

June 3, 1941.

R. P. BOOTH ET AL  
WIRE LINE TRANSMISSION

2,243,851

Filed June 6, 1940

FIG. 1

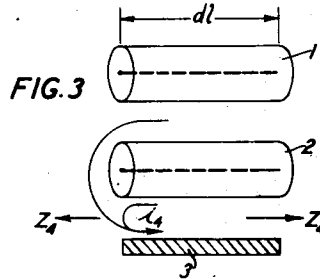
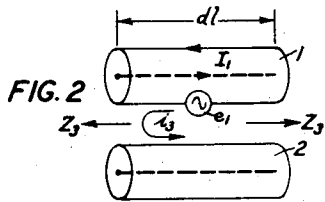
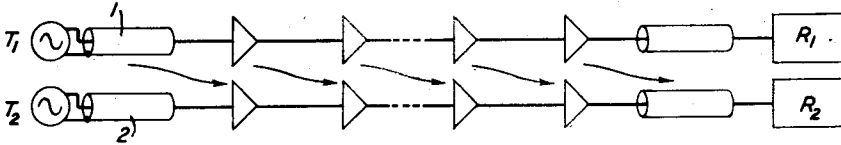


FIG. 4

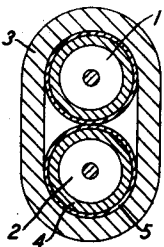


FIG. 5

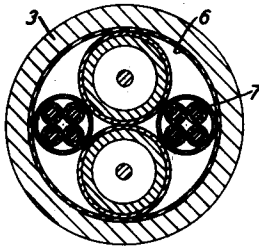


FIG. 6

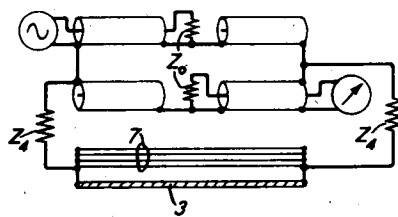
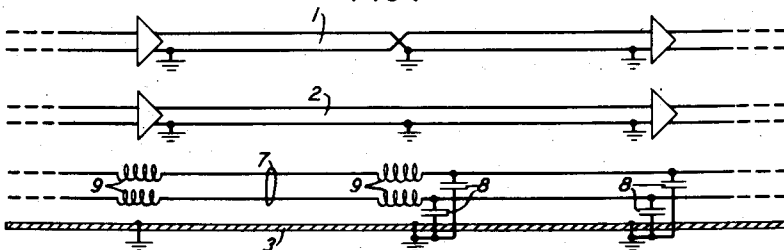


FIG. 7



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## UNITED STATES PATENT OFFICE

2,243,851

## WIRE LINE TRANSMISSION

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Application June 8, 1940, Serial No. 339,038

9 Claims. (Cl. 179-78)

The present invention relates to multicircuit cables for communication purposes and more particularly to the design of cables and cable systems in relation to cross-interference effects between shielded signaling circuits.

It has been found heretofore that in a cable comprising a plurality of coaxial conductor circuit pairs, there exists, despite the geometrical and electrical symmetry of the coaxial conductor circuit and the excellent shielding properties of the outer conductor thereof, a distributed coupling between the pairs that gives rise to cross-interference. It can be shown mathematically that even for two adjacent coaxial circuits in free space and whether or not the circuits are in contact or insulated from each other, cross-interference will take place, the magnitude of the interference currents depending on several factors such as the physical characteristics of the conductors and of the intervening space, if any, the frequency of the signals and the length of the circuits. In general, the "cross-talk" currents induced from the "disturbing" circuit to the "disturbed" circuit tend to be propagated to both terminals of the latter, although in practice unidirectional devices, such as repeaters in the disturbed circuit, will preclude transmission of the cross-talk except to the receiving end of the line. If the cross-talk appears at the terminal of the cable at which the disturbing signals are delivered to the line, the cross-talk is known as near-end cross-talk, whereas if the cross-talk appears at the remote end of the cable it is called far-end cross-talk. The magnitude of the cross-interference appearing at the receiving end of the disturbed circuit is a limiting factor in the design of cable systems and it is essential that by one means or another the distributed coupling giving rise to it be kept at or below a predetermined value usually expressed in terms of the ratio of current in the disturbed and disturbing circuits at specified transmission levels. In general, the effective cross-talk coupling is greater the longer the cable system and in general, too, it can be reduced by increasing the thickness of the outer conductors of the coaxial circuits or otherwise increasing the shielding of those circuits.

Inasmuch as cross-talk is a limiting factor in the design and operation of multicircuit cables, it is of paramount importance that one designing a

cable comprising a plurality of coaxial conductor pairs be able to predict accurately what the total cross-talk will be in a given projected cable system. Otherwise it may be found on completion of the cable that the total cross-talk is at an intolerably high level so that the system is practically inoperative, or it may be found that the coaxial outer conductors have been made unnecessarily thick and heavily shielded and, therefore, unnecessarily costly. In a cable that is of optimum design from a cross-talk standpoint, the cross-talk coupling is neither excessively high nor unnecessarily low but at a predetermined tolerable value. In a very real and practical sense, therefore, there is for any given system an optimum cross-talk coupling.

Unexpected difficulty was encountered in practice heretofore in the design of multicircuit coaxial cables, however, in that the cross-talk appeared to be unpredictable, and in particular in that the total cross-talk did not vary with the length of cable in any comprehensible manner. We have found that the erratic cross-talk behavior heretofore experienced is due to the presence of auxiliary coupling circuits or "tertiary" circuits that are present in cables comprising a plurality of coaxial conductor pairs and which serve to receive cross-talk from a disturbing circuit and to distribute that cross-talk to the disturbed circuit throughout its length. The cross-talk component due to the tertiary circuits we denominate "interaction cross-talk." We have discovered also the various cable parameters affecting the interaction cross-talk and the laws governing the relation of these parameters to the total cross-talk. We have found further that the interaction cross-talk can be controlled by proper design so that it tends to give optimum neutralization of the cross-talk that would exist between the coaxial pairs in free space.

One of the objects of the present invention is to provide a multicircuit coaxial conductor cable in which the various cable parameters are so interrelated that the cross-talk coupling is of optimum value.

Another object is to provide a cable in which a minimum of shielding is employed on the individual coaxial pairs consistent with a predetermined over-all cross-talk.

A further object of the invention is to provide

a cable comprising a plurality of coaxial conductor pairs in which conducting elements of the cable are so configured and arranged relative to each other that the cross-talk coupling between the coaxial pairs is minimum.

Still another object is to preserve and enhance the cross-talk neutralizing effect of a tertiary circuit in practical cable systems where its effectiveness would be impaired by following present practice.

In the preferred embodiments of the present invention a cable is provided comprising a plurality of coaxial conductor pairs, each pair having copper surfaces for the flow of signaling currents and the outer conductors of the pairs having an outer surface impedance that is high as compared with that of a copper conductor, the outer conductors being arranged together with one or more low impedance conductors and/or an external lead sheath, symmetrically disposed in relation to and insulated from the coaxial pairs, the thickness of the outer conductors of the coaxial conductor pairs or more generally the shielding efficiency of the outer conductors being of a predetermined optimum value fixed by over-all system cross-talk.

Subsidiary features of the invention relate to the treatment of the tertiary circuits at repeater and transposition points.

The nature of the present invention and its various objects, features and advantages will appear more fully in the following discussion and description of preferred embodiments and exposition of the principles underlying their design. Reference will be made to the accompanying drawing, in which:

Fig. 1 illustrates a repeated cable system in which far-end cross-talk tends to appear;

Figs. 2 and 3 are diagrams illustrating induction effects occurring in multipair coaxial cables;

Figs. 4 and 5 are cross-sectional views of cables in accordance with the invention;

Fig. 6 illustrates how interaction cross-talk may be measured; and

Fig. 7 represents a cable system in which tertiary conductors are blocked at repeater and transposition points.

It has been shown by S. A. Schelkunoff and T. M. Odarenko, the latter being one of the present applicants, in a paper appearing in the April, 1937, issue of Bell System Technical Journal, what the factors are that govern cross-talk between two coaxial conductor units in free space. Reference is made to that paper for an explanation of several of the effects to be considered hereinafter and for a derivation of some of the equations employed in the course of this specification.

For simplicity we shall consider first only far-end cross-talk such as would appear in a cable system of the kind illustrated in Fig. 1, in which two signals are transmitted in the W-E direction over individual coaxial conductor circuits 1 and 2 from respective signal sources T<sub>1</sub> and T<sub>2</sub> through spaced signal repeaters to respective receiving terminals R<sub>1</sub> and R<sub>2</sub>. Treating coaxial pair 1 as the disturbing circuit, it will be understood that signals in pair 1 from source T<sub>1</sub> induce cross-talk into pair 2 as suggested by the arrows, and that this cross-talk then appears at terminal R<sub>2</sub>. By way of further and more specific example, it may be assumed that the signals involved are television signals occupying the frequency range from 50 to 2,500 kilocycles per sec-

ond, and that the signal repeaters are spaced about five miles apart.

It is shown in the Schelkunoff et al. paper, supra, that if two parallel coaxial circuits are in free space and insulated from each other the voltage drop  $e_1$  along the outer surface of the outer coaxial conductor in an elemental length  $dl$  of the disturbing circuit is

$$e_1 = I_1 Z_{as} dl \quad (1)$$

where

$I_1$  is the signal current flowing through the outer conductor; and

$Z_{as}$  is the surface transfer impedance per unit length between the inner and outer surfaces of the outer coaxial conductor;

and that in a long line or one in which the intermediate circuit is terminated in characteristic impedance this voltage gives rise to a current  $i_3$ :

$$i_3 = \frac{e_1}{2Z_3} \quad (2)$$

which flows in the intermediate or tertiary circuit of characteristic impedance  $Z_3$  formed by the two outer conductors.

The current  $i_3$ , represented diagrammatically in Fig. 2, flows along the outer conductor of the disturbed circuit 2 and produces a voltage on the inner surface of that conductor which in turn gives rise to a component of cross-talk in the disturbed circuit. In a long line each elemental length of the disturbed circuit is also affected by the current  $i_3$  arising in each other elemental length inasmuch as the latter current is propagated through the intermediate circuit. When the effects are integrated, it is found that the far-end cross-talk due to this interaction component is a complicated function of the various cable parameters as appears from Equation 40 of the Schelkunoff et al. paper.

If, however, the coaxial pairs are in substantially continuous contact with each other, the formula for the far-end cross-talk  $F_3$  expressed as a current ratio is substantially simplified:

$$F_3 = \frac{Z_{as}}{2Z_3} l \quad (3)$$

where  $l$  is the length of continuous exposure,  $Z$  is the characteristic impedance of each of the coaxial circuits, and  $Z_{33}$  is the series impedance per unit length of the intermediate circuit and equal to  $Z_3 \gamma_3$ ,  $Z_3$  being the characteristic impedance of the intermediate circuit and  $\gamma_3$  its propagation constant. This simplification results from the fact that the intermediate circuit in the case assumed has such high attenuation that interaction cross-talk between elemental lengths  $dl$  cannot exist. The cross-talk in such a case is solely "direct" cross-talk.

If a lead or other metallic sheath 3 is placed symmetrically around but insulated from the two coaxial pairs and whether or not the latter are insulated from each other, an intermediate or tertiary circuit is formed, as indicated diagrammatically in Fig. 3, comprising the sheath as one side and the outer conductors of the coaxial pairs in parallel as the other. The voltage  $e_1$  effective in an elemental length  $dl$  gives rise to a current  $i_4$  that flows in this intermediate circuit and that is propagated therethrough. The magnitude of this current is

$$i_4 = \frac{e_1}{4Z_4} \quad (4)$$

where  $Z_4$  is the characteristic impedance of the intermediate circuit. Half of the current  $i_4$  is carried by the outer conductor of the disturbed coaxial circuit in opposition to  $i_3$  and is propagated through the aforesaid tertiary circuit, thus producing current in every other elemental length of the disturbed circuit. When the effects are integrated over a length of cable  $l$ , the far-end cross-talk component  $F_4$  due to this tertiary circuit current is found to be as follows:

$$F_4 = -\frac{Z_{23}}{16Z_4 Z_4} \left[ \frac{2l}{\gamma_4 \gamma_4^2 - \gamma^2} - \left( \frac{2(\gamma_4^2 + \gamma^2)}{(\gamma_4^2 - \gamma^2)^2} - \frac{e^{-(\gamma_4 - \gamma)l}}{(\gamma_4 - \gamma)^2} - \frac{e^{-(\gamma_4 + \gamma)l}}{(\gamma_4 + \gamma)^2} \right) \right] \quad (5)$$

where  $\gamma_4$  is the propagation constant of the tertiary circuit of characteristic impedance  $Z_4$ .

It may be noted that in so far as the effects here described are concerned, any conductor symmetrically disposed with respect to the coaxial pairs would function in the same manner as the sheath, hence the tertiary circuit represented in Fig. 3 may be understood as comprising either the sheath or such other insulated conductors as may be present or, as a good approximation, both in parallel and lumped together as circuit member 3.

If the sheath and/or such other conductors are in substantially continuous contact with the coaxial pairs so that the attenuation of the intermediate circuit is extremely large, the formula for far-end cross-talk  $F_4$  reduces to the following simple relation:

$$F_4 = -\frac{Z_{23}}{16Z_4 Z_4} \frac{2l}{\gamma_4} = -\frac{Z_{23}}{8Z_4 Z_4} l \quad (6)$$

where  $Z_{44}$  equals  $Z_4 \gamma_4$ . It is important to note that the total cross-talk  $F_1$  in this case is the sum of the cross-talk components  $F_3$  and  $F_4$  as given by equations 3 and 6, respectively, or

$$F_3 + F_4 = F_1 = \frac{Z_{23}}{2Z} \left[ \frac{l}{Z_{33}} - \frac{l}{4Z_{44}} \right] \quad (7)$$

In the last equation, the second term in the bracket represents the contribution of the tertiary circuit comprising the sheath and it is seen to be opposite in sign to the first term which represents the cross-talk which would exist in the absence of the sheath. The equation further illustrates mathematically the fact that conducting material in contact with the coaxial pairs acts to reduce the cross-talk coupling. Since both components are directly proportional to length, the total is also proportional to length.

From Equation 7 the significant deduction can be made that the total cross-talk would be zero if  $Z_{33}$  and  $4Z_{44}$  were equal. Although this highly desirable condition cannot be perfectly realized in practice it can be very closely approximated if the outer conductors of the coaxial pairs comprise respective wrappings of iron or steel tapes or if they are otherwise arranged to have high external surface impedance. In such case, neglecting external inductance and proximity effects,  $Z_{33}$  would be equal to twice the surface self-impedance of a single outer conductor and  $Z_{44}$  would be equal to one-half of the surface self-impedance of a single outer conductor, treating the self-impedance of the sheath as being negligible in comparison with that of the iron or steel covering. Thus to a first approximation  $1/Z_{33}$  would equal  $1/4Z_{44}$  and the cross-talk would tend to vanish. Actually, a reduction in cross-talk of the order of fortyfold has been obtained in accordance with this phase of the

present invention, although even this figure might be bettered.

Fig. 4 shows in cross-section a typical embodiment of the subject-matter last discussed comprising two coaxial conductor units 1, 2, each of the units having an outer conductor that is made up of a tubular copper portion 4 and an over-layer 5 of iron or steel. The portion 4 may comprise a strip of copper rolled into tubular form and provided with a longitudinal seam as disclosed fully in Seeley Patent 2,126,290, August 9, 1938. The ferrous portion 5 may comprise an iron or steel tape wrapped helically about the copper tube 4 or two such wrappings so disposed that one overlies the interturn gaps of the other. Enclosing both coaxial units and in intimate conductive contact with the respective outer conductors thereof is a lead sheath 3. Inasmuch as the sheath is in continuous contact with the outer conductors it is not essential that the latter contact each other directly.

If, in the cable illustrated in Fig. 4, the sheath and any other conductors external of the coaxial pairs are insulated from the coaxial outer conductors, the total cross-talk may be obtained by combining Equations 3 and 5:

$$F_1 = \frac{Z_{23}}{2Z} \left[ \left( \frac{l}{Z_{33}} - \frac{l}{4Z_{44}} \frac{\gamma_4^2}{\gamma_4^2 - \gamma^2} \right) + \frac{\gamma_4}{4Z_{44}} \left( \frac{\gamma_4^2 + \gamma^2}{(\gamma_4^2 - \gamma^2)^2} \right) - \frac{\gamma_4}{4Z_{44}} \left( \frac{e^{-(\gamma_4 - \gamma)l}}{2(\gamma_4 - \gamma)^2} + \frac{e^{-(\gamma_4 + \gamma)l}}{2(\gamma_4 + \gamma)^2} \right) \right] \quad (8)$$

It is to be noted that the first term of Equation 8 is proportional to the length, that the second is independent of length and that the third involves length exponentially. For cable lengths such as are ordinarily used between repeaters the intermediate or tertiary circuits are electrically long and the third term vanishes:

$$F_1 = \frac{Z_{23}}{2Z} \left[ \left( \frac{l}{Z_{33}} - \frac{l}{4Z_{44}} \frac{\gamma_4^2}{\gamma_4^2 - \gamma^2} \right) + \frac{\gamma_4}{4Z_{44}} \left( \frac{\gamma_4^2 + \gamma^2}{(\gamma_4^2 - \gamma^2)^2} \right) \right] \quad (9)$$

For electrically short lengths, the second and third terms of Equation 8 combine to cancel the second half of the first term:

$$F_1 = \frac{Z_{23}}{2Z} \left[ \left( \frac{l}{Z_{33}} - \frac{l}{4Z_{44}} \frac{\gamma_4^2}{\gamma_4^2 - \gamma^2} \right) + \frac{\gamma_4}{4Z_{44}} \left( \frac{\gamma_4^2}{\gamma_4^2 - \gamma^2} - \frac{l^2}{2} \right) \right] = \frac{Z_{23}}{2Z} \left[ \frac{l}{Z_{33}} - \frac{\gamma_4 l^2}{4Z_{44} 2} \right] \quad (10)$$

For cable lengths short enough that the term of Equation 10 involving  $l^2$  is negligible, the cross-talk increases directly with length. Where Equation 9 holds the first term is still proportional to length, but it is important to observe in this case that it consist of the difference of two components, one component representing the cross-talk that would be present in the absence of a tertiary circuit, and the second representing one part of the cross-talk component introduced by the presence of a tertiary circuit.

In view of the last observation, it will be understood that if the surface impedance of the outer conductors is large as compared with the self-impedance of the sheath or other equivalent tertiary circuit conductor so that

$$\frac{\gamma_4^2}{\gamma_4^2 - \gamma^2} \approx 1 \quad (11)$$

then the cross-talk component due to the tertiary conductor will substantially offset or neutralize the other component in the manner discussed with reference to Equation 7. What remains is the residual cross-talk, proportional to the length but much lower in magnitude than either com-

ponent alone, plus another component independent of length but considerably lower in magnitude than would exist for two coaxials in free space. Even for perfect cancellation of the first terms, this term which is independent of length is the minimum for a given configuration.

The desirable condition indicated by Equation 11 can be approximately realized in practice by overlaying the copper portion of each outer coaxial conductor with a sheath or wrapping of ferrous metal in the manner described above. Fig. 5 shows in cross-section an illustrative embodiment comprising two metallic contacting coaxial units 1, 2, each as in Fig. 4, enclosed by a lead sheath 3 and insulated therefrom by a paper, fabric or other insulating inner liner 6. The cable may have also disposed in the interstices between the coaxial pairs and the sheath and symmetrically related to the coaxial pairs, two quads 7 each comprising four wire conductors insulated from each other and from the coaxial pairs. The circuits provided by the quads may be metallically continuous from one end of the cable system to the other or individual repeaters may be inserted therein at a few of the signal repeater stations. These circuits may be used for low frequency signaling or control purposes.

Having now set forth the laws governing quantitatively the far-end cross-talk in a system of the kind described with reference to Figs. 1 and 5, the next step is the practical application of these laws to the optimum design of the cable.

Whereas Equation 8 permits calculation of the total cross-talk that will be obtained in any given multipair coaxial cable of the kind described and of any given length, it is not a solution of the immediate problem, viz., ascertaining the optimum proportions for a given cable of given length. More specifically the problem is to ascertain the optimum value for the surface transfer impedance of the coaxial outer conductors and to ascertain what is the minimum shielding effect of the outer conductors consistent with tolerable over-all cross-talk whereby the cross-talk requirements can be met with a minimum expenditure of material for the outer conductor and its high impedance over-layer.

A mathematical approach to the solution of this problem is impractical generally unless supplemented by certain measurements because of complexities introduced by the presence of a large number of coaxial pairs in the same cable, some being used for transmission in one direction and some for transmission in the opposite, but at least in cables of simple configuration where the outer conductor comprises homogeneous layers, the various factors in Equation 8 can be determined by mathematical procedure known to those skilled in the art. Alternatively and preferably, however, the data required for the next step in the practical design procedure are obtained by measurements on a short sample of cable of substantially the configuration desired, the data obtained from these measurements being then inserted in Equation 8 to permit calculation of the over-all cross-talk in a cable of the desired length and having the cross-sectional proportions of the sample tested. Thereafter, by calculation, the degree of change in the surface transfer impedance or the change in thickness of the outer conductor required to bring the total cross-talk to the optimum value is ascertained. Thus by measurements made on a few feet of cable of the approximate proportions desired a transcontinental cable system, for example, can be constructed so that the over-all cross-talk requirement is met without waste of material.

structured so that the over-all cross-talk requirement is met without waste of material.

In accordance with the method outlined, an electrically short length of cable of approximