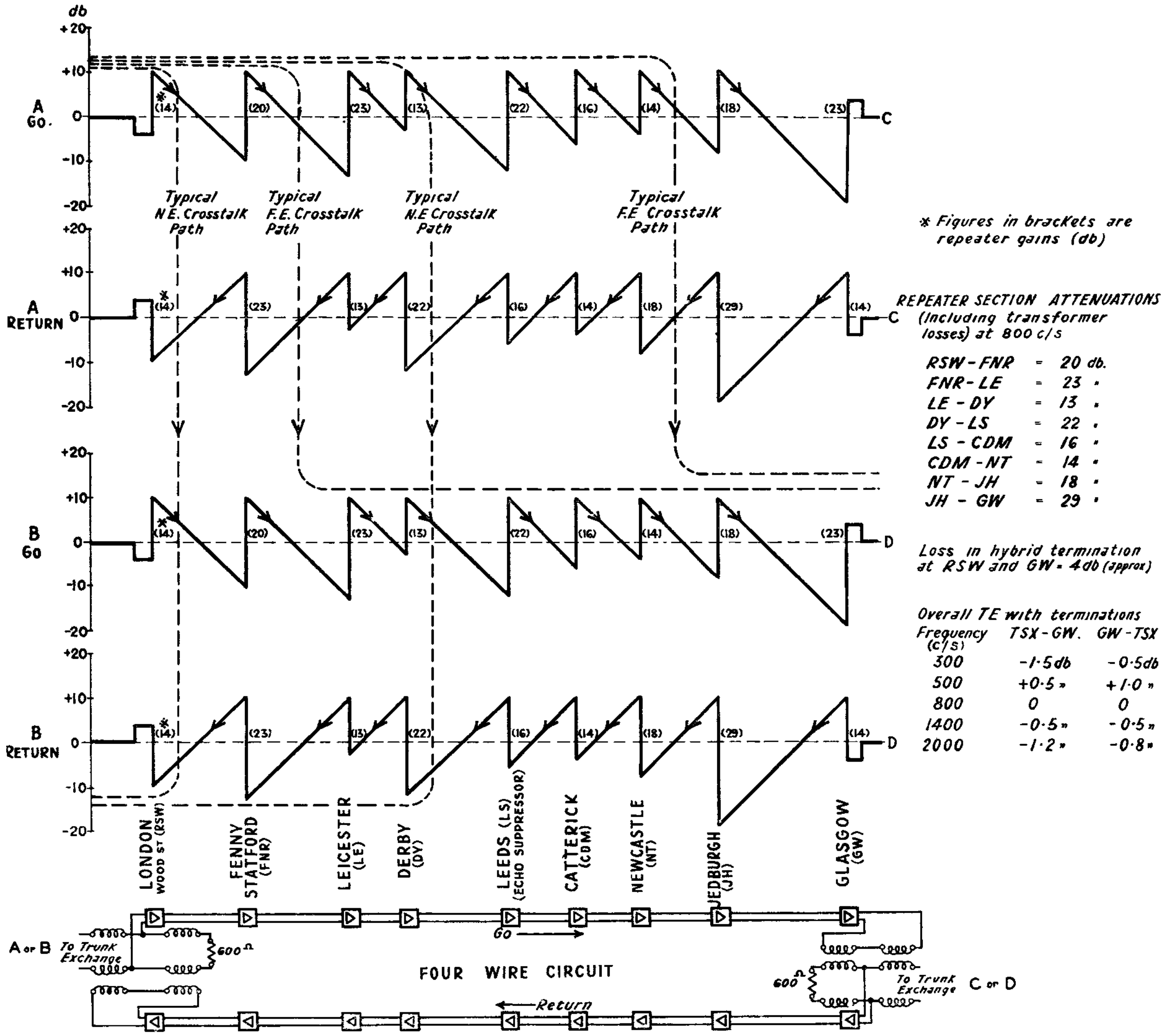


Fig. **26**.—Level Diagram of a typical London-Glasgow Zero Circuit showing two Near-end and two Far-end Crosstalk Paths.

Effect of Repeater Section Crosstalk on Crosstalk between the ends of 4-wire Circuits.

Considering the first of the two dotted near-end crosstalk paths shown between the Go pair of circuit AC and the Return pair of circuit BD in Fig. **26**, it is clear that if between Fenny Stratford and Glasgow there is no crosstalk whatever, the near-end crosstalk attenuation between A and B due to the RSW-FNR repeater section

= + 4 (loss in Go hybrid) – 14 (gain of Go repeater at London) + near-end crosstalk attenuation of the London end of the RSW-FNR repeater section – 14 (gain of Return repeater at London) + 4 (loss in Return hybrid) db.

= Near-end crosstalk attenuation as measured at London end of RSW-FNR repeater section – 20 db.

= Near-end crosstalk attenuation as measured at London end of RSW-FNR repeater section – attenuation of RSW-FNR repeater section.

Or, again, if the Derby-Leeds repeater section is the only one to contribute crosstalk, the near-end crosstalk attenuation between A and B due to the second path

= + 4 (loss in Go hybrid) – 14 (gain of Go repeater at London) + 20 (RSW-FNR repeater section attenuation) – 20 (gain of Go repeater at FNR) + 23 (FNR-LE repeater section attenuation) – 23 (gain of Go repeater at LE) + 13 (LE-DY repeater section attenuation) – 13 (gain of Go repeater at DY) + near-end crosstalk attenuation at the Derby end of the DY-LS repeater section – 22 (gain of Return repeater at DY) + 13 (DY-LE repeater section attenuation) – 13 (gain of Return repeater at LE) + 23 (LE-FNR repeater section attenuation) – 23 (gain of Return repeater at FNR) + 20 (FNR-RSW repeater section attenuation) – 14 (gain of Return repeater at RSW) + 4 (loss in Return hybrid) db.

= Near-end crosstalk at DY end of DY-LS repeater section – 22 db.

= Near-end crosstalk at DY end of DY-LS repeater section – attenuation of DY-LS repeater section.

Similarly, it can be established that the near-end crosstalk attenuation between the 2-wire terminals of 4-wire zero circuits of similar composition (*i.e.*, routed on similarly loaded cable pairs) resulting from crosstalk in any particular repeater section is equal to the near-end crosstalk attenuation of that section, at the end nearer the 2-wire terminations in question, minus the attenuation of the repeater section.

If the circuits are not of similar composition, the subtraction to be made is the attenuation of the Return circuit in the particular repeater section concerned.

For circuits which are not of zero overall equivalent, the overall loss is as a rule introduced by reducing the gain of the last repeater on the Return circuit. This improves the terminal near-end crosstalk by an amount equal to the overall equivalent of the circuit.

The combination of the human ear and telephone receiver is most sensitive at frequencies in the neighbourhood of 1,050 c/s and in audio crosstalk problems it is the line attenuation at this frequency which should be used in calculations. Fortunately, however, there is little difference between the attenuation of lines at 800 c/s and 1,050 c/s and so measurements made at 800 c/s purely from the transmission standpoint are of considerable help in crosstalk problems.

Typical near-end and far-end crosstalk frequency curves between similarly loaded pairs in a cable repeater section are shown in Fig. **27**. In the near-end case the curve is very irregular because the paths of the various minor crosstalk currents, which in the aggregate constitute the total crosstalk, are all different in length. Crosstalk currents passing between A and B by the two paths may agree in phase at one frequency and be 180° out of phase at some other frequency. In the first case the crosstalk attenuation is lowered and in the second increased, hence the irregular curve.

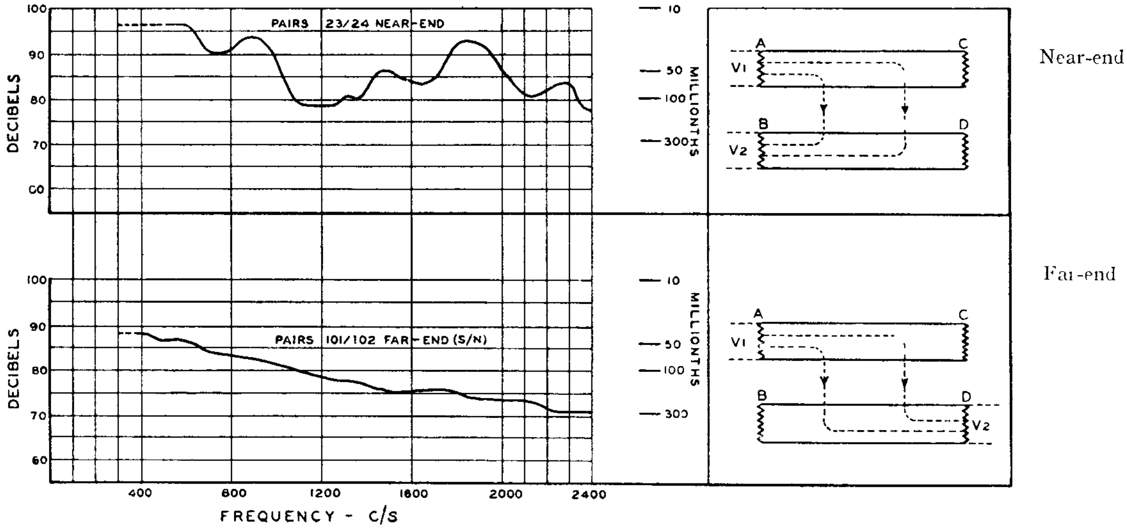


FIG. **27**. — TYPICAL NEAR-END AND FAR-END CROSSTALK-FREQUENCY CURVES. 40 LB. CONDUCTORS LOADED WITH 120 mH. COILS AT 1.136M SPACING.

The far-end crosstalk curve is smooth because the paths of the constituent crosstalk currents are all of equal length and as the pairs are similarly loaded the phase change at any particular frequency is the same for all paths and consequently the phase relationships between currents travelling by different paths are not affected by frequency change.

The curves show that near-end crosstalk is subject to greater attenuation distortion than far-end crosstalk and consequently near-end crosstalk in a repeater section should tend to be less intelligible than far-end crosstalk. The maxima and minima points on the near-end curve occur in a pure chance manner, depending on the distances between the unbalances in the cable which produce the crosstalk. If the near-end crosstalk for a very large number of repeater sections were allowed to accumulate, the pure chance distribution of the maxima and minima points should tend to produce a smooth crosstalk frequency curve similar to the far-end curve. On long 4-wire circuits it is quite usual to have up to, say, ten repeater sections in tandem and a comparatively smooth near-end curve would then be expected.

All repeater sections contribute to the total near-end crosstalk and accumulation is usually assumed to take place very roughly in proportion to the square root of the circuit length.

It is apparent from consideration of the two dotted paths shown between the Go pair of circuit AC and the Go pair of circuit BD in Fig. **26** that far-end crosstalk paths between pairs transmitting in the same direction are all of equal length. If the pairs have similar loading, the velocity of transmission in these paths is the same and if the far-end crosstalk contributed by, say, the Fenny Stratford-Leicester repeater section is in the same sense as that contributed by the Newcastle-Jedburgh repeater section, the two crosstalk currents or voltages received at the terminal will agree in phase and add directly.

The circuits in question are at the same level at all points and thus, if the first-named repeater section has a far-end crosstalk attenuation of 200 millionths, 74 db. S/N, and the other a far-end crosstalk attenuation of 100 millionths, 80 db. S/N, in the absence of any more crosstalk paths, the far-end crosstalk at the terminal D will be

$$200 + 100 = 300 \text{ millionths, } 71 \text{ db. S/N.}$$

On the other hand, if the two crosstalk currents or voltages contributed by these two sections are in the opposite sense, the resultant far-end crosstalk at terminal D will be $200 - 100 = 100$ millionths, 80 db. S/N.

In practice, not only the two repeater sections named contribute to the crosstalk received at terminal D, but the whole eight repeater sections between London and Glasgow do likewise. The crosstalk currents or voltages add and subtract in a pure chance or random manner, but on the average accumulate very roughly in proportion to the square root of the length. Thus, if nine repeater sections of cable are each of approximately the same length and have the same average far-end crosstalk between the pairs of, say, 200 millionths, 74 db. S/N, then the average far-end crosstalk when the nine repeater sections are joined together end to end would, as an estimate, be approximately—

$$200 \times \sqrt{9} = 600 \text{ millionths}$$

$$\begin{aligned} \text{or } 20 \log_{10} \frac{10^6}{200 \times \sqrt{9}} &= 20 \log_{10} 5{,}000 - 10 \log_{10} 9 \\ &= 74 - 9.5 \\ &= 64.5 \text{ db. S/N.} \end{aligned}$$

For a zero circuit, the power sent into the 2-wire terminals of the 2-wire/4-wire termination is the same as that received at the 2-wire terminals at the far-end and thus the Signal/Noise far-end crosstalk attenuation is equal to the far-end crosstalk attenuation in the sense of its definition.

Probable Values of Near-end and Far-end Crosstalk Attenuation between long Zero Circuits.

The values of near-end and far-end crosstalk attenuations which are likely to obtain between the ends of zero 4-wire circuits of, say, 600 miles in length and which are routed together on similarly loaded pairs in cables which conform to the limits set out in Table 3, are next considered. It is assumed that the route is composed of eight repeater sections and that the repeaters each have a maximum gain of 35 db.

Near-end.

In a zero circuit the total repeater gains must equal the total line and transformer losses and, as Fig. **26** shows, each intermediate repeater neutralises the attenuation of the preceding repeater section. Modern 4-wire repeaters of standard type are capable of giving at least 40 db. gain and thus repeater section attenuations up to 40 db. would be possible. To allow a working margin, however, the maximum repeater gain is usually limited to 35 db. and consequently the maximum repeater section attenuation is rather less than 35 db., as small losses exist in the line transformers.

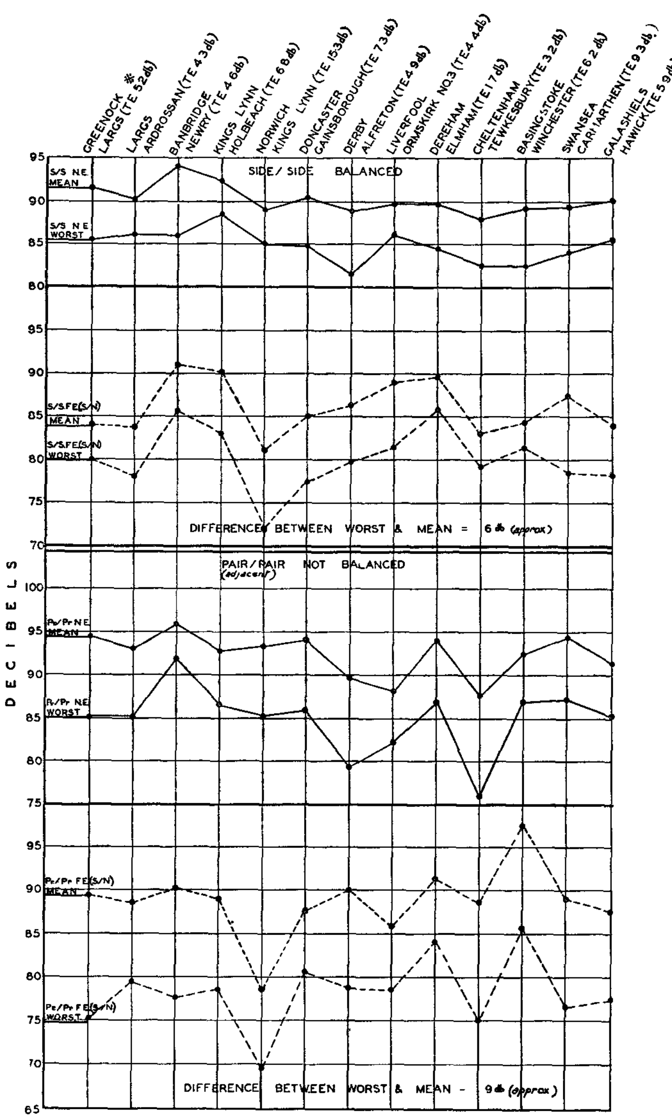
Assuming that the maximum repeater section attenuation is 34 db. and that the Go and Return circuits in the cable are in groups which conform to the limit of 100 db. shown in Table 3, then the worst possible near-end crosstalk at the terminals of the circuits due to one repeater section is

$$100 - 34 = 66 \text{ db.}$$

In the remaining seven sections, if the 4-wire groups are reasonably large, it is very improbable that a worst value of 100 db. will again occur between the pairs carrying the same two circuits. Average values are more likely to obtain and this is assumed in the following estimate of the worst near-end value likely to obtain in practice.

It is found that the average between-pair cable crosstalk is as a rule some 9 db. better than the worst value, if no balancing has been attempted and some 6 db. better, if balancing has been carried out. This point is illustrated in Fig. **28**.

No balancing is done between Go and Return 4-wire groups and it may therefore be taken that the average



※ TE AT 1000 c/s

FIG. 28.—TYPICAL MEASURED NEAR-END AND FAR-END CROSSTALK ON P.C.Q.T. CABLE LOADED WITH 88 mH. COILS AT 1.136M. SPACING—RELATION BETWEEN WORST AND MEAN VALUES.

near-end crosstalk between Go and Return pairs in a repeater section is 109 db. The remaining seven repeater sections will therefore make seven contributions to the total near-end crosstalk of

$$109 - 34 = 75 \text{ db.}$$

The total near-end crosstalk between two circuits at the terminals will therefore probably consist of one contribution of 66 db. and seven contributions of 75 db. This addition taken on a random basis would give a value of the order of 60 db.

Far-end.

Reference to Table 3 shows that the permissible far-end crosstalk S/N within a group, such as would consist of Go and Return pairs all transmitting in the same direction, is 62 db. Balancing between side circuits is carried out within group and the average value of far-end crosstalk will therefore probably be approximately 68 db. for a repeater section.

If the worst value of far-end crosstalk is 62 db. between two Go or two Return circuits in one repeater section, it is most improbable that in any other of the seven sections a similar value will again occur between pairs carrying the same two circuits. Average values are more likely and this is assumed.

With a worst far-end value S/N in one section of 62 db. and an average in other sections of 68 db., the overall far-end S/N value will be the accumulation of one 62 db. contribution and seven 68 db. contributions. On the basis of random accumulation this gives a value of 57 db. approximately.

Crosstalk between 2-wire circuits and short 4-wire circuits.

The probable values of crosstalk between 2-wire circuits or shorter 4-wire circuits may be deduced in a manner similar to the foregoing. In 2-wire circuits, as one pair of wires carries both directions of transmission, it is not possible to segregate pairs of high and low power levels. Cables themselves have physical limitations in this respect as it is not possible in a small cable to provide a screening layer of pairs between opposite going 4-wire groups. Reference to Table 3 shows that the near-end crosstalk between pairs in a group such as are used for 2-wire repeatered circuits, may be as low as 76 db., and that between pairs in groups not completely segregated, as are used for short 4-wire circuits, it may be 80 db. Such values limit the length of repeater section which may be permitted, for, when considering the effect of near-end crosstalk of a repeater section on the overall crosstalk, it is, as already pointed out, necessary to deduct the attenuation of the repeater section.

Crosstalk between carrier circuits.

Although the accumulation of crosstalk and the effect of repeater section attenuation has been considered only in relation to audio circuits, exactly similar considerations apply to carrier circuits. Thus to obtain the minimum figure of 60 db. quoted in Table 3 for near-end crosstalk between audio channels in different carrier groups using the same frequency band, it is necessary for at least an equal figure to obtain at the terminal between the corresponding carrier channels before demodulation. As repeater section attenuations up to 60 db. are permissible, this necessitates a near-end crosstalk between opposite going pairs of—

$$60 + 60 + X = 120 + X \text{ db.}$$

The value X depending on the number of repeater sections is the allowance for accumulation. Further reference to Table 3 shows that to meet this requirement, a near-end value of 135 db. is specified for 95% of crosstalk combinations between pairs in different cables of a twelve-circuit system.

Noise and Babble.[6]

The crosstalk volume which may be tolerated at the receiving end of a circuit without endangering secrecy

---

[6] See Appendix II.

is not a fixed quantity and a desirable limiting figure for standard type telephones has not yet been agreed. It depends largely on the nature of the crosstalk and on the levels of line and room noise. The occurrence of crosstalk between two circuits only is unlikely, unless it is due to a definite fault, and it is more usual for a circuit to be affected at one time by a number of disturbing circuits. The aggregate crosstalk is termed " babble " and may be regarded as line noise. The effect of babble is to make crosstalk between individual circuits less intelligible.

The effects of line and room noise on intelligibility may be seen from Fig. **29** ; with 56 db. in the variable attenuator, and a line noise of 0.25 *m*V and a room noise of 35 phones, less than 25% of words are understood, but under conditions of silence, the percentage is greater than 90.

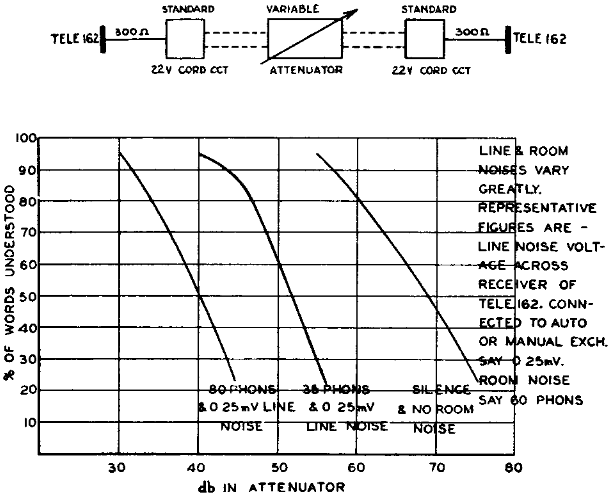


FIG. **29**.—EFFECT OF LINE AND ROOM NOISE ON INTELLIGIBILITY.

C.C.I.F. Recommended Limits.

At the meeting of the Commission de rapporteurs of the Comité Consultatif International Telephonique held at Oslo in 1938 limits of crosstalk were recommended as follows:—

Near-end and far-end crosstalk between 0.8 neper (7 db.) 4-wire circuits routed entirely in cable under traffic conditions to be not less than 7.5 nepers (65 db.) for 90% combinations, and not less than 6.8 nepers (59 db.) for 100% combinations.

Near-end and far-end crosstalk between 1.0 neper (8.7 db.) 2-wire circuits routed entirely in cable under traffic conditions to be not less than 6.8 nepers (59 db.) for 100% combinations.

PART V.

CROSSTALK REDUCTION.

In the design stage there are, broadly speaking, two methods of preventing crosstalk between circuits. These may be described as

(1) Preservation of balance, and
(2) Separation.

Referring to Fig. **30**, the preservation of balance between two circuits AB and CD implies the satisfying

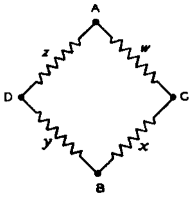


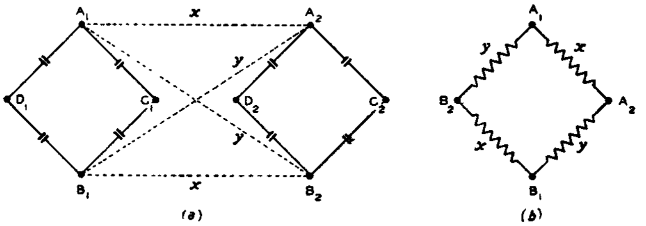
FIG. **30**.

of the relationship $wy = xz$, where w, x, y and z are the equivalent admittances (or impedances) between the wires of the circuits.

Separation is affected either physically by arranging that AB is so far distant from CD that there is no electrostatic or electromagnetic influence between them, or electrically by the use of some form of screen between the circuits.

The well known star-quad formation used in modern cables and in certain other types of wiring is an example of a balanced arrangement of two circuits, for with this formation the separating distances between the wires of one pair and another are all equal (within fine limits) as are also the distances between each wire and earth. This results in admittances w, x, y and z all being essentially equal and the practical fulfilment of the condition that $wy = xz$. The symmetry of the quad formation is not, of course, in any way upset whatever " lay " is given to the quad.

Between circuits in different quads, however, a condition of balance no longer exists if the quads have the same lay. The lack of symmetry is shown for one particular position of the wires of one quad A_1, B_1, C_1 and D_1 and the wires of another quad A_2, B_2, C_2 and D_2 in Fig. **31**(*a*).



(*a*) (*b*)

FIG. **31**.

Wire A_1 being at approximately the same distance from A_2 as B_1 is from B_2, may be assumed to have an admittance x to A_2 which is the same as the admittance of B_1 to B_2. Similarly, wire A_1 has approximately the same admittance y to B_2 as B_1 has to A_2. Owing to the greater proximity of the wires, admittance x is greater than admittance y and the equivalent bridge network as shown in Fig. **31**(*b*) is obviously unbalanced. Further considerations of this nature show that unbalance is to be expected between pairs in different quads having the same lay and that crosstalk is therefore likely to occur between such pairs unless special precautions are taken. The same difficulty does not arise between quads of different lays because the rotation of one quad with respect to the other tends to equalize the average values of x and y.

In audio cables quads having the same lay in the same layer are screened from one another by interposing a quad of different lay between them. This quad provides an effective electrostatic screen, although its value as an electromagnetic screen is by no means great. This latter fact is, however, immaterial with audio cables as at low frequencies electrostatic unbalances only have appreciable effect. In carrier cables, however, both electromagnetic and electrostatic unbalances are equally important and the use of the same lay for different quads is undesirable.

Relative effects of electrostatic and electromagnetic couplings.

The relative effects of electrostatic and electromagnetic couplings on audio circuits (loaded with 88 *m*H coils at 1.136 *m* spacing) of average impedance of 1,100 ohms at 1,050 c/s and on unloaded carrier circuits of 140 ohms impedance at 60 kc/s are considered in the next paragraphs.

Let K $\mu\mu$F. be an electrostatic coupling, M microhenries a magnetic coupling and $|Z|$ the circuit impedance.

$$\text{Crosstalk due to K} = \frac{\omega K|Z|}{8 \times 10^6} \text{ millionths}$$

$$\text{Crosstalk due to M} = \frac{\omega M}{2.|Z|} \quad \text{,,}$$

$\therefore$ Ratio of crosstalk at 60 kc/s to crosstalk at 1,050 c/s.

$$\text{due to K} = \frac{2\pi \times 60 \times 10^3 \times 140}{2\pi \times 1050 \times 1100}$$

$$= 7 \text{ (approx.)}$$

$$\text{and due to M} = \frac{2\pi \times 60 \times 10^3 \times 1100}{2\pi \times 1050 \times 140}$$

$$= 450 \text{ (approx.)}$$

Thus, a given value of electrostatic coupling produces only seven times the crosstalk in a carrier cable at 60 kc/s that it does in an audio cable at 1,050 c/s, but an electromagnetic coupling causes 450 times as much.

Reference to Table 2 shows that for carrier type cable unbalance values of between 13 and 37 $\mu\mu$F. and 0.06 and 0.15 μH. are quite usual on 176 yards lengths. An electrostatic unbalance value of 25 $\mu\mu$F. and an electromagnetic unbalance of 0.1 μH. may therefore be regarded as representative of unbalances met in practice between pairs.

Crosstalk at 60 kc/s from a 25 $\mu\mu$F. unbalance

$$= \frac{2\pi \times 60 \times 10^3 \times 25 \times 140}{8 \times 10^6}$$

$$= 165 \text{ millionths.}$$

Crosstalk at 60 kc/s from 0.1 μH.

$$= \frac{2\pi \times 60 \times 10^3 \times .1}{2 \times 140}$$

$$= 135 \text{ millionths.}$$

This demonstrates the almost equal importance of electrostatic and electromagnetic couplings in carrier cables.

Cable balancing.

Although perfect symmetry is the aim in design, it is not possible to attain this in practice owing to small irregularities which inevitably occur in manufacture and, so far as cables are concerned, it is necessary to resort to means in the field of more nearly satisfying the condition $wy = xz$. This is referred to as " balancing " and its implications with respect to audio cables are so well-known as to need no further description. Balancing of carrier cables by means of networks introduces special problems, however, and these are dealt with in Part VI of this paper. In addition to network balancing, carrier cables are balanced in the field by crossing wires and pairs during installation as is done for audio cables, and the procedure adopted, which differs considerably with different contractors, is briefly outlined below.

Every cable length (176 yds. or rather less) is tested either in the factory or in the field at audio frequency, and selected joints are made between adjacent lengths for the reduction of some or all of the following:—

Mutual capacity deviation,
Side-to-side capacity unbalance,
Side-to-phantom capacity unbalance,
Side-to-earth capacity unbalance.

Groups of four lengths so formed are jointed together to give " slings " of eight lengths; the joint between the two groups being selected to reduce either the same unbalances as above or far-end side-to-side admittance unbalance, measured at some convenient carrier frequency, say 60 kc/s.

The joints between the eight-lengths slings are made either straight, with straightening-out crosses, with wire crosses for reducing far-end side-to-side admittance unbalance, with wire crosses for reducing far-end crosstalk, or with quad crosses for the reduction of mutual capacity deviation between the end 176-yard lengths of different slings. The actual choice of joint depends largely on the degree of balance existing in the single lengths.

The object of balancing phantom-to-side and side-to-earth unbalances is to reduce, as far as possible, indirect crosstalk *via* phantom and earth circuits. Such crosstalk cannot be balanced out satisfactorily with networks because of the difference in the phase and attenuation constants of side, phantom and earth circuits. Mutual capacity equalisation is carried out to make the pairs similar as regards their attenuation and phase constants. The importance of this in network balancing is discussed in Part VI.

Balancing between standard lengths of cable (176 yards) considerably improves far-end crosstalk, but effects very little improvement in near-end crosstalk. Fig. **32**(*a*) illustrates the phase change which occurs in a carrier cable at 60 kc/s calculated from primary constant values: $R = 80$ ohms, $L = 1.1 \times 10^{-3}$ henrys, $G = 280 \times 10^{-6}$ mhos, and $C = 0.054 \times 10^{-6}$ farads $(P = \sqrt{(R + j\omega L)(G + j\omega C)})$. It will be noted that the phase change per 176 yard length is 16.7° so that two near-end crosstalk currents arising from equal and opposite capacity unbalances at the approximate centre points of two adjacent lengths and which completely balance one another at audio fre-

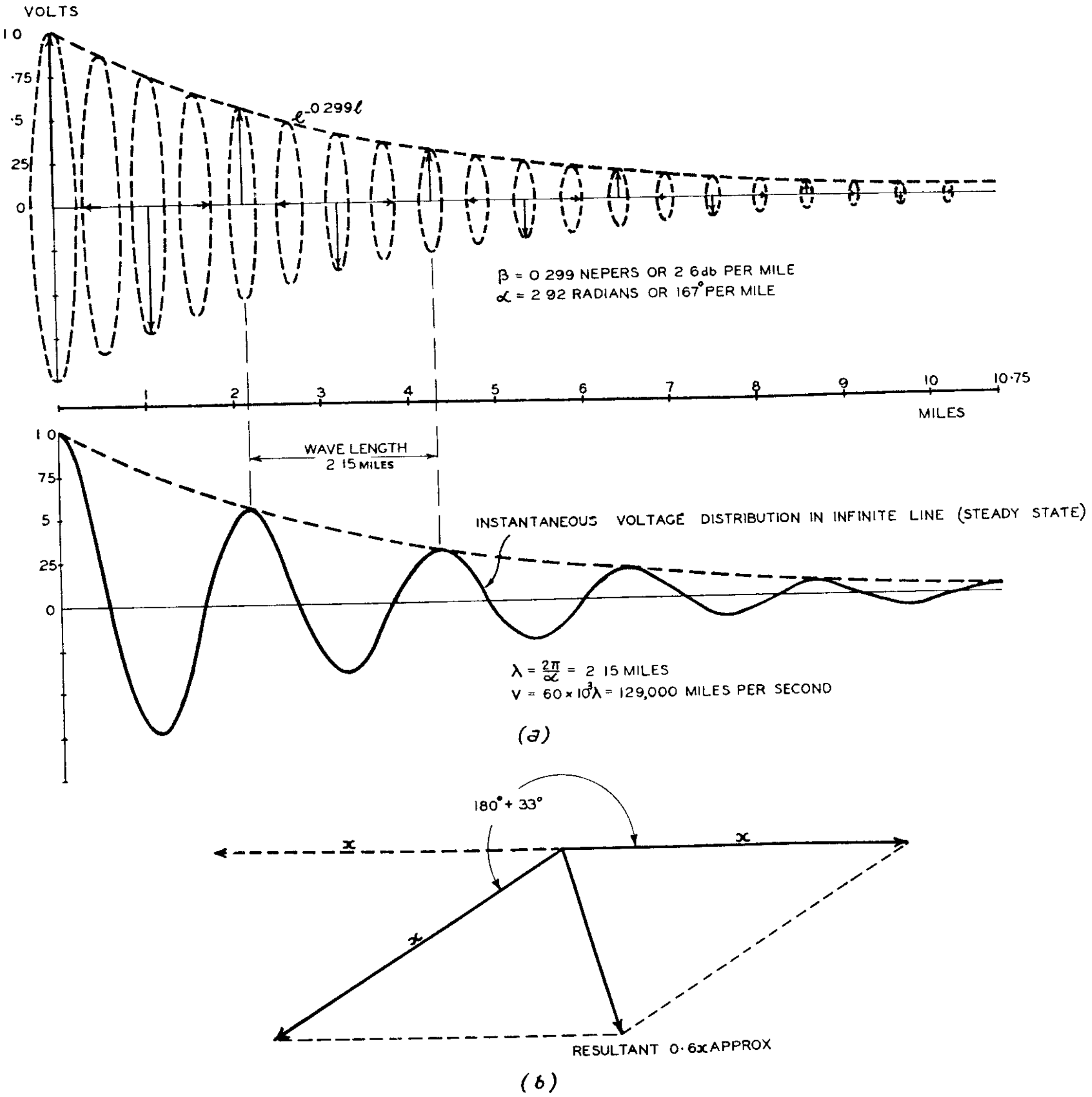


FIG. 32.—ATTENUATION AND PHASE CHANGE IN HALF A REPEATER SECTION OF 24/40 P.C.Q. CARRIER CABLE. FREQUENCY 60 KC/S. LENGTH 10.75 M.

quencies, have a phase difference of $180 + (2 \times 16.7) \fallingdotseq 213°$ at 60 kc/s and instead of cancelling give rise to a residual crosstalk of 0.6 *x* approximately, where *x* is the crosstalk (neglecting line attenuation) resulting from one of the unbalances by itself. This is illustrated in Fig. **32**(*b*).

To obtain real improvement in near-end crosstalk over the whole frequency range up to 60 kc/s from field balancing, it would be necessary to limit the lengths to, say, 44 yards. This would ensure that the unbalances could never be more than 88 yards apart and unbalances which neutralised at audio frequency would then give reasonably small residuals at 60 kc/s.

Good near-end crosstalk is desirable in carrier cables, as, when reflected, it may contribute to far-end crosstalk as described in Part VI of this paper. Balancing in very short lengths to achieve this end would, however, be hardly justifiable on economic grounds and a high degree of balance in the cable itself, especially in those lengths near the ends, appears to be the best way of reducing near-end crosstalk.

Screens.

The physical separation of circuits by a distance so great that they have no electrostatic or electromagnetic influence on one another is rarely possible in practice, but nevertheless separation between items of apparatus in different circuits is afforded as far as practicable, especially in repeater stations where power level differences are at a maximum. Separation electrically by screening is, however, very widely employed.

To screen a circuit electrostatically, a very thin shield totally enclosing the circuit is all that is required. It is effective at high and low frequencies. To screen a circuit electromagnetically, however, a thick shield of good conducting material is essential.

Electromagnetic screens become more effective as the frequency increases.

Relays, transformers and loading coils are provided where necessary with magnetic screens, but within cables, where thick screening would involve heavy expense, screens which are effective from the electrostatic standpoint only are normally employed. Such a screen is generally used around a pair intended for music transmission, and consists of a helical lapping of metallised paper or thin metal foil.

The action of an electrostatic screen around a pair is clear from reference to Fig. **33**. In Fig. **33**(*a*), AB is a screened pair and CD is an unscreened pair. The capacity network between these two pairs is given in Fig. **33**(*b*) and the corresponding admittance diagram in Fig. **33**(*c*). There is one point of connection only, *via* S, between the two networks associated with the two pairs. For AB to have any influence on CD, there must be at least two points of connection and as this is not the case, AB has no electrostatic influence on CD. Similarly CD has no influence on AB.

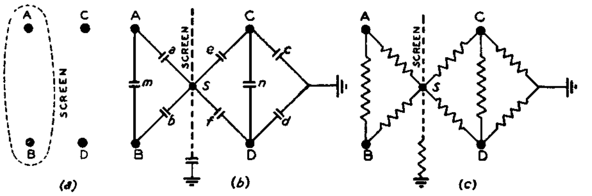


Fig. **33**.

To ensure that there is no direct capacity between wires A or B and wires C or D throughout the length of a cable, it is essential that at all joints the screens should overlap one another. Actual metallic contact between the screens is, however, unnecessary and if the screening consists of paper metallised on one side only, the lapping of one screen over the other for an inch or two is all that is required. Screens in cables should be kept insulated from earth, as otherwise earth currents are liable to circulate in them and cause noise.

As the screens used around music pairs are too thin to reduce magnetic couplings appreciably, it is desirable that such pairs should have different lays from one another and from those of surrounding pairs.

Grouping of pairs in cables.

Audio cables are now generally designed on a 4-wire basis and separation between opposite going pairs of widely differing power levels is achieved by attention to the grouping. Fig. **34** shows a typical grouping for a fairly large cable containing four screened pairs. Four groups are shown in addition to the screened pairs which are usually designated as Group 1.

The grouping is effected by arranging that throughout the length of the cable quads in each of the four groups represented by the numbers 5/6—83/4, 85/6—147/8, 149/50—211/12 and 213/14—293/4, are jointed to quads bearing numbers within the same group. Within each group systematic jointing, for the limitation of pair-to-pair crosstalk, and within-quad balancing, chiefly for the reduction of side-to-side crosstalk, are employed.

The jointing of a cable is much simplified if the beginning and end of a group can be made to coincide with the beginning and end of a layer as in Groups 2 and 5.

Group 2 is completely screened electrostatically from Group 5 by the intermediate pairs, and audio crosstalk between these groups is therefore of a very small order. These groups are suitable for the " Go's " and " Returns " of 4-wire long-distance circuits where a high standard of near-end crosstalk is essential.

The crosstalk between Groups 3 and 4 is not so good as that between Groups 2 and 5, but as the bulk of the quads in Group 3 are in a different layer from those in Group 4, it is nevertheless good enough for shorter distance 4-wire circuits. Crosstalk between adjacent layers is generally good, especially when they contain a large number of quads, because as the layers are stranded in opposite directions, a quad in one layer lies adjacent to any particular quad in the other layer for but a short distance relative to the length of the cable.

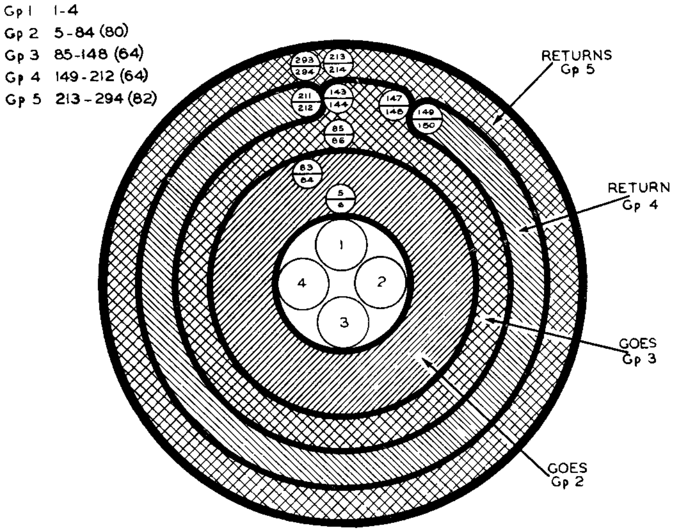


Fig. **34**.—Typical Grouping of Pairs in 4 40 S. + 290/20 P.C.Q.T. Cable.

If the cable shown in Fig. **34** were jointed straight throughout, the near-end crosstalk between the groups would be good, with the exception of that between quads 147/8 and 149/50 and between quads 211/12 and 143/4. Far-end within group crosstalk could probably be improved to the required standard by tail balancing at one point only along the length of the cable, providing the loading were the same for all pairs in a group. Only side-to-side and adjacent pair-to-pair crosstalk would need reduction. The desirable features of straight jointing and of balancing at one point only could therefore probably be achieved at the expense of poor near-end crosstalk between certain combinations of pairs in four quads. If a use for these four quads could be found, there appears to be no reason why straight jointing, with very greatly simplified balancing, should not be employed on certain audio cables. It may be possible to use the four quads for V.F. telegraphs where rather worse

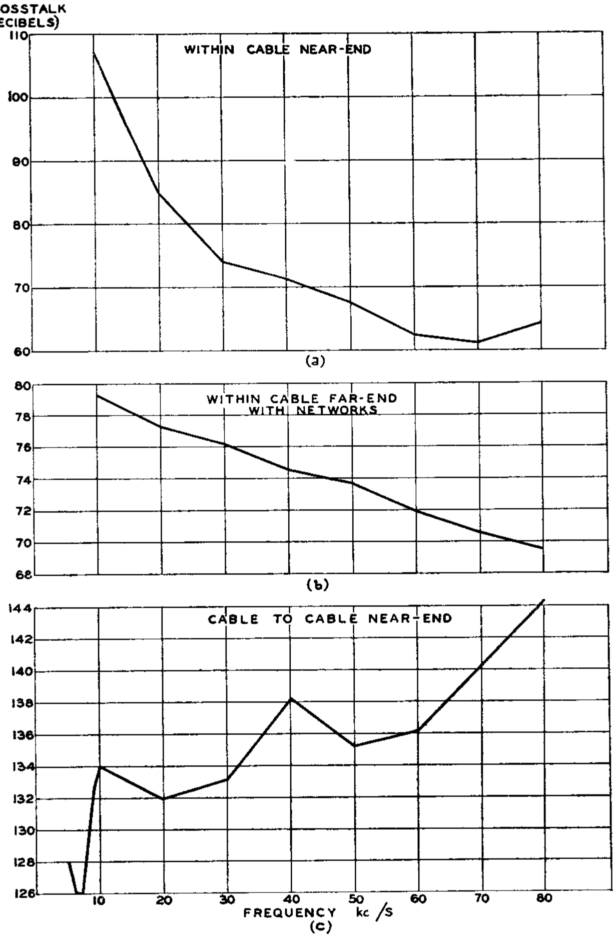


Fig. 35.—Measured Crosstalk between Pairs in and between 24/40 P.C.Q. Carrier Cables.

crosstalk can be tolerated than on speech circuits, but a definite conclusion has not yet been formed by the authors on this point.

Carrier cable—Within and between cable crosstalk.

Figs. 35(*a*) and (*b*) show crosstalk within a 24/40 carrier cable becoming worse with rise of frequency, while Fig. 35(*c*) shows crosstalk between cables becoming better with rise of frequency, owing to the screening effect of the lead sheaths. No electrostatic couplings can exist between pairs in different cables and therefore the improvement in crosstalk with rise of frequency is solely due to the reduction of magnetic couplings by reason of the greater screening effect of the lead sheaths.

It is interesting to note that the insertion of insulating gaps in the sheaths of the Go and Return cables, for the purpose of reducing electrolytic corrosion, worsens the near-end between cable crosstalk. As would be expected the effect of the gaps is greater the nearer they are to the testing end. The difficulty can be overcome by bridging the gaps with condensers (2 μF. or larger). The following figures refer to 12-circuit carrier cables in which insulating gaps were fitted in a particular repeater section 1.0 mile (approx.) from the testing end; they give an indication of the crosstalk degradation to be expected:—

Worst near-end between cable crosstalk at 60 kc/s
(*a*) with no gaps ... ... 140 db.
(*b*) with gaps ... ... 119 db.
(c) with gaps bridged by
2 μF. condensers ... 139 db.

Compandor.

Crosstalk may be greatly improved by the use of equipment termed a " compandor " which operates on a principle entirely different from any of those just described. At the sending end of the line a " compressor " unit operates in such a manner that the normal volume range of the elements composing the signal, expressed in decibels relative to a given peak signal level, is compressed to one half of its normal spread before the signal is transmitted to line. Thus a loud signal element at peak level passes to line unchanged in level, but a weak signal element of say -50 db. is transmitted to line at -25 db. relative to the peak

⟶

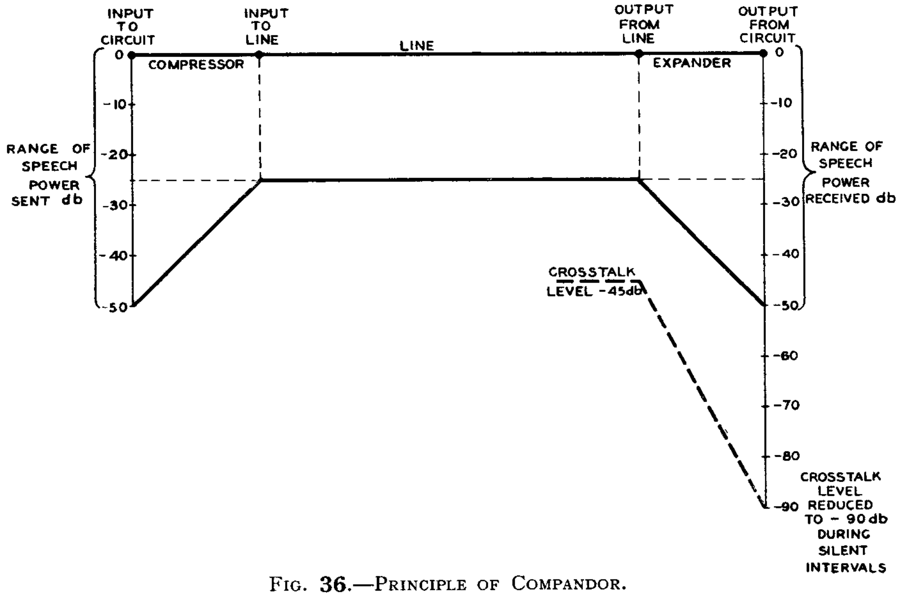


Fig. 36.—Principle of Compandor.

level. The signal-to-noise ratio on the cable is therefore improved during the transmission of low level signal elements, where improvement is most required, but remains unchanged for signal elements of peak level, where interference is completely masked by the signal.

At the receiving end of the circuit, the volume range of the signal elements is restored to the original spread by means of an " expander " unit. The improved signal-to-noise ratio is unchanged by this expansion, since the additional loss required to reduce the level of a weak signal element to its correct value also reduces the crosstalk level by the same amount. The principle is illustrated by the level diagram of Fig. **36**.

When, during the silent intervals occurring in a conversation, the crosstalk alone is received, this acts upon the expander exactly as would a signal of similar level. If this level were say -45 db. relative to peak level (corresponding to bad crosstalk), after passing through the expander, this would be reduced to $2 \times -45 = -90$ db. which would be a sufficiently low level for the crosstalk to be inaudible.

The compressor unit consists essentially of an amplifier, the gain of which is controlled by the level of the applied signal elements so that it is kept equal to half the difference between the level of the input signal and the peak level.

The expander unit inserts a loss equal to the difference in level between the input signal and the peak level. This loss is therefore equal to the gain introduced by the compressor.

Compandor equipment was put into service during September of the present year on a London-Rotterdam circuit routed on a double phantom in the Anglo-Dutch No. 3 submarine cable. Prior to the installation of the compandor the crosstalk level was so high as to render the circuit unworkable, but with the equipment fitted, it is reduced during quiet intervals to a practically inaudible level.

PART VI.

CROSSTALK BALANCING.

Crosstalk balancing in its limited sense is usually taken to mean the reduction or cancellation of far-end crosstalk on a complete repeater section of cable, more particularly for carrier working, and it is in this sense that it is referred to here. It is not intended to discuss further the well-known principles of self-balancing by means of selected joints within the section, nor the not-so-well-known principles involved in the design of cables.

Consider two pairs which are inter-connected electrostatically and electromagnetically, such that a signal applied to one of them induces voltage and current in the other.

This induction will give rise to an unwanted voltage at the receiving end of the disturbed circuit, and in general this voltage is directly proportional to that in the disturbing circuit. It follows that if a portion of the disturbing voltage can be tapped by means of a high-impedance potentiometer and applied to the disturbed circuit, it should be possible to neutralise the crosstalk voltage.

This is in fact true at any one frequency, but the problem is complicated by the necessity of dealing with a range of frequencies, and furthermore what has been arbitrarily called the disturbed pair is itself a disturbing pair. The diagrams in Fig. **37** illustrate the method of obtaining the potentiometer effect and indicate the factors that have to be considered.

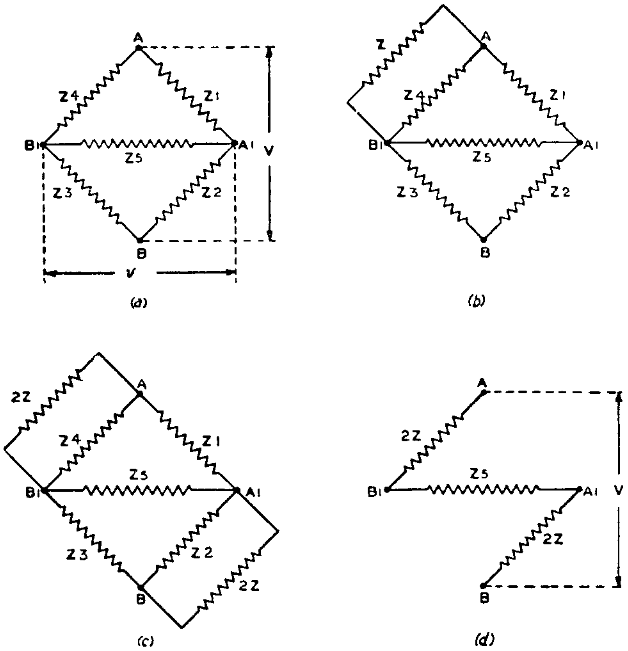


FIG. **37**.

For the purpose of an example, the case considered is that of a balance at the receiving end of the section.

(*a*) shows the effective cable impedances at the end of the section. V is the voltage received on the disturbing pair AB and *v* the crosstalk voltage on the disturbed pair A_1B_1. Z_1, Z_2, Z_3, and Z_4 are effective wire-to-wire impedances. That is, they cannot be directly measured, but are such that, when considered as a bridge network in conjunction with Z_5, a voltage V at AB produces the voltage *v* on A_1B_1. Z_5 is the actual impedance at A_1B_1. In this case it is the impedance of the pair in parallel with the impedance of the termination.

It is clear that for a voltage to appear across A_1B_1 the equivalent bridge network is unbalanced, *i.e.*, Z_1Z_3 is not equal to Z_2Z_4. It can be balanced by modifying the impedance Z_4 say with an impedance Z in parallel until the products are equal (*b*). In this condition there is no voltage across A_1B_1 due to V ; that is, the crosstalk voltage *v* has been neutralised by the addition of a wire-to-wire impedance Z. The components forming this impedance are usually termed a balancing network.

For calculation purposes it is easier to consider the added impedance split into two, 2Z across Z_4 and 2Z across Z_2 (*c*). The error introduced is very slight as Z_2 and Z_4 are in practice very nearly equal, and small compared with Z. (*d*) then gives the potentiometer equivalent to the balancing impedance. The voltage on A_1B_1 due to the balance $= \frac{Z_5V}{4Z + Z_5}$ for neutralization. This may be written $\frac{Z_5 \cdot V}{4Z}$ without sensible error, because the greatest value Z_5 can have is that of the characteristic impedance of the cable, when the terminal impedance is infinite, and for crosstalk not due to faults Z is large compared with the cable impedances. The expression $\frac{Z_5 \cdot V}{4Z}$ may be used to give the magnitude and phase of the far-end crosstalk voltage relative to the voltage received on the disturbing pair.

The neutralizing voltage is proportional to Z_5, or to $\frac{Z_0Z_T}{Z_0 + Z_T}$, where Z_T is the impedance of the termination and Z_0 is the impedance of the pair. The crosstalk voltage on the termination is proportional to $\frac{Z_T}{Z_0 + Z_T}$ (Thévenin's Theorem), and therefore a change in Z_T will affect the crosstalk and balancing voltages equally. This assumes that the impedance of the pair is sensibly the same in each direction.

At any one frequency, a resistance and condenser are sufficient for the balancing network. In normal cases the capacity effect predominates and it is often sufficient to use a condenser balance only.

The balance must still be effective when the pairs are "poled."[11] That is, a balance suitable for pair X to pair Y, with pair X as the disturbing circuit, must also be suitable for pair Y to pair X, with pair Y as the disturbing circuit. If the crosstalk is different on poling the pairs then the balance must be given a compromise value.

Fig. **38** illustrates a case of this kind. Vector OA represents the far-end crosstalk between pair X and pair Y, and OB that between pair Y and pair X. If the balance is such that OA is neutralised, then on poling the residual crosstalk will be represented by AB. Conversely, if the balance neutralises OB, then the residual on poling is represented by BA. The best balance in this case would be such that it would neutralise a far-end crosstalk voltage represented by OC, where AC = CB = ½ AB. The residual crosstalk with the best compromise balance would thus be 6 db. better than the residual obtained on poling the pairs after balancing to zero.

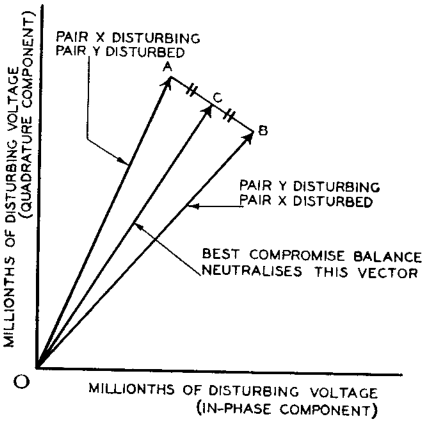


FIG. **38**.—ILLUSTRATION OF BEST COMPROMISE BALANCE WITH BAD POLING.

This residual crosstalk on poling after balancing is a measure of the "goodness" of the cable from a balancing point of view.

Fig. **39** shows the incidence curve of residual far-end crosstalk for the Leeds-Barnsley section of the Derby-Leeds No. 1 multiple-twin cable after deloading. The curves refer to all cases originally of 66 db. or worse. The balance is at the receiving end (Leeds). With the best compromise balances, even if no other factors are involved, the crosstalk will be improved only to that indicated by the dotted curve.

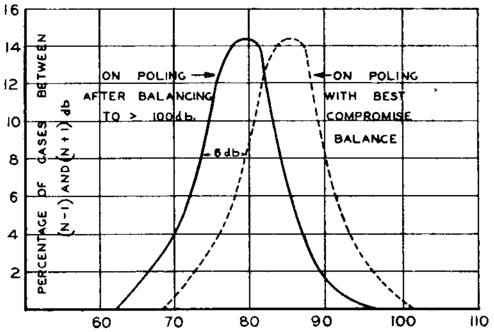


FIG. **39**.—INCIDENCE OF RESIDUAL FAR-END CROSSTALK IN MULTIPLE TWIN CABLE AT 60 KC S.

It has been pointed out that the balancing voltage is directly proportional to Z_5, made up of Z_0 and Z_T. Z_0 is actually the cable impedance that would be measured at the end of the section. This may be different when measured from along the cable looking towards the end, especially in older cables. The voltage from the balance depends on the former "Z_0," the crosstalk voltage on the latter. This, coupled with the fact that the effect is probably not equal for the two pairs, will cause a difference in the balance required, quite apart from any changes in the crosstalk couplings themselves.

A similar effect will be noted if the terminal impedances of the pairs are not equal, for the voltage supplied to the balance depends on the terminal impedance of the disturbing pair. This makes it possible to correct poling troubles to some extent by modifying the terminal impedance of one pair slightly, provided that there are not too many cases in the same section.

On a bad case of far-end crosstalk, a small phase angle between balance and crosstalk voltages is sufficient to cause quite a large residual.

The effect of change of frequency has now to be considered. Referring again to Fig. **37**(*a*) etc., the balancing impedance is dependent on the voltages V and *v* and the impedance Z_5. The effect of the impedance Z_5 for end-section balancing is the same for both crosstalk and balancing voltages. If, however, the variation with frequency of this impedance varies from pair to pair, then poling troubles will arise.

---

[11] See Appendix II.

V will be affected by frequency change due to the attenuation β_1 and phase-change α_1 altering with frequency. The crosstalk voltage v will be similarly affected, but partly by the attenuation β_2 and phase-change, α_2 of the disturbed pair. · The voltage due to a coupling at a given point is dependent in the first place on the voltage of the disturbing pair at that point. The induced voltage then undergoes the attenuation and phase-change of the disturbed pair until it appears across the termination. The voltage v is the summation of the voltages due to individual couplings.

For twelve-channel carrier cables at least, the difference in attenuation and phase-change between pairs is negligible, and the ratio $\frac{V}{v}$, and therefore the balancing impedance is not upset by consideration of changes in β and α with frequency.

The couplings themselves may change with frequency, as described in Part III of this paper. The chief difficulty occurs when there is a considerable resistance component required in the balance, which may be due to complex magnetic couplings (possibly non-reversible), or to differences in α and β, as already mentioned. It is found that, where it exists, this resistance effect usually gets worse as the frequency is increased, and the resulting crosstalk does not " pole " as well as the reactive crosstalk, with poling of pairs, due to non-reversible couplings. In a bad case of this nature, a simple two-element balance would be of little use, as the resistance component would degrade the balance at the lower frequencies. A three-element balance is better, consisting of two condensers and one resistance, with one of the condensers in series with the resistance. This decreases the effect of the resistance at lower frequencies. It has been found that, for unloaded cables, this type of variation of crosstalk couplings with frequency can be met by a three-element balance, the values of the components being calculated from measurements made with the admittance-unbalance set.

The use of inductance in balancing has not yet been found necessary in this country on unloaded cables. For cables designed for twelve-channel carrier working, a simple capacity balance is usually quite good enough, even up to frequencies high enough to include a further twenty-four channels.

The difficult cases arise when older cables are used for carrier circuits.

It has been assumed up to now that the balance is at the receiving end. It can of course be at the sending end (in " Zwei-band " working the same balance may be at either end, depending on the channel) or somewhere in between, preferably near the middle of the section.

When the balance is placed at the sending end, the balancing voltage depends on the sending end impedance of the disturbed pair, and can therefore be affected independently of the far-end crosstalk. The balancing voltage received at the far-end is dependent on the β and α of the disturbed circuit only.

When the balance is at the middle of the section, it is not affected by terminal impedances to any appreciable extent, and works into an impedance of $\frac{Z_0}{2}$, there being an impedance of Z_0 in each direction. In this respect, it behaves more like the crosstalk it is neutralising, and may on that account take care of some of the cases of bad poling. Another advantage is that the neutralizing voltage received at the end of the circuit is dependent equally on the attenuation and phase constants of both pairs. Where these constants differ from pair to pair a mid-section balance strikes a good mean, in cases where the effective centre of the couplings is near the middle of the section.

A disadvantage is the expense of erecting special huts and leading in the cable in the middle of repeater sections, and the danger of low insulation on the balancing frames when installed in these huts. Furthermore, adjustment of the balances is made a little more difficult when the actual result of the balancing is directly observable only at the receiving end of the section, an objection which applies also to sending-end balancing. Mid-section balancing has been applied up to the present on modern cables where in actual fact its advantages do not apply so obviously.

In illustration of some of the preceding observations, Fig. **40** shows the loci of admittance-unbalance vectors with change of frequency for a side-to-phantom combination of the Anglo-Dutch No. 3 cable.

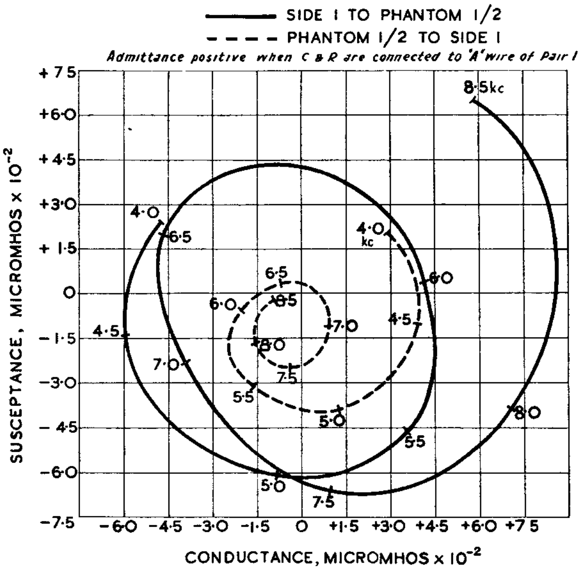


FIG. **40**.—ADMITTANCE UNBALANCE FREQUENCY CHARACTERISTICS OF CIRCUITS IN ANGLO-DUTCH NO. 3 CABLE. (BALANCE AT SENDING-END).

The general difference in vector length between the two curves is due to the difference in attenuation of the two circuits. The balance being at the sending end, for side-to-phantom balancing the balancing voltage undergoes the attenuation of the whole length of the phantom circuit, while the mean crosstalk attenuation, apart from that due to the coupling itself, is for half the side circuit length and half the phantom. The phantom attenuation being the higher, more balancing voltage must be supplied to the phantom at the sending end to allow for this extra attenuation. This implies a lower impedance potentiometer, *i.e.*, higher admittance, and this is in fact the case. The effect is more marked with increase of frequency. It would appear that at a frequency somewhat below 4 kc/s the effect would be reversed, showing that the phantom attenuation is then lower than that of the side circuit.

It will be seen that the vectors rotate in opposite directions, owing to the different phase constants of the side and phantom circuits. For if A_p is the total phase-change along the phantom circuit, and A_s the total phase-change for the side circuit, then the mean phase-change of the crosstalk voltage along the cable is $\frac{A_p}{2} + \frac{A_s}{2} = \frac{A_p + A_s}{2}$, and this is the same on poling. The phase-change of the balancing voltage for the side-to-phantom balance is A_p and for the phantom-to-side balance A_s.

$A_p > \frac{A_p + A_s}{2} > A_s$ and as the differences increase with frequency the vectors must rotate in opposite directions relative to the true crosstalk admittance unbalance. It should be noted that the convention adopted for the unbalance vectors makes a susceptance due to a capacity positive, so that the positive sense of rotation is clockwise. The balancing voltage applied to the side circuit at the sending end has to be made more leading as the frequency is increased, showing that A_s is lagging more at higher frequencies, *i.e.*, $A_s < \frac{A_p + A_s}{2}$

It was found, as would be expected, that with the balance at the receiving end, the side-to-phantom balance behaved like the sending end phantom-to-side balance, and vice versa.

Longitudinal balancing by means of series impedances was tried on this combination and gave results equivalent to the transverse balances. There is apparently no advantage in using longitudinal balancing.

There are one or two practical points regarding balancing which might be mentioned.

It is usual to balance a cable before the terminal equipment is connected, and therefore temporary terminations have to be provided. When the impedance of the terminal equipment is not known fairly definitely when balancing, then it is safest to balance with Z_0 terminations. The terminations finally used may have a singing point of down to 20 db. at 60 kc/s, and near-end crosstalk attenuated by this amount may thus appear, apparently as far-end crosstalk, due to reflection. The impedance of the terminations also affects the crosstalk couplings near the ends of the cable, besides the voltage applied to the balance. Hence it is better, if the equipment impedance is known, to simulate this as closely as possible when balancing, and not use Z_0 terminations. Nothing of course can be done about reflected near-end crosstalk over an extended frequency range, as its phase will change with frequency, but it can be taken care of in the region where it most matters, if the balancing is done with practical terminations.

Reflected crosstalk appearing as far-end crosstalk between two pairs is shown in Fig. **41**.

The far-end crosstalk received at D under working conditions is made up of crosstalk from four sources—

(1) The residual far-end after balancing (with Z_0 terminations).
(2) Crosstalk reflected from C *via* the balancing network.
(3) The reflected near-end *via* the cable between A and B.
(4) The reflected near-end *via* the cable between C and D.

It is convenient to consider item (2) as a reflection through the balancing network when magnitudes only are required. When phase is also being considered it is necessary to regard the effect as being due to a change in the transmitted voltage applied to the network.

Whether or not networks may be fitted at the end depends primarily upon the magnitude of item (2). Now consider this question for twelve-circuit carrier cable. Two factors govern the magnitude of item (2).

(*a*) The singing point of termination C
and (*b*) the attenuation of the path through the balancing network.

The specifications for the cable and apparatus ensure a good match between line and apparatus and singing points rather better than the following normally obtain:—

Frequency in kc/s	12-30	40	60
Singing point, db.	14	17	20

Typical values of crosstalk between pairs in a repeater section are:—

Far-end at 60 kc/s before balancing	75 db. average. 60 db. worst.
Far-end at 60 kc/s after balancing	85 db. average. 75 db. worst.
Near-end at 60 kc/s	75 db. average. 62 db. worst.

The attenuation of the path through a network is fixed by the value of the far-end crosstalk prior to the fitting of the network. For example, to improve far-end crosstalk from say 60 db. before balancing to 75 db. or more after balancing the neutralizing crosstalk introduced by the balancing network must be very nearly equal to 60 db.

Now consider the far-end crosstalk at 60 kc/s likely to arise from the accumulation of the four sources shown in Fig. **41**, assuming 20 db. singing point terminations. If the worst values of near-end crosstalk at both ends and the worst value of far-end crosstalk before balancing all occurred between the same two pairs the crosstalk from

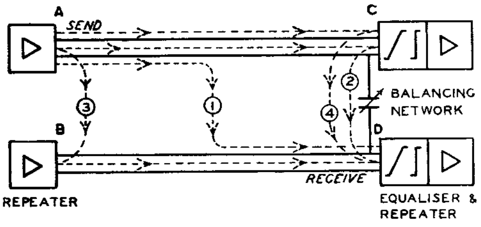


Fig. **41**.—Far-end Crosstalk between two Pairs in a Repeater Section.

source 1 would be ... ... 75 db. or 178 millionths (the worst case is assumed)

source 2 would be 60 + 20 = 80 db. or 100 millionths

source 3 would be 62 + 20 = 82 db. or 79 millionths

source 4 would be 62 + 20 = 82 db. or 79 millionths

Total 436 millionths

Thus in the very unlikely case of all four crosstalk voltages being in phase the resultant far-end crosstalk would be 436 millionths or 67 db. Random accumulation of the four voltages would be a more reasonable assumption and a worst value of about 69 db. would be expected. It is unlikely that the worst case of uncorrected far-end crosstalk would occur between pairs having worst near-end values at both ends. Average near-end values would be more probable and in this case the crosstalk from

source 1 would be ... ... 75 db. or 178 millionths

source 2 would be 60 + 20 = 80 db. or 100 millionths

source 3 would be 75 + 20 = 95 db. or 18 millionths

source 4 would be 75 + 20 = 95 db. or 18 millionths

By direct accumulation this gives a value of 314 millionths or 70 db. and by random accumulation at least 71 db. would be expected.

Thus it is deduced that the worst value of far-end cross-talk under working conditions which may be expected in a repeater section with balancing networks fitted at the end is at least 69 db. The average value will be from 8-10 db. better, say 78 db.

In the case considered the frequency has been 60 kc/s, but no difficulty will arise at lower frequencies with networks at the end because both near-end and far-end cable crosstalk improve by about 6 db. per octave decrease in frequency.

The overall far-end crosstalk between pairs at the end of a 200 mile cable consisting of 10 repeater sections each having a mean value of 78 db. and a worst value of 69 db. would probably be 68 mean and rather better than 60 db. worst. These values are satisfactory and network balances may therefore be permitted at the end of repeater sections on twelve-circuit carrier cables. The networks may be fitted at either the receiving or transmitting end, but for ease of adjustment there is some advantage in their being at the receiving end. In future twelve-circuit schemes it is probable that the far-end crosstalk balancing net-

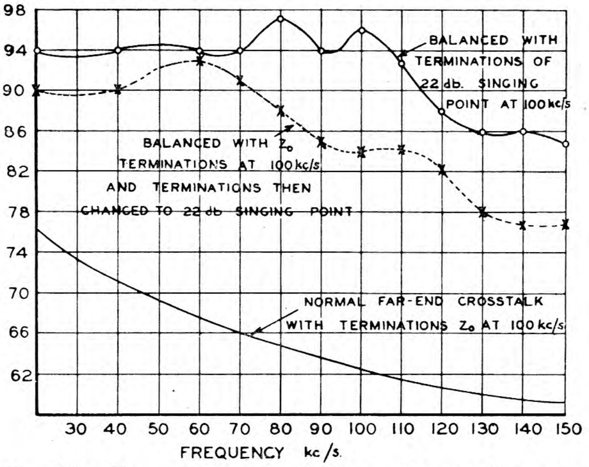


FIG. 42.—VARIATION OF END BALANCED FAR-END CROSSTALK DUE TO CHANGE IN TERMINATIONS.

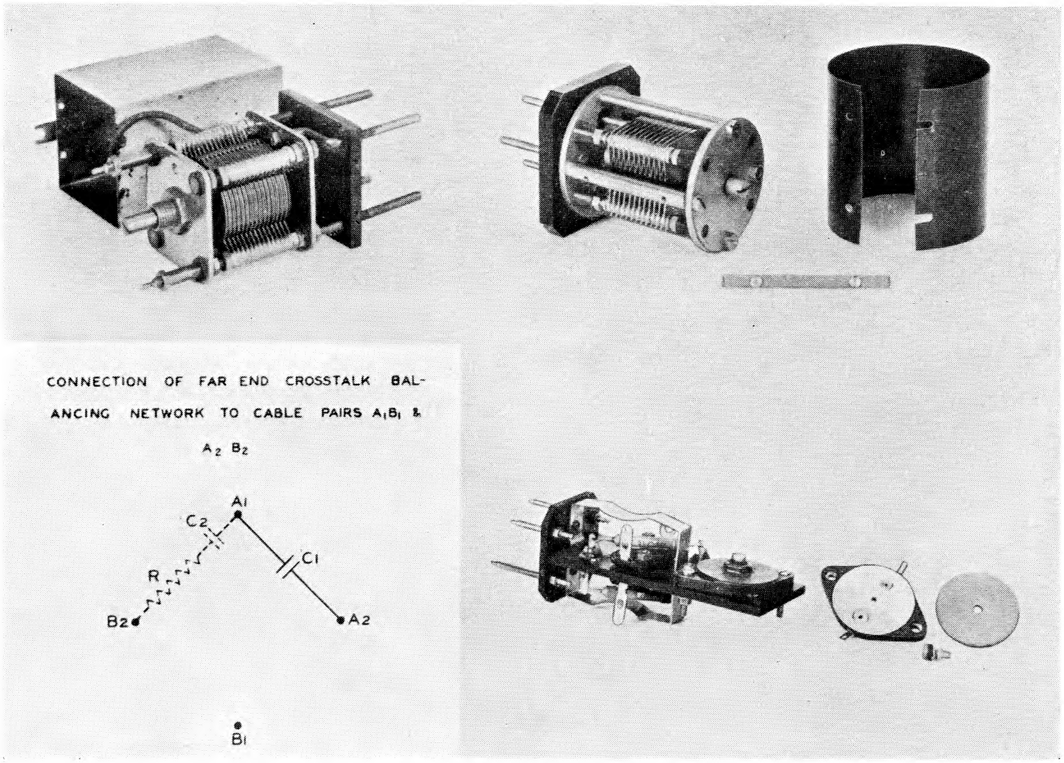


FIG. 42(a).—FAR-END CROSSTALK BALANCING NETWORKS.

works will be fitted at the receiving repeater stations, a balancing network frame for one cable only being installed at terminal repeater stations and frames for both cables at intermediate stations.

Fig. **42** shows the effect of changing the terminations after balancing. The measurements were made from 20-150 kc/s on an $8\frac{1}{2}$ mile section of the London-Cambridge 24/40 carrier cable between pairs 17 and 8. The balance was at the receiving end and consisted of capacity only. It was adjusted to give maximum improvement at 100 kc/s.

The chief component of a balancing impedance is a condenser, which may be either differential or plain. If differential, one of the pairs is connected to the two sets of fixed plates, and one wire of the other pair to the moving plates. This can be done before any initial balancing is carried out, because the effective capacity can be swung quite easily from one side to the other. On the other hand, more material is required to obtain a given capacity, and should one side of the differential become disconnected or develop a high-resistance connection, then half the differential appears directly as an unbalance on the other side, and the crosstalk may be worse than it was before balancing.

The components of three different designs of balancing networks are shown in Fig. **42**(*a*); a S.T. & C. differential condenser is shown on the top left, a G.E.C. differential condenser on the top right and a Siemens unit at the bottom. The Siemens unit embodies a ceramic type variable condenser. All three units provide a means of placing an adjustable value of C_1 (see sketch in photograph) between A_1 and A_2 or A_1 and B_2 or alternatively between B_1 and B_2 or B_1 and A_2 as required. The Siemens unit shows additional resistances and fixed condensers for making up a three-element balance.

PART VII.

MISCELLANEOUS CROSSTALK CONSIDERATIONS.

Crosstalk under calling conditions at P.M.B.X.s and C.B. Exchanges.

When two pairs in a perfectly balanced twin or quad type cable are connected to apparatus which has a different impedance between the A line and earth and the B line and earth, crosstalk may occur between the two pairs. This is in no way due to any defect in the cables, but arises in the manner discussed in the next paragraphs.

Between any two pairs AB and CD in a well-balanced cable, the wire-to-wire admittances *w* are all essentially equal, as are also the wire-to-earth admittances *e*.

The admittances associated with two such pairs are shown in Fig. **43**(*a*) and the simplified equivalent network in Fig. **43**(*b*). The latter network is clearly a balanced bridge and a voltage V applied to AB produces no voltage across CD.

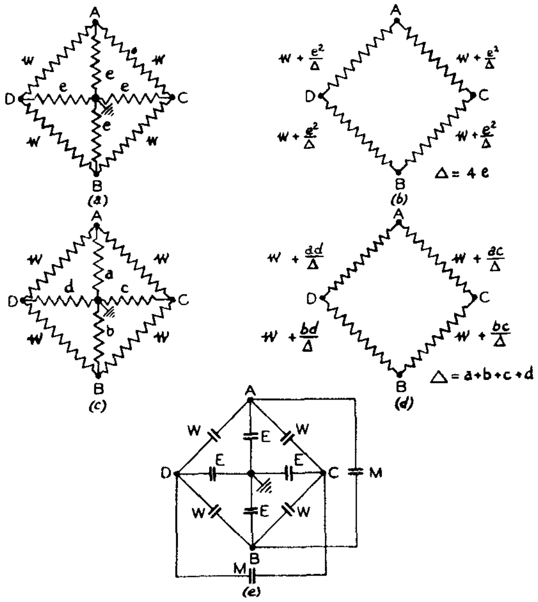


FIG. 43.

If the two pairs are connected to apparatus having unbalance to earth between the A and B wires and the C and D wires, the admittance network becomes as in Figs. **43**(*c*) and (*d*), where *a* differs from *b* and *c* differs from *d*. If a voltage V is applied across AB, there is a resulting crosstalk voltage *v* across CD.

$$v = V\left(\frac{\dfrac{1}{w+\dfrac{ac}{\Delta}}}{\dfrac{1}{w+\dfrac{ac}{\Delta}}+\dfrac{1}{w+\dfrac{bc}{\Delta}}} - \frac{\dfrac{1}{w+\dfrac{ad}{\Delta}}}{\dfrac{1}{w+\dfrac{ad}{\Delta}}+\dfrac{1}{w+\dfrac{bd}{\Delta}}}\right)$$

$$= V\left(\frac{\dfrac{1}{w+\dfrac{ac}{\Delta}}}{\dfrac{2w+\dfrac{c}{\Delta}(a+b)}{\left(w+\dfrac{ac}{\Delta}\right)\left(w+\dfrac{bc}{\Delta}\right)}} - \frac{\dfrac{1}{w+\dfrac{ad}{\Delta}}}{\dfrac{2w+\dfrac{d}{\Delta}(a+b)}{\left(w+\dfrac{ad}{\Delta}\right)\left(w+\dfrac{bd}{\Delta}\right)}}\right)$$

$$= V\left(\frac{w + \frac{bc}{\Delta}}{2w + \frac{c}{\Delta}(a+b)} - \frac{w + \frac{bd}{\Delta}}{2w + \frac{d}{\Delta}(a+b)}\right)$$

$$= V\left(\frac{2w^2 + \frac{2bcw}{\Delta} + \frac{dw}{\Delta}(a+b) + \frac{bcd}{\Delta^2}(a+b) - 2w^2 - \frac{2bdw}{\Delta} - \frac{cw}{\Delta}(a+b) - \frac{bcd}{\Delta^2}(a+b)}{\left(2w + \frac{c}{\Delta}(a+b)\right)\left(2w + \frac{d}{\Delta}(a+b)\right)}\right)$$

$$= V\left(\frac{\frac{2bw}{\Delta}(c-d) - \frac{w}{\Delta}(a+b)(c-d)}{\left(2w + \frac{c}{\Delta}(a+b)\right)\left(2w + \frac{d}{\Delta}(a+b)\right)}\right)$$

$$= V\left(\frac{\frac{w}{\Delta}(c-d)(2b-a-b)}{\left(2w + \frac{c}{\Delta}(a+b)\right)\left(2w + \frac{d}{\Delta}(a+b)\right)}\right)$$

$$= -V\left(\frac{w(a-b)(c-d)}{\left(2w\Delta + c(a+b)\right)\left(2w + \frac{d}{\Delta}(a+b)\right)}\right) \quad \text{..(1)}$$

The two diagrams on the left hand side of Fig. **44** show lines connected to apparatus which has an unbalance to earth between the legs. The condition is found at P.M.B.X.s and at C.B. exchanges during the period when the caller is awaiting the attention of the operator. If from the data given in Table 4 values for admittances *w*, *a*, *b*, *c* and *d* are derived and inserted in expression ....(1) above it can be demonstrated that for a particular length of cable, and for given values of $(a - b)$ and $(c - d)$, the crosstalk between two calling circuits is greater for pairs in the same quad in quad cable than for adjacent pairs in twin cable.

Experience has shown that crosstalk between two exchange or extension line circuits both in the calling condition arises if the following combination of circumstances obtains—

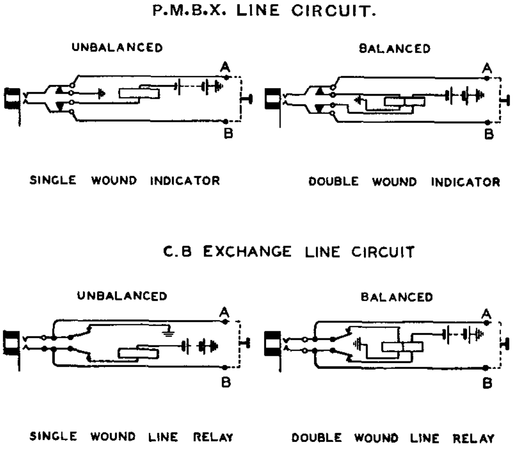


FIG. **44**.—UNBALANCE INTRODUCED BY APPARATUS.

TABLE 4.

	Typical values for 1 mile of 10lb. cable.							
	Quad Type (P.C.Q.L.) Adjacent pairs same quad				Twin Type (P.C.T.) Adjacent pairs			
For meaning of W, E and M, see Fig. 43 (e).	W	E	M	(mutual) $W+M+\frac{E}{2}$	W	E	M	(mutual) $W+M+\frac{E}{2}$
Capacity μF. *Admittance Mhos. *Impedance ohms.	.0352 23.2×10^{-5} 4,300	.0581 38.4×10^{-5} 2,600	.0088 5.8×10^{-5} 17,200	.0731 48.3×10^{-5} 2,070	.0088 5.8×10^{-5} 17,200	.0528 34.9×10^{-5} 2,900	.0352 23.2×10^{-5} 4,300	.0704 46.5×10^{-5} 2,150
*Impedance ohms. „ „	Typical single-wound P.M.B.X. indicator, Fig. 44, 12,000 $\underline{/53^\circ}$ „ „ „ C.B. exch. line relay „ „ 1,200 $\underline{/58^\circ}$							

---

* at 1050 c/s.

(1) The two circuits concerned are in the same twin or quad cable and are separated by only a few pairs or quads.
(2) The length of cable is sufficient.
(3) Both circuits are in the calling condition at the same time.
(4) The operators are slow to answer, and
(5) One of the callers becomes impatient and speaks.

When one caller is waiting for an operator to answer and the other is speaking to an operator or another subscriber, overhearing may also occur, although to a much less extent, under conditions equivalent to the above.

The necessary combination of circumstances is not likely to occur very frequently, but nevertheless there has been considerable difficulty from time to time with overhearing of this nature. The complaints are most likely to arise when the telephones concerned are connected to two pairs of a quad in the cable and when room noise is at a very low level. A complete cure can be effected by providing balanced apparatus by means of double-wound indicators or relays as shown on the right of Fig. **44**. Improvements of the order of 45 db. can be effected by this means. Changing of indicators and relays, however, is only carried out when the Engineer-in-Chief is satisfied that the circumstances warrant this exceptional action. No fresh designs of C.B. exchanges are likely in view of the policy of automatisation, but in future designs for P.M.B.X.s all calling equipments (with the exception of those for short extensions on lamp signalling boards) will be balanced.

Amplified circuits.

(*a*) 4-*Wire Amplifier Circuits.*

In a 4-wire amplifier circuit it is convenient to use the phantom on the Go and Return pairs for D.C. signalling. Because of level differences, it is desirable from the crosstalk standpoint to transmit and receive on pairs segregated in opposite-going 4-wire groups. Unfortunately, these two features are not reconcilable, as will be apparent from reference to Fig. **45**.

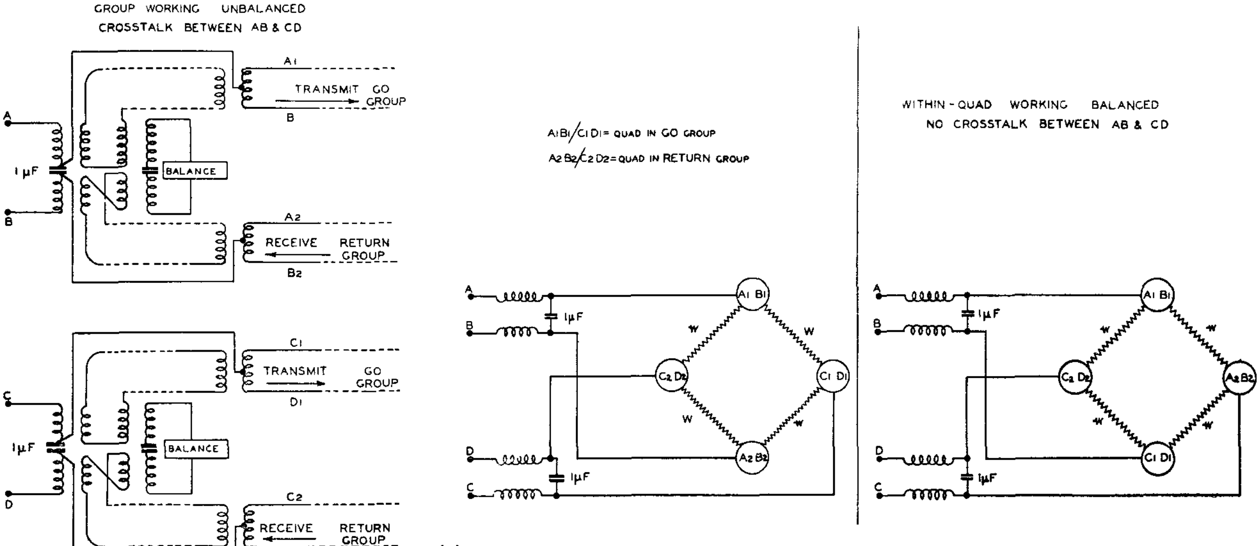
If A_1B_1/C_1D_1 and A_2B_2/C_2D_2 are quads in different 4-wire groups, very high crosstalk will be experienced between phantom circuits made up of a side circuit from each of these quads. The network shown at the bottom of Fig. **45**(*a*) depicts the condition. The admittances W between A_1B_1 and C_1D_1 and between C_2D_2 and A_2B_2, being between pairs in the same quad, are much greater than the admittances *w* between A_1B_1 and C_2D_2 and between C_1D_1 and A_2B_2, because of the wide separation between the pairs in the latter instance. The network is therefore unbalanced and disturbing power in circuit AB produces crosstalk in circuit CD by way of the unbalances existing between phantoms A_1B_1/A_2B_2 and C_1D_1/C_2D_2. The 1 μF. condensers tend to reduce the magnitude of the crosstalk, but as the impedance of a 1 μF. condenser is 152 ohms at 1,050 c/s, the most important crosstalk frequency, they do not remove it entirely and group working on amplifier circuits with D.C. signalling has given rise to trouble.

Reference to Fig. **45**(*b*) shows the conditions for within-quad working. The separating distances between A_1B_1 and pairs A_2B_2 and C_2D_2, and between C_1D_1 and pairs A_2B_2 and C_2D_2 are all essentially the same and the four admittance arms of the network are equal. The network is therefore balanced and no crosstalk, other than that due to normal minor unbalances, occurs between AB and CD.

If repeater sections are to be made reasonably long, a higher standard of crosstalk is necessary between the opposite-going pairs than is possible between pairs of adjacent quads and group working is imperative. A re-design of D.C. signalling circuits is therefore being considered in which group working will be preserved, but the signalling circuits will be worked within quad. No such difficulty as that outlined exists when 4-wire circuits with 500/20 c/s ringing or other voice-frequency signalling are worked on a group basis.

(*b*) *Earth Unbalance in Terminating Units.*

Serious crosstalk between the 2-wire extensions of amplifier circuits may arise from earth unbalances



(*a*) (*b*)

FIG. **45**.—4-WIRE AMPLIFIER CIRCUITS.

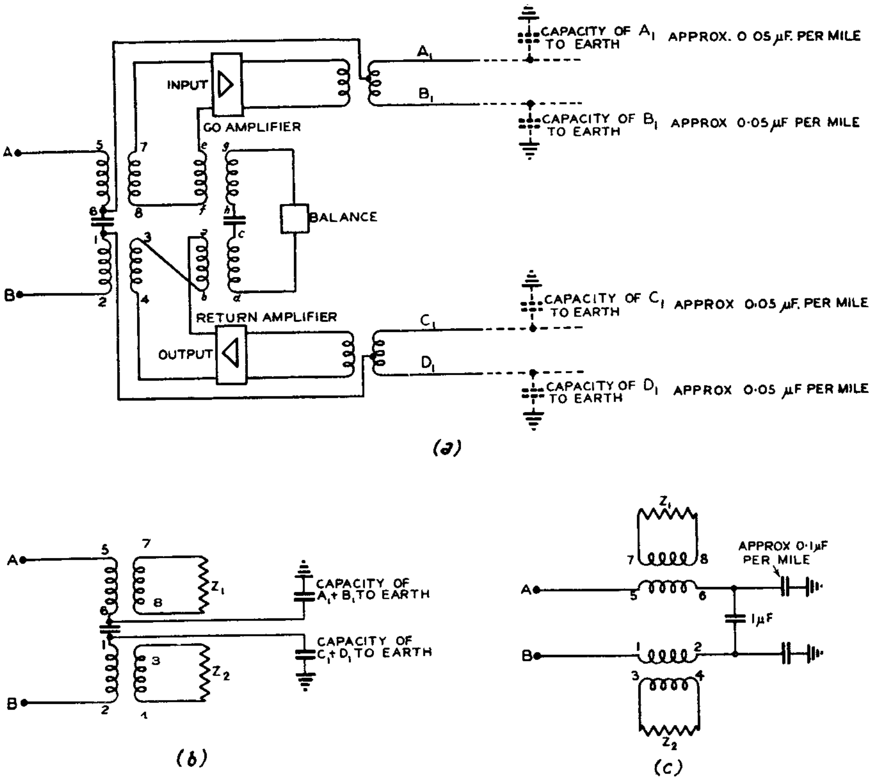


FIG. 46.—CAUSE OF EARTH UNBALANCE IN TERMINATING UNITS.

introduced by the 2-wire windings of terminating units. Fig. **46**(*a*) represents a terminal amplifier and a terminating unit, and Figs. **46**(*b*) and (*c*) illustrate the manner in which the unbalances arise.

If transformer 1-2, 3-4 is identical with transformer 5-6, 7-8 and impedance Z_1 equals impedance Z_2, then the admittance of terminal A to earth is equal to the admittance of terminal B to earth and under these conditions no unbalance exists. If, however, impedance Z_1 differs from impedance Z_2, or transformer 1-2, 3-4 has different characteristics from transformer 5-6, 7-8, an earth unbalance is introduced between A and B.

Z_1 depends on the input impedance of the Go amplifier and should not vary, but Z_2 is affected by the impedance of the Return amplifier output valve. Valves may vary considerably and differences between Z_1 and Z_2 are to be expected. Also, windings 1-2 and 5-6 carry different signalling currents and the transformer cores become magnetised to different extents. Hence transformers 1-2, 3-4 and 5-6, 7-8 may have different characteristics. These factors have been found in practice to give rise to serious unbalance and severe crosstalk may be experienced if the 2-wire extensions are sufficiently long.

The difficulty has been overcome by arranging for windings 1-2, 3-4, 5-6 and 7-8 to be on one core so that variations in the core, or differences between Z_1 and Z_2, affect the admittances of A to earth and B to earth equally. In the past a double transformer with a single core has been used for windings 1-2, 3-4, *a-b* and *c-d* and a similar transformer for windings 5-6, 7-8, *e-f* and *g-h* and a wiring alteration only has therefore been necessary to change the connections so that windings 1-2, 3-4, 5-6 and 7-8 are accommodated on one of these double transformers.

Cable Repairs.

(*a*) *Audio Cables.*

The maintenance of an adequate standard of crosstalk during and after repairs to main underground cables requires careful consideration. As is well known, the usual method of repair when damage is extensive is to substitute a lead-covered interruption cable, usually of the quad local type, for the faulty length, which is then either

(*a*) resheathed and replaced with the wire crosses which originally existed, or

(*b*) scrapped and replaced by a new length of similar type cable, either with or without rebalancing.

If resheathing is possible, or if a new length is provided and balanced in, little or no crosstalk degradation results. Consideration has therefore to be given only to

(1) the degradation introduced by interruption cable of P.C.Q. local type, and

(2) the degradation resulting from the introduction of a new length of trunk type cable without rebalancing.

When audio cables are laid, within-quad crosstalk is reduced by balancing; pair-to-pair crosstalk is kept within reasonable limits by the use of systematic jointing, which mixes up the quads as thoroughly as possible so that the unbalances accumulate, not directly, but in a pure chance manner ; and group-to-group crosstalk is kept low by virtue of separation between groups.

If interruption cable is inserted, providing its pair-to-pair capacity unbalance values are of the same order as those in the replaced length and the make-up is such that the grouping can be preserved, no degradation of pair-to-pair or group-to-group crosstalk can arise. In actual fact P.C.Q. local type cable is but slightly inferior to trunk type in so far as pair-to-pair and group-to-group capacity unbalances are concerned, the maximum capacity unbalance permitted by specification for a standard 176 yd. length between one pair and any other pair being 100 $\mu\mu$F for trunk type cable and 125 $\mu\mu$F. for local type (with local type cable 10% of the lengths manufactured are permitted to have individual values as high as 200 $\mu\mu$F.) and the insertion of P.C.Q.L. interruption cable therefore causes little or no degradation in pair-to-pair and group-to-group crosstalk. The introduction of a new length of P.C.Q.T. cable should not cause any degradation in these quantities.

Degradation of side-to-side within-quad crosstalk is the remaining factor to be considered. The capacity unbalance limits allowed by specification for a standard length of cable are 33 $\mu\mu$F. mean and 125 $\mu\mu$F. max. (50 $\mu\mu$F. mean and 200 $\mu\mu$F. max. for 10% of lengths manufactured) for P.C.Q.T. type and 125 $\mu\mu$F. mean and 750 $\mu\mu$F. max. (200 mean and 1000 max. for 10% of lengths manufactured) for P.C.Q.L. type. It is, therefore, possible for a length of P.C.Q.L. interruption cable to have a side-to-side unbalance as high as 1000 $\mu\mu$F. and for a replacing length of P.C.Q.T. cable to have one as high as 200 $\mu\mu$F.

When a length of cable is removed from a well-balanced loading section, the unbalance characteristics of the remaining lengths are similar to those of the length removed. When the interruption length or permanent replacing length is joined in, these unbalances in the remaining lengths add to or subtract from the unbalances in the replacing length in a random manner.

In modern cables the maximum side-to-side unbalance permitted by specification in a loading section is 100 $\mu\mu$F. and, as the maximum possible unbalance in the length to be replaced is 200 $\mu\mu$F., the maximum possible residual unbalance of the remaining lengths in the loading section is 200 + 100 = 300 $\mu\mu$F.

It therefore follows that the absolute maximum side-to-side unbalance possible as a result of introducing (*a*) a length of P.C.Q.L. cable is 1000 + 300 = 1300 $\mu\mu$F. and (*b*) a length of P.C.Q.T. cable is 200 + 300 = 500 $\mu\mu$F. Such values would most probably never occur in practice as the unbalances have been obtained by adding worst cases, moreover P.C.Q.T. and P.C.Q.L. cable lengths rarely have unbalances as high as the specifications permit, but it is convenient to consider the absolute worst conditions possible.

The crosstalk resulting from unbalances of 1300 $\mu\mu$F. and 500 $\mu\mu$F. between pairs having a normal impedance of, say, 1100 ohms at 1050 c.p.s. will now be calculated.

Crosstalk at 1050 c.p.s. from 1300 $\mu\mu$F. unbalance

$$
\begin{aligned}
&= 20 \log_{10} \frac{8 \times 10^{12}}{\omega \times K \times |Z|} \\
&= 20 \log_{10} \frac{8 \times 10^{12}}{2\pi \times 1050 \times 1300 \times 1100} \\
&= 20 \log_{10} 848 \\
&= 20 \times 2.93 \\
&\fallingdotseq \underline{\underline{59 \text{ db.}}}
\end{aligned}
$$

Similarly, crosstalk at 1050 c.p.s. from a 500 $\mu\mu$F. unbalance

$$
\begin{aligned}
&= 20 \log_{10} \times \frac{8 \times 10^{12}}{2\pi \times 1050 \times 500 \times 1100} \\
&= 20 \log_{10} 2205 \\
&= 20 \times 3.34 \\
&\fallingdotseq \underline{\underline{67 \text{ db.}}}
\end{aligned}
$$

Side-to-side within-quad crosstalk is only important in so far as it affects near-end crosstalk between 2-wire circuits, and far-end crosstalk between 4-wire pairs transmitting in the same direction.

The magnitude of the near-end crosstalk introduced between two circuits by unbalances in a replacing length depends on the circuit attenuation between the cable temination and the replacing length. Thus, as indicated in Fig. **47**(*a*), a single source of crosstalk of 59 db., as may be introduced by a length of interruption cable, would give rise to a near-end value of 4 + 59 + 4 = 67 db. between A and B and a near-end value of 10 + 59 + 10 = 79 db. between C and D.

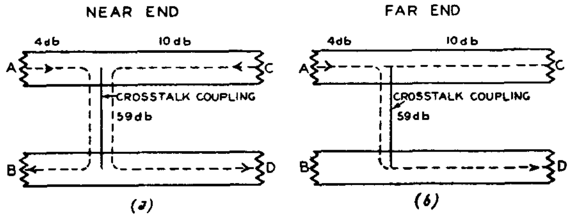


FIG. **47**

The same source of crosstalk would, however, give rise to a 59 db. far-end S/N value between C and D at whatever point it were introduced, if lines AC and BD are of similar attenuation.

Crosstalk contributions of 59 db. from a length of P.C.Q.L. cable and 67 db. from a length of P.C.Q.T. cable would be exceptional, as the direct addition of worst values has been assumed in computing these figures. In practice, worst values better by some 3 db. at least would almost certainly obtain and they would only appear between relatively few pairs. The average value between pairs would probably be from 6 to 9 db. higher still.

Thus it is not possible to foretell accurately what the worst crosstalk contribution will be, as it depends on how the unbalances come together and on whether they add or subtract, but it can be stated quite definitely that it cannot be worse than 59 db. for a P.C.Q.L. length and 67 db. for a P.C.Q.T. length. Having these figures in mind, reasonable contributions from a P.C.Q.L. length may be regarded as, say, 59 + 3 = 62 db. worst, and 70 db. average, and from a P.C.Q.T. length 67 + 3 = 70 db. worst and 78 db. average.

The crosstalk attenuation in a main cable prior to the insertion of a length should be at least (Table 3), near-end 76 db. worst (82 db. average) and far-end 62 db. worst (68 db. average). The crosstalk introduced by the insertion of a length accumulates with this normal crosstalk in some random manner. If the insertion of a P.C.Q.L. length near the end of the cable is concerned, the near-end crosstalk resulting from this length will be so much greater than the normal near-end crosstalk, that the resultant over-all near-end crosstalk at the end in question will be essentially that due to the interruption length alone. If, however, a small allowance of, say, 1 db. is made for accumulation, the probable over-all values will be, worst 61 db., and average 69 db.

The normal crosstalk has slightly more effect when a P.C.Q.T. length is introduced. The resulting over-all near-end crosstalk when values of 70 db. worst and 78 db. average are introduced into a cable having normal values of 76 db. worst and 82 db. average would probably be of the order or 68 db. worst and 75 db. average if the new length were near the end.

The maximum level difference met in practice between 2-wire amplified circuits is about 14 db. and with this difference in level, a 61 db. value of near-end crosstalk attenuation is not adequate. The average value of 69 db. is just commercially satisfactory, but no more. Thus, if 2-wire repeatered circuits are working in a cable, the introduction of a P.C.Q.L. interruption length near to one end is likely to cause overhearing between one or two pairs. The majority of the pairs will be just satisfactory. If the interruption length is remote from the ends of the cable, only a very slight degradation of near-end crosstalk will result.

It has been deduced that the introduction of a new length of P.C.Q.T. cable without rebalancing will probably give worst and average figures some 6 to 8 db. better than those resulting from the introduction of a P.C.Q.L. length, so that even when the length introduced is near to one end, the worst value of crosstalk will be just tolerable.

Far-end crosstalk is not likely to be greatly upset by the introduction of either type cable, because in the worst possible case the S/N contribution will be 59 db. and this is only 3 db. lower than the worst value of 62 db. S/N permitted by specification in a new cable. When allowance is made for accumulation the S/N ratio is unlikely to be less than, say 57 db. in the worst case. This is particularly fortunate as the majority of modern long distance cables are worked on a 4-wire grouped basis, and as with this method of working good near-end crosstalk is assured by segregation, the effect on far-end crosstalk only needs to be considered.

The above deductions are based on the assumption that the length of cable replaced conforms to present-day specification as regards capacity unbalance. In many of the older cables, this is not the case and a length in situ may contain very high unbalances which have been selected to balance out others in the same loading section. Thus, if such a length were replaced by a new length with small unbalances, the residual unbalances of the loading section may be very high and serious crosstalk may result.

Summing up the position, it may be said that in general the use of P.C.Q.L. cable for interruption purposes is permissible, and that rebalancing is as a rule unnecessary when a length in a modern cable is replaced by a length of similar type cable, but that caution is necessary if 2-wire repeatered circuits are involved and the length is introduced near to the end of the cable. Rebalancing is advisable when lengths in old type balanced cables are replaced, especially where phantom circuits are concerned.

Decisions as to whether or not rebalancing is necessary in any particular case can only be given after consideration of the age and known characteristics of the cable. In practice, whenever a length is replaced without rebalancing, near-end within-quad crosstalk tests are carried out from the end of the cable nearer the new length, and these results are closely examined and recorded in graphical form after each repair so that any serious degradation in crosstalk may be brought to light and rectified.

In one case recently examined where ten lengths had been replaced without rebalancing at various points in a cable 50 miles long, no perceptible degradation in near-end or far-end crosstalk had taken place. The cable is of the P.C.Q.T. type laid in 1931.

(*b*) *Carrier Cables.*

From a limited experience of replacing lengths in P.C.Q. carrier cables, there are indications that the insertion of a new length (176 yds.) of carrier-type cable without rebalancing is unlikely to degrade the far-end repeater section crosstalk by more than 2 or 3 db. Re-adjustment of balancing networks after a repair is not therefore an urgent necessity and may be safely left until a convenient opportunity occurs.

The worst case of far-end crosstalk at 60 kc/s likely to arise from the introduction into a repeater section of one length of ordinary P.C.Q.T. cable is next considered. It is assumed that the section was well balanced by the networks prior to the insertion of the length and that the residual capacity and magnetic unbalances for the whole section were so small as to be negligible.

The maximum capacity unbalance permitted by specification in a 176 yd. length of P.C.Q.T. cable is 200 $\mu\mu$F. between pairs in a quad. No magnetic coupling values are specified for this type of cable, but reference to Table 1 shows that a maximum value of 0.53 μH. was measured in a specimen length of 90 yds. between pairs in alternate quads having the same lay. This corresponds to $\frac{0.53 \times 176}{90} = 1.05\,\mu\text{H.}$ (approx.) in a 176 yd. length assuming direct accumulation.

The capacity unbalance between alternate quads is very small because of the screening effect of the intermediate quad so that these two unbalances of 200 $\mu\mu$F. and 1.05 μH. will not occur between the same pairs and the crosstalk from each may therefore be considered separately.

In P.C.Q. carrier-type cable the maximum capacity unbalance between pairs in a quad may be 120 $\mu\mu$F., and the maximum magnetic coupling between pairs in alternate (that is, not adjacent) quads

0.2 μH. (see Table 2). When a length is removed from a balanced repeater section the maximum residual unbalances on the remaining lengths in the section will be of this order and therefore the maximum total capacity unbalance of the repeater section when a length of P.C.Q.T. cable is joined in may be

$$200 + 120 = 320\ \mu\mu\text{F}.$$

and the maximum magnetic coupling—

$$1.05 + 0.2 = 1.25\ \mu\text{H}.$$

The approximate impedance of carrier cable pairs at 60 kc/s is 140 ohms and the far-end S/N crosstalk from a 320 $\mu\mu$F. unbalance at 60 kc/s is therefore equal to—

$$\begin{aligned} & 20 \log_{10} \frac{8 \times 10^{12}}{\omega K |Z|} \\ &= 20 \log_{10} \frac{8 \times 10^{12}}{2\pi \times 60 \times 10^3 \times 320 \times 140} \\ &= 20 \log_{10} 474 \\ &= 20 \times 2.68 \\ &= \underline{\underline{54 \text{ db.}}} \end{aligned}$$

and the far-end S/N crosstalk from a 1.25 μH. unbalance is equal to—

$$\begin{aligned} & 20 \log_{10} \frac{2 \times 10^6 \times |Z|}{\omega M} \\ &= 20 \log_{10} \frac{2 \times 10^6 \times 140}{2\pi \times 60 \times 10^3 \times 1.25} \\ &= 20 \log_{10} 594 \\ &= 20 \times 2.77 \\ &= \underline{\underline{55 \text{ db.}}} \end{aligned}$$

Values of 54 or 55 db. are not desirable figures for far-end crosstalk S/N, but circuits with crosstalk of this standard are regarded as being commercial. The values have been obtained by assuming accumulation of rather extreme values of unbalance and figures considerably better than 54 would be expected normally. It is therefore possible to replace temporarily a single length in a carrier-type cable working up to 60 kc/s by a length of P.C.Q.T. cable without any serious effect on the circuits carried. The comparative inferiority of P.C.Q.T. type, however, particularly as regards magnetic unbalance, makes it desirable that any cable inserted permanently, or any length of interruption cable longer than say a quarter of a mile, should be of P.C.Q. carrier type.

Cable with capacity unbalance figures as high as those permitted by the specification for P.C.Q. local type cable would be unsuitable for use for interruption purposes on twelve-channel cables. Generally speaking, however, the maximum unbalance in a length of cable is very much smaller than that permitted by specification and in an emergency there would be no hesitation in making good a single length of carrier cable with P.C.Q.L. type.

(*c*) *Coaxial Cables.*

In coaxial cables with more than one coaxial tube the crosstalk between any two tubes is, by reason of the design, much the same in all lengths. Hence, no crosstalk problems are involved when a length is replaced in this type of cable. Typical crosstalk values for this type of cable are given in I.P.O.E.E. Paper No. 164.*

Mid Section Loading.

To improve transmission over old cables which have loading sections of 4,000 yards or more, it is necessary to raise the cut-off by loading at more frequent intervals. On grounds of economy, the existing loading manholes are generally utilised to accommodate new loading pots and additional loading points are established at the mid-points of the original loading sections.

The system of balancing normally employed for audio cables relies on matching unbalances in one length against unbalances of similar magnitude in other lengths in the same loading section in such a manner that they neutralise one another. It is therefore quite normal for a +100 $\mu\mu$F. unbalance, say, in one half of a 4,000 yd. loading section to be matched against an equal unbalance of opposite sign in the other half, as indicated in Fig. **48**(*a*).

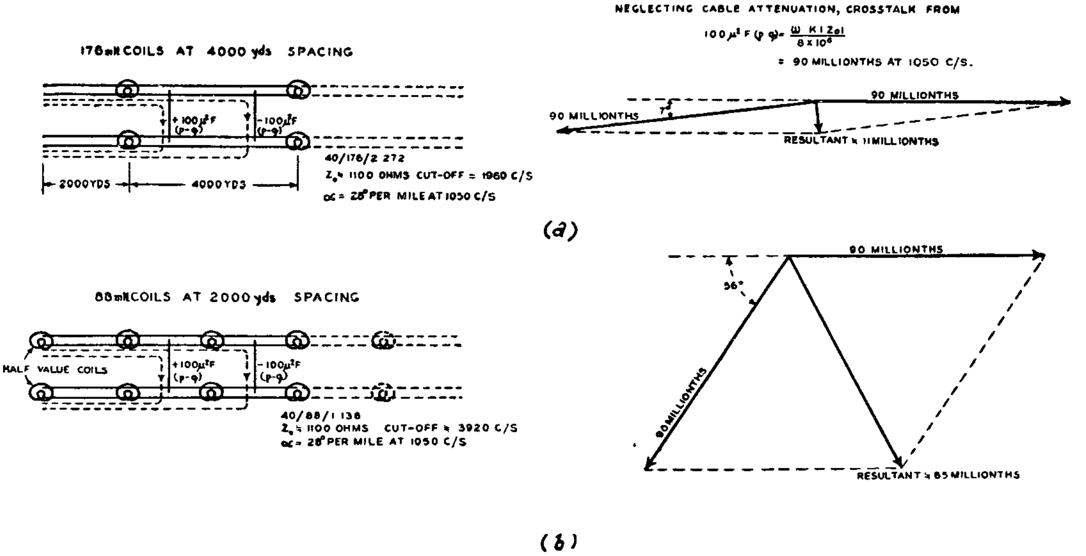


Fig. **48**.—Intermediate Loading.

---

* " The London-Birmingham Coaxial Cable System," by A. H. Mumford, 1937.

During transmission in a coil-loaded cable, practically all the phase change in the current or voltage takes place at the coils. Only a small phase change occurs in the loading section itself, and hence the near-end crosstalk currents arising in this section, due to the equal but opposite $(p-q)$ unbalances shown in Fig. **48**(a), differ in phase by almost 180° and practically cancel one another as indicated in the vector diagram in the same figure. The nearer the actual sources of the unbalances are together, the more complete is the cancellation.

If loading coils are now inserted at the mid-points the one crosstalk current passes through two more coils than the other as shown in Fig. **48**(*b*). With the particular loading shown, the phase change per mile at 1,050 c/s is approximately 28° and as this occurs chiefly at the coils, the phase of the two near-end crosstalk currents will differ by approximately 180° + 56°. The vector addition of these two currents is illustrated in Fig. **48**(*b*) and it is clear that the resultant crosstalk is considerable.

When, therefore, coils are inserted at the mid-points of loading sections, to obtain satisfactory near-end crosstalk it is necessary to rebalance the newly formed sections. If all pairs are similarly loaded rebalancing is quite unnecessary from the standpoint of far-end crosstalk paths through the $+100$ $\mu\mu$F. and the -100 $\mu\mu$F. unbalances. The phase difference remains 180° because both crosstalk currents pass over the same length of circuit and through the same number of coils.

Multi-Phone Systems.

In multi-phone systems speech is fed simultaneously to a number of telephone stations over lines connected in parallel to the output of an amplifier. It is not uncommon for upwards of 100 stations to be fed in this manner, and if a large number of circuits is carried in one cable, difficulty is liable to arise from the accumulative effect of crosstalk induced by these circuits in other pairs.

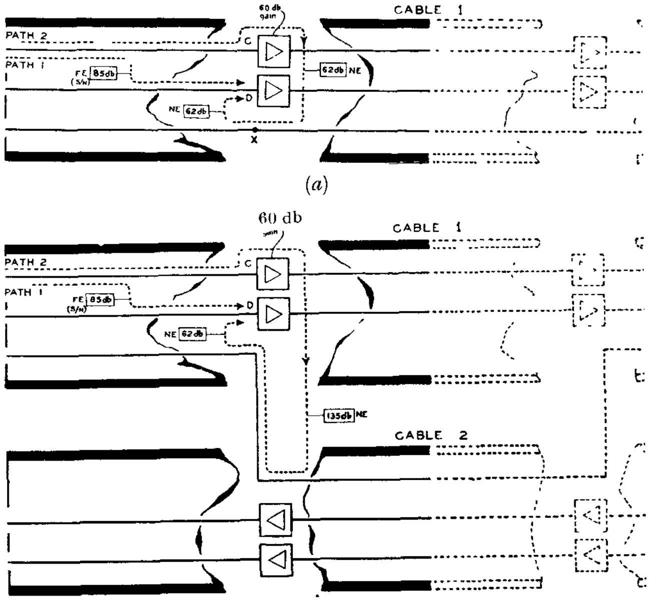
Crosstalk from a number of pairs to one particular pair does not as a rule add directly, but it accumulates in a manner which approaches pure chance. As an approximation, it may be taken that 100 circuits, all carrying the same speech simultaneously, produce $\sqrt{100} = 10$ times the voltage or current disturbance which would result from one disturbing circuit only. Because of this accumulation cables used for carrying circuits connected to multi-phone installations must conform to a higher degree of balance than normal, the standard of balance required depending upon the number of circuits routed in one cable. Before such systems are installed, it is therefore necessary to investigate the crosstalk standard of any cabling involved.

The effect of accumulation is to some extent mitigated by the relatively good pair-to-pair crosstalk which usually obtains in local cables. The mean value is generally at least some 9 db. better than the mean side-to-side value. This means, assuming random accumulation, that the disturbance caused to a pair by nine circuits in other quads is equivalent only to that produced by one circuit in the same quad. This is particularly fortunate in view of the possible extended use in future of verbal announcements, which, of course, involve the distribution of the same speech over a number of pairs in the local network.

Through Pairs in Carrier Cables.

If pairs in one repeater section are extended directly through to pairs in another section, serious degradation of far-end crosstalk is liable to occur *via* indirect near-end crosstalk paths.

In Fig. **49**(*a*), the normal far-end crosstalk between pairs AC and BD is shown as path 1, 85 db. S/N. This figure would obtain until the unamplified pair is joined through at X. When X is joined through, a further source of far-end crosstalk *via* path 2 is completed between circuits AC and BD. The attenuation of this path between C and D is -60 (gain of amplifier) + 62 (near-end crosstalk between one amplified pair and the through pair) + 62 (near-end crosstalk between through pair and the other amplified pair) = 64 db. Thus the original good value of 85 db. S/N far-end crosstalk is reduced to some value rather less than 64 db. S/N. If several pairs are joined through without repeaters, they each produce a similar indirect crosstalk path and a value of far-end crosstalk considerably less than 64 db. S/N, may result.



(*a*)

(*b*)

FIG. **49**.—CROSSTALK IN CARRIER CABLES DUE TO EXTENSION OF PAIRS WITHOUT AMPLIFIERS.

There are three methods of overcoming the difficulty—

(1) By fitting amplifiers in all pairs. As these transmit in one direction only, there can then be no path from the output of one amplifier to the input of another. Such action is, however, obviously uneconomical.

(2) By inserting low-pass filters at X in all wires joined directly through.

(3) By crossing over the through pairs from "Go" cable 1 to "Return" cable 2, as shown for one pair in Fig. **49**(*b*). This introduces the near-end cable-to-cable crosstalk attenuation into path 2 and in the example shown improves the crosstalk of path 2 from 64 to

$$-\ 60 + 135 + 62 = 137 \text{ db.}$$

Far-end crosstalk of 137 db. S/N has no appreciable effect on the original value of 85 db. S/N.

The action outlined in (2) or (3) above is necessary when both audio and carrier circuits are worked in the same cable, for the higher attenuation of the carrier circuits usually necessitates the insertion of carrier amplifiers at more frequent intervals than audio amplifiers. It will also probably be necessary, if a proposed experiment to work certain pairs in twelve-circuit carrier cables up to 160 kc/s materialises. Similar precautions are also necessary when pairs are extended through from repeater section to repeater section for maintenance testing purposes.

APPENDIX I.

Proof of validity of simplified electrostatic crosstalk calculation.

(Referred to in Part III.)

Referring to Fig. **50**

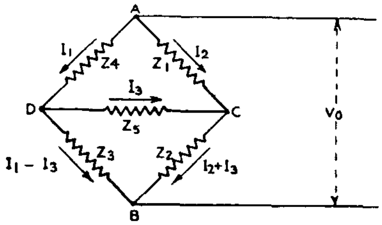


FIG. **50**.

$Z_4I_1 - Z_1I_2 + Z_5I_3 = 0$ ....(1)

$Z_3I_1 - Z_2I_2 - (Z_2 + Z_3 + Z_5)\, I_3 = 0$ ....(2)

$(Z_1 + Z_2)\, I_2 + Z_2I_3 - V_0 = 0$ ....(3)

(Mult. (1) by Z_3) $Z_3Z_4I_1 - Z_1Z_3I_2 + Z_3Z_5I_3 = 0$ ......(4)

(Mult. (2) by Z_4) $Z_3Z_4I_1 - Z_2Z_4I_2 - Z_4\,(Z_2 + Z_3 + Z_5)\, I_3 = 0$......(5)

Subtract (5) from (4) $(Z_2Z_4 - Z_1Z_3)I_2 + (Z_3Z_5 + Z_4(Z_2 + Z_3 + Z_5)\,)I_3 = 0$.........(6)

From (3) $I_2 = \dfrac{V_0 - Z_2I_3}{Z_1 + Z_2}$. Substitute for I_2 in equation (6)

Then

$$\frac{(Z_2Z_4 - Z_1Z_3)\,(V_0 - Z_2I_3)}{Z_1 + Z_2} = -\,(Z_3Z_5 + Z_4\,(Z_2 + Z_3 + Z_5)\,)\,I_3$$

$$\therefore\ I_3 = -\frac{(Z_2Z_4 - Z_1Z_3)V_0}{(Z_1 + Z_2)(Z_3Z_5 + Z_4(Z_2 + Z_3 + Z_5)\,) + Z_2(Z_1Z_3 - Z_2Z_4)}$$

The term $Z_2(Z_1Z_3 - Z_2Z_4)$ in the denominator is very small compared with the first term and may be ignored.

The equation then becomes

$$I_3 = -\frac{(Z_2Z_4 - Z_1Z_3)V_0}{(Z_1 + Z_2)\,(Z_3Z_5 + Z_2Z_4 + Z_3Z_4 + Z_4Z_5)}$$

Now in a cable $Z_1 + Z_2 + Z_3 + Z_4$ will closely approximate to 4 Z_1 or $4x$, but the difference between these terms will not be zero. Hence let

$Z_1 = x + \delta_1x,\ Z_2 = x + \delta_2x,\ Z_3 = x + \delta_3x$ and $Z_4 = x + \delta_4x$.

$$\text{Then } I_3 = -\frac{V_0x\{(\delta_2x + \delta_4x) - (\delta_1x + \delta_3x)\}}{2x(2x^2 + 2xZ_5)}$$

Now the voltage v between C and D will be

$$I_3Z_5 = v = -\frac{Z_5.V_0.x.\{(\delta_2x + \delta_4x) - (\delta_1x + \delta_3x)\}}{4x^3 + 4x^2Z_5}$$

$$= \frac{Z_5V_0\{(\delta_1x - \delta_2x) - (\delta_4x - \delta_3x)\}}{4x^2 + 4xZ_5}$$

In a short length of cable Z_5 is considerably less than x and the equation becomes

$$\frac{v}{V_0} = \frac{Z_5\{(\delta_1x - \delta_2x) - (\delta_4x - \delta_3x)\}}{4x^2}$$

The foregoing formulæ express the unbalance in the form of a series impedance δx whereas in practice it is necessary to deal with the equivalent parallel impedance unbalance. Therefore it is required to find the relationship between δx and y. (See Fig. **51**.)

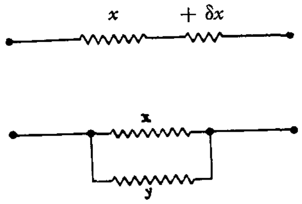


FIG. **51**.

$$x + \delta x = \frac{x.y}{x + y}$$

$$x^2 + x\delta x + x.y + \delta x.y = x.y$$

$$x^2 + \delta x(x + y) = 0.$$

$\therefore\ \delta x = \dfrac{-x^2}{x + y}$. Now assume x small compared with y then $\delta x = -\dfrac{x^2}{y}$

....

The value $(\delta_1 x - \delta_2 x) - (\delta_4 x - \delta_3 x)$ can be reduced to one term δx, resultant unbalance. Hence $\frac{v}{V_0} = \frac{Z_5 \delta x}{4x^2}$ for a short length of cable. Now δx is equal to $\frac{-x^2}{y}$ where y is the resultant shunt unbalance and is equal to the parallel impedance required to be added to one arm of the bridge to ensure balance. If $y = \frac{1 \times 10^{12}}{j\omega K}$, where K is a small capacity in micro-microfarads.

$$\therefore \frac{v}{V_0} = \frac{-Z_5}{4.y} = \frac{-j\omega K Z_5}{4 \times 10^{12}}$$

but Z_5 is normally $\frac{Z_0}{2}$ for terminated crosstalk measurements,

$$\text{hence } \frac{v}{V_0} = \frac{-j\omega K Z_0}{8 \times 10^{12}}$$

The phase relationship between v and V is not often of great importance and the comparison of magnitudes only is normally required. In this case the minus sign, the j operator and the angle of Z_0 may be disregarded and the crosstalk attenuation expressed as $20 \log_{10} \frac{8 \times 10^{12}}{\omega K \, |Z_0|}$ db.

APPENDIX II.

Terms, Definitions, etc.

The Nomenclature and Symbols Committee of the Engineer-in-Chief's Office has recently suggested definitions for crosstalk and other kindred terms. These definitions are reproduced below.

(1) *Crosstalk.* The sound heard in a receiver associated with a telephone channel and resulting from telephone currents in another telephone channel. The magnitude of the crosstalk may be expressed either as crosstalk attenuation or as crosstalk volume.

(2) *Crosstalk attenuation.*

(*a*) The attenuation between the sending terminals of the disturbing circuit and the receiving terminals of the disturbed circuit.

(*b*) The ratio (in millionths) of the crosstalk current (or voltage) in the receiving circuit to the current (or voltage) transmitted into the disturbing circuit, correction being made where specified to compensate for the differences between the sending and receiving impedances. In order to convert to attenuation as defined in (*a*) above, it is essential to apply this correction for impedance.

Notes:

1. Far-end crosstalk is usually measured by the comparison of voltages at the receiving terminals of the disturbing and disturbed circuits and the measured values must be corrected to take account of the relative level at the receiving terminals of the disturbing circuit.
2. Where crosstalk attenuation is quoted, the actual crosstalk volume can only be determined if the volume of the disturbing signal is known.

Authors' Note:

Note (1) indicates that far-end crosstalk is usually measured by comparing the voltages at the receiving end of the disturbed and disturbing circuits. It is generally referred to in this sense in this paper, but to avoid confusion when so used it is, where necessary, suffixed by S/N to indicate signal-to-noise ratio.

(3) *Crosstalk volume.* The volume of cross-talk sound expressed in decibels referred to Reference Telephonic Power.

(4) *Near-end crosstalk.* Crosstalk which is propagated in a disturbed channel in the direction opposite to the direction of propagation of the current in the disturbing channel. The terminal of the disturbed channel at which the near-end crosstalk is present is ordinarily near, or coincides with, the energised terminal of the disturbing channel.

(5) *Far-end crosstalk.* Crosstalk which is propagated in a disturbed channel in the same direction as the direction of propagation of the current in the disturbing channel. The terminal of the disturbed channel at which the far-end cross-talk is present and the energised terminal of the disturbing channel are ordinarily remote from each other.

(6) *Babble.* The aggregate crosstalk from a number of disturbing channels.

(7) *Signal-to-noise ratio at a point in a transmission system.* The ratio expressed in decibels of the effective voltage of the desired signal to that of noise, crosstalk and/or babble.

Notes:

1. Although primarily requiring an aural balance, it is commonly estimated by means of volume meters. The results obtained will depend upon the type of volume meter used.
2. It is also used to express the ratio between the voltages due to signals impressed at points of equal level on disturbed and disturbing circuits respectively.

(8) *Reference Telephonic Power, abbreviation R.T.P.* (*Reference Volume*). That speech power into 600 ohms, the peaks of which, when measured on the S.F.E.R.T. volume indicator (*q v*) gives a zero reading.

Notes:

1. The sensitivity of the instrument is varied by means of a dial calibrated in decibels. With speech currents the readings of the volume indicator are not steady and the reading used for measurement of the power is the maximum deflection of the needle, such as ordinarily occurs about once in three seconds. The number of decibels read on the dial is then a measure of the relative volume at the testing point in terms of R.T.P.

2. It is not possible to relate the quantity " R.T.P." to any steady rate of dissipation of energy (expressed in watts) since the duration of the various peak voltages caused by speech is purely fortuitous.

(9) *Volume Indicator* (*Volume Meter*). A voltmeter having specified characteristics employed for the comparative measurement of speech levels.

(10) *Volume Indicator* (*S.F.E.R.T.*). A particular form of volume indicator having electrical and mechanical characteristics which have been internationally agreed.

Notes:

1. The calibration is in decibels relative to 6 milliwatts into 600 ohms at 800 or 1000 c.p.s.
2. " S.F.E.R.T." is the " Système Fondamental Européen de Référence pour la Transmission Téléphonique."

(11) *Poling*. The interchange of the conductors at a point in a transmission path in order to detect an alteration in electrical characteristics, due to such interchange. (The authors have found it convenient to extend this meaning of the term poling and refer to the interchange of pairs as " the poling of pairs.")

(12) *Channel*. A means of one-way communication.

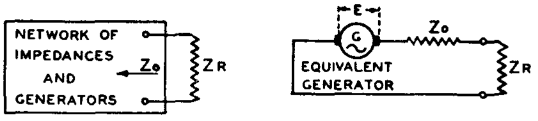
(13) *Circuit*.

(1) A means of bothway communication. It comprises associated " Go " and " Return " channels.

(2) A path in which an electric current may flow. By common usage the term is also employed to designate (*a*) an aggregation of paths, and (*b*) a specific part of a complete path.

APPENDIX III.

Thévenin's Theorem, which is of wide application in crosstalk problems, is stated below. (See Fig. **52**.)



E = OPEN CIRCUITED VOLTAGE

FIG. 52.

Thévenin's Theorem. The current in any impedance Z_R, connected to two terminals of a network, is the same as if Z_R were connected to a simple generator, whose e.m.f. is equal to the open-circuit voltage at the terminals in question and whose impedance is equal to the impedance of the network looking back from the terminals, all generators being replaced by impedances equal to the internal impedances of those generators.

NOTES ON THE DISCUSSION.

Mr. R. M. Chamney stated that the whole subject of crosstalk and noise interference was one not only of great interest but also of very considerable complexity. For many years the C.C.I.F. have been trying to obtain an answer as to what amount of crosstalk and noise should be allowable on a line and how should the allowable amount be partitioned between the various countries traversed by the line. To his mind this seems an almost insoluble problem since in the case of noise this may be of many kinds. He instanced the case of Mr. J. G. Hill, lately A.S.E. in Research, telling him that he could not concentrate his thoughts in comfort on a frosty night when travelling in the District railway since the flickering of the lights forced him to attempt to read Morse signals. Mr. Hill was, of course, an old telegraph operator. A noise which may become an annoying factor depends on the listener as to the extent of its annoyance value. In a similar way it is difficult to give the volume of crosstalk which should be a limiting factor. Extremely minute crosstalk from a music line will immediately compel attention whereas perhaps ten times the amount of indistinct conversation crosstalk is of very little moment.

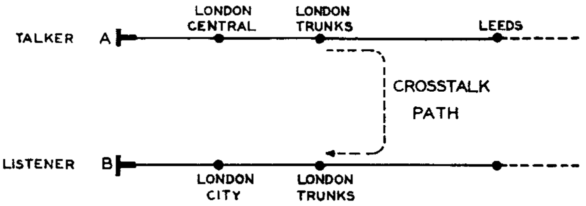
Capt. A. C. Timmis intimated that he was pleased to see due prominence given to the Compandor as a method of crosstalk reduction and proceeded to give a more detailed account of its construction and behaviour.

Mr. R. H. Franklin referred to the advantages to be gained from pad switching and illustrated these by reference to Figs. **53** and **54**. He pointed out that not only would crosstalk between instruments within a short electrical distance from their zone centres be improved by approx. 8 db. but that if the zone to group links were upgraded to zero loss then the group to minor or dependent links could be allowed to have a transmission equivalent as high as 7.5 db. with consequent savings in the cost of line plant.

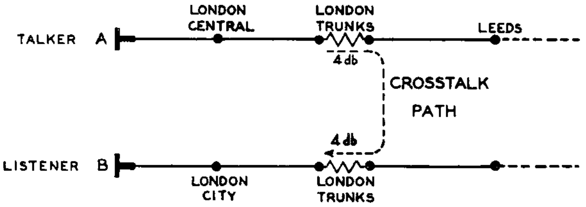
Mr. W. Bocock, whilst congratulating the authors on their informative paper, expressed disappointment that maintenance problems as they were affected by crosstalk had not been dealt with more fully, *e.g.*, those cases where open lines extending quad local cable pairs were subject to unequal insulation conditions.

Crosstalk difficulties had been experienced in Scotland with carrier working on long open wire circuits and in certain cases it had been necessary to double the number of transpositions. Four-wire trunk circuits on open lines had been similarly affected.

If, in future, carrier working were to be extended on pole lines, it would be advisable to pay more attention to equalizing the length of transposition sections and

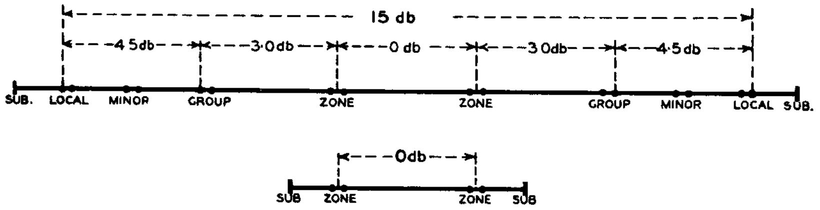


(a) CROSSTALK WITH PRESENT TRANSMISSION PLAN

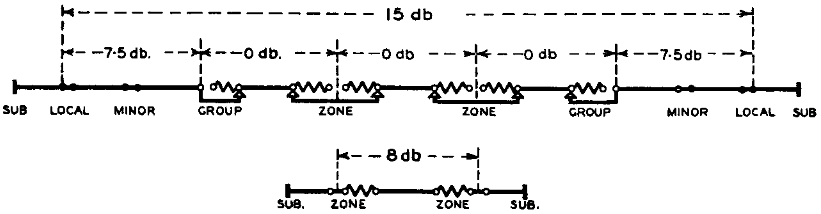


(b) CROSSTALK WITH PAD SWITCHING

Fig. 53.



(a) PRESENT TRANSMISSION PLAN



(b) TRANSMISSION PLAN WITH PAD SWITCHING

Fig. 54.

on pole lines having 8-wire arm sections and 4-wire arm sections to fix junction points at ends of transposition sections. Consideration of these matters when a pole line is being built would obviate reconstruction at a later stage.

Mr. Bocock asked whether group working within cables with both A.C. and D.C. signalling on 4-wire circuits would prove satisfactory when the new signalling circuit design is introduced.

MR. S. HANFORD asked whether it was not a fact that the balanced type of crosstalk set was equally as good as the unbalanced type providing transformers of the same degree of balance were used in both sets. He stressed the necessity for restoring the balance of a trunk cable after a temporary repair by effecting the permanent repair to the original unbalance limits with cable of the correct type. He asked for an assurance that it was not the intention to regard a repair made with P.C.Q.L. type cable as permanent. He felt that too great weight should not be given to the one case mentioned in the paper where 10 lengths of cable had been replaced in an audio trunk cable without rebalancing with no apparent detriment to the crosstalk, because such a case may not be fairly representative. Mr. Hanford drew attention to the inferiority of switchboard cable from a crosstalk point of view when compared with first class trunk cable. In conclusion, he mentioned the useful testing device whereby measurements of crosstalk are sometimes made on open circuited pairs, an allowance of 6 db. being made for the doubling of the voltage with respect to its value in the terminated condition.

MR. S. HANFORD (*communicated later*):

I should be glad if you can give a little more consideration to my first point regarding the balanced type of crosstalk set. If it could be made clear that if the transformers used in the crosstalk set shown in Fig. **12** are as good as those used in the crosstalk set shown in Fig. **13** then the likelihood of error in the measurement of crosstalk being more than negligible is remote, I think it would be an addition which would represent more nearly the truth. Certainly, in our opinion, the main source of trouble would then be not any question of unbalance to earth in the amplifier transformer but the question of perfection of screening of all leads and connections, which by the way is a point which is not touched upon at all in the paper; in fact the diagrams in so far as they show any screens at all would appear to convey the impression that the testing leads need not even be screened which, of course, is not a fact. An inch or two of the listen lead without a screen will cause a tremendous difference in the crosstalk reading when small values are being measured. To state that " thus a false reading on the potentiometer may be obtained " is rather too strong a statement for the potentiometer set when once the special transformers have been put into it.

The accuracy of the Fig. **13** type of set can be affected by capacities across the resistances forming the attenuator network. So far as our experience in the last three years is concerned we have had far less trouble with the potentiometer type of set since the good transformers were produced than, we understand, accompanies the use of the attenuator type. It is, of course, possible to earth one side of the potentiometer assembly in exactly the same way that you earth one side of the unbalanced type set, in fact we do so when measuring on coaxial type cables at lower carrier frequencies, and it seems to me to be fair to assume that if the transformers will stand up to having one side earthed in the unbalanced type of set they will certainly stand up to having one side by no means fully earthed in the balanced type of set.

MR. L. G. DUNFORD referred to the mention made in the paper that audio frequency crosstalk may in many cases be measured with pure tone. He pointed out that near-end measurements on cable circuits made at a single frequency are apt to be very misleading on account of the well known irregular frequency characteristics of this type of crosstalk and said that a buzzer of the type mentioned in the paper is used for the Department's acceptance tests of contract laid cables. He mentioned that so far as measurements of crosstalk at carrier frequencies are concerned the cable testing officers have found that consistent results can be obtained when measuring values of the order of 140 db. at 60 kc/s with the balanced type of crosstalk set using a potentiometer and a carrier-type balanced and screened transformer.

MR. J. R. BRINKLEY also drew attention to the inferiority from a crosstalk point of view of internal wiring used in exchanges and repeater stations when compared with high grade underground cable. He questioned the wisdom of this and said that it was within his experience at a terminal repeater station that the high level outputs from 17 c/s ringers, used on the 2-wire ends of repeatered circuits, caused considerable disturbance which could be detected when monitoring on other circuits. He asked whether difficulty from instability was experienced on circuits equipped with compandors when working without echo-suppressors.

MR. E. S. RITTER asked whether the psophometer weighting curve shown represented finality or whether it would require alteration as telephones with better frequency response characteristics became more widely used. He also asked for more information as to the relative merits of twin and quad type cable. He stressed the difficulties which are sometimes experienced with D.C. and A.C. signalling on 4-wire amplified circuits.

MR. A. J. JACKMAN said that some authorities consider that on a long uniform line the electrostatic and magnetic couplings would neutralise each other, he was unable to accredit or disprove this theory but it emphasises the importance of the " indirect paths " in far-end crosstalk. He drew attention to the desirability of reducing phantom-to-side and wire-to-earth unbalances in carrier cables in order to obtain close agreement in the crosstalk values when the disturbing and listening leads are reversed.

MR. R. J. HALSEY drew the attention of the authors to a case of pair-to-pair crosstalk on the Bristol-Plymouth carrier cable which had been worsened from 80 to 65 db. by a simple AB cross in the wiring of the apparatus at an intermediate repeater station, the value of 80 db. having been obtained with

Z_0 terminations before connecting the apparatus. He stated that he did not favour the use of the term electrostatic to describe the capacitative type of coupling and suggested that, as high frequencies give an impression which is anything but static, electric coupling would be a more suitable term.

MR. C. E. PALMER JONES (*communicated*):

Noise Conditions.

It is well-known that the line or system under test for crosstalk invariably has intrinsic noise due to induction, carrier leak, etc., and that the standard attenuator against which comparison is being made has practically no intrinsic noise. With the degree of amplification necessary to measure crosstalk either visually or aurally, this noise becomes a real hindrance to the measuring process, being frequently comparable with the crosstalk being observed. In fact, the visual method has frequently to be abandoned on this account, except where the induction happens to be of single-frequency nature, so that it can be eliminated by a rejector circuit.

As to aural measurements in the presence of line noise, one must make a test to believe how extraordinarily sensitive the ear is to the presence of background noise. An error of many decibels can be made by ignoring the fact that one is listening alternately to faint signals with a quiet background and to faint signals with a noisy background. Our ears in fact appear to behave as though they were fitted with automatic volume control as in a modern radio receiver! I have observed an error in a crosstalk measurement amounting to 15 db. due to this cause. The means of overcoming this psychological difficulty is recorded in Research Report No. 7896, the device adopted being a two-input amplifier in the listening lead. One of these amplifier inputs is changed over between the line and the attenuator in the usual way while the other is connected to the attenuator or line respectively. Thus, the total output of the amplifier always includes the attenuated test signal and the total noise of the entire system is heard continuously. The attenuated signal comes alternately *via* crosstalk path and *via* the attenuator. I suggest that use of this device be made standard for all crosstalk measurements by comparison.

Occurrence of Crosstalk.

I think Part III also might have included reference to the above-mentioned Research Report in connection with the random occurrence of crosstalk as measured on the two ends of a long cable length, *e.g.*, one repeater section. The conclusion was that the occurrence of bad values was purely random and thus that if $x\%$ of the pairs were to be rejected at one end on a stringent test, it could be fairly assumed that a further $x\%$ of the pairs would likewise be rejected when testing at the other end. (x is assumed small.) Thus in a preliminary survey a single-end test result may be doubled for an approximate result.

Inter-channel Crosstalk.

While I admit that much attention is now focussed on multi-channel carrier working (12 channels or over), there are carrier systems still which employ one and three channels. A great deal of work was done in the measurement and reduction of crosstalk from one channel to the other in the voice + 1 carrier system, in which the mechanism of crosstalk was studied and in which elaborate methods of measurement were devised. Testers R.P. 26 and 27 have been standardised by the Lines Branch in this connection and take their primary standard calibration from the light-film record of unintelligible crosstalk used in the writer's method of absolute measurement.

THE AUTHORS' REPLY:

Several speakers have commented upon the general poorness of switchboard and other internal wiring from the point of view of crosstalk when compared with underground cables. While it is admitted that such is the case it must not be overlooked that in exchanges the power level differences between circuits is relatively small and the necessity for such a high degree of immunity from crosstalk as obtains in main cables does not arise. Admittedly in repeater stations high differences of power levels exist, but here special attention is paid to the segregation of circuits of widely differing levels.

Pad switching appears to have many attractive features, not the least of which is the increase of the permissible group to minor or dependent exchange loss from 4.5 to 7.5 db. Such an increase would no doubt effect very substantial savings even when the increased cost of upgrading the zone to group links were deducted. Pad switching would undoubtedly improve crosstalk, but it would degrade those very good calls we now obtain over zero circuits when speaking between stations not very far removed electrically from their zone centre exchange. The authors are not sure that this reduction of all calls to a more nearly common level is desirable. Pad switching calls for a multiplicity of switching points, but apparently this does not cause much trouble judging from the favourable reports from those countries, such as America, where pad switching is in operation. In this country up till now the simplicity and flexibility of a zero loss trunk network has been preferred.

The authors are not prepared to make a definite pronouncement on the rather thorny subject as to whether quad cable is inferior to twin. Certainly under conditions of balance the quad is equal to or rather better than twin. But where unbalanced apparatus is concerned quad cable is apt to be inferior to twin, the reason being that, owing to its more compact form, the direct capacities between wires within a quad in quad cable are considerably higher than those between pairs in twin cable. The authors feel, however, that much of the criticism directed against quad cable could, with more justice, be directed against unbalanced apparatus.

For satisfactory working of carrier circuits on overhead lines a far more exacting transposition system than that employed on audio routes is required. This is largely due to the fundamental unbalance which exists between circuits run on the "straight." To correct this unbalance, transposition must be frequent and carried out with great exactitude, and indeed it appears likely that transposition points in the exact middle of spans may be necessary. This would involve the use of a special insulator and the Research Branch has been considering a design for an insulator to effect mid-span transposition.

The proposed new method of signalling aims at preserving group working for the transmission paths. The signalling circuits will be provided on phantom circuits, each made up from the two side circuits of a single quad. D.C. signalling circuits worked on this basis should be as immune from crosstalk as A.C. signalling circuits are at present when worked on a group basis.

A permanent repair to a carrier cable would always be made with carrier type cable. Balancing in the field and adjustment of the balancing networks will probably be required in the majority of cases. The reference to the use of P.C.Q.L. type cable for making good a carrier cable or an audio trunk cable is intended to refer to temporary cable inserted in an emergency to restore service.

The authors feel with Mr. Hanford that it would be dangerous to assume that ten lengths could be introduced into all modern audio cables without adversely effecting the crosstalk performance. So much depends upon the size and " goodness " of the cable and upon the method of working the circuits which it carries.

The authors would like to explain in greater detail the considerations which prompted them to draw attention to the errors which obtain with the " balanced " type of crosstalk measuring set. It is not intended to infer that the " balanced " type of set cannot be operated without error, but to point out the greater chance of error which exists in this type of circuit compared with the " unbalanced " circuit, even when the same type of well balanced transformers are employed in both.

In the balanced type of circuit, Fig. **12**, when once the equality of the resistances, Q, is established, the remaining possible source of trouble is in the earth impedance unbalance introduced by the resistance R and its associated wiring, which will cause the voltage applied to the amplifier input transformer to be unbalanced with respect to earth. This is important, since the degree of balance of the applied voltage determines what fraction of the total current flowing to the transformer primary winding will flow *via* the earth impedances of the winding. The fraction is greatest when the voltage is completely unbalanced and least when balanced, and varies for unbalances between these extremes. These earth currents in the primary winding will give rise to voltages at the amplifier input additional to that set up by the main current through the primary winding which is itself proportional to the P.D. across the resistance R. Hence, providing the same degree of balance of applied voltage is obtained both from the resistance R and the disturbed line transformer, all will be well since the earth currents set up will have the same distribution and magnitude relative to the main current in both cases. But where the degree of balance of voltage from the resistance R differs from that supplied by the line transformer then the voltages, due to the earth currents, supplied to the amplifier transformer secondary will differ in the two cases to an unknown degree.

Thus the voltage applied to the first valve of the amplifier will depend not only on the voltage which is the one indicated by the ratio $\frac{R}{2Q+R}$, but on the degree of balance of this voltage with respect to earth.

This type of error cannot be checked by the usual devices of observing that when the resistance R is at zero, there is no deflection on the galvanometer, or that there is no change in galvanometer deflection when the amplifier input connections to the resistance R are reversed.

The degree to which trouble may be experienced depends on the value of the resistances R and Q, the degree of earth impedance unbalance in the resistance R and associated wiring, and the values of the earth impedances of the primary winding of the amplifier input transformer. The use of a potentiometer network sub-divided by a balanced and screened transformer would certainly minimise the possible error.

This possible source of error is not present in the unbalanced type of set since the relative earth currents will remain the same under the conditions of connection to the potentiometer and connection to the disturbed line, since in both cases voltages will be completely unbalanced with respect to earth.

It has been mentioned that the self capacities of the paste resistances employed in the potentiometer will give rise to error. It is agreed that this can happen, but it is a trouble which is common to both the " balanced " and " unbalanced " sets. To ensure that this trouble is negligible, it is only necessary to give careful attention to the selection of resistance values.

It is agreed that very careful screening of all wiring and leads is essential to the success of a good crosstalk set.

The psophometer weighting curve given in the paper conforms to the recommendations of the Comité Consultatif Internationale Téléphonique (C.C.I.F.) and represents the relative effects of frequencies within the 50-4,000 c/s range on an average human ear listening to an average present day receiver. It can be anticipated that in the future the frequency response curve for the average receiver will be much improved and it will then be necessary to revise the weighting curve. It should perhaps be pointed out that the C.C.I.F. recommend the use of a somewhat different curve for noise measurements on music circuits.

It is agreed that the use of a single frequency disturbing tone for measuring audio near-end cable crosstalk may lead to error and that the use of a pure tone should be restricted to those cases where the crosstalk-frequency characteristic is regular.

It is interesting to learn that the 17 c/s ringing used on the 2-wire ends of voice-frequency signalling 4-wire circuits can be overhead when monitoring on other circuits. At such a low frequency one would not expect trouble from capacity unbalance couplings in cable, even of the internal type. Excessive ringing current, causing disturbance *via* magnetic couplings, may be at the root of the matter, or again the ringer output may be rich in harmonics.

Circuits equipped with compandors may be worked with or without echo suppressors. The London-Rotterdam circuit referred to in the paper is not equipped with echo suppressors. It has an overall equivalent of 0.8 nepers and no difficulty due to instability has been experienced.

In reply to Mr. Halsey's first point regarding the effect of an AB cross at the input or output of an intermediate repeater on the Bristol-Plymouth carrier cable, the authors are of the opinion that if the balancing networks were not re-adjusted on connection of the apparatus, then the extra crosstalk on crossing the wires of a pair must primarily be within the apparatus. It is felt, however, that a definite reason cannot be advanced without more data.

Referring to the second point, the authors agree that the two types of coupling might well be termed electric and magnetic respectively, the addition of " static " to the former term being rather a misnomer in view of the alternating nature of the field. It would be an advantage if the expression " electric coupling " were adopted, to refer to " electro-magnetic coupling " as " magnetic coupling," for here the increase in generality would not be serious.

The authors agree with Mr. Jackman that the reduction of phantom-to-side and wire-to-earth unbalances in carrier cables is important. For simple far-end balancing networks fitted at one point to effect maximum improvement it is essential that the balancing carried out between cable lengths in the field should aim at reducing unbalances between adjacent lengths; the nearer the neutralizing unbalances are together the better.

The points raised by Mr. Palmer Jones are interesting and they make a valued contribution to the paper. With regard to the effect of noise on the measurement of crosstalk in cables at carrier frequencies it should perhaps be mentioned that the noise level has been measured on a number of cables and in no case was it found to be worse than 130 db. below 1 milliwatt into 150 ohms. This measurement was made on an old multiple twin cable carrying working audio circuits only. Such a level would give a signal-to-noise ratio of 70 db. at 60 kc/s at the receiving end of a repeater section. The noise levels on new carrier cables are considerably better than 130 db. below 1 milliwatt and consequently are unimportant. As far as crosstalk from other carrier channels is concerned the use of a tuned circuit generally affords sufficient discrimination, but in addition oscillator output levels are generally made 20 or 30 dbs. greater than the system outputs. Incidentally it is always possible to determine whether a deflection on the crosstalk set is due to noise by the simple process of switching off one's own oscillator and observing that the deflection disappears.

Mr. Palmer Jones' point in reference to carrier leak arises mainly in overall system crosstalk tests and the arrangement he suggests overcomes the necessity for the provision of special filters in the measuring equipment to suppress carrier leak at the receiving end.

With regard to the measurement of interchannel crosstalk it is generally found that a frequency run with pure tone gives sufficient indication for most purposes. It is thought that if a complex tone is required for simultaneous testing at a number of frequencies the source should consist of a number of pure tones each at the same level and sent together. This would ensure that the galvanometer deflection would be steady, which would not be the case for scrambled speech. Incidentally this type of multitones test could only be used on a system if the attenuation length of the circuits were constant with frequency, *i.e.*, after equalisation.

In conclusion, the authors desire to acknowledge their indebtedness to the Lines Branch Drawing Office for their assistance in the preparation of slides and to thank Messrs. H. E. Barnett, R. H. Franklin, A. J. Jackman, R. E. Jones, H. J. Josephs, E. D. Latimer, E. M. Richards and J. M. Walton for their help and advice during the preparation of the paper.

Dorling & Co. (Epsom), Ltd. A7056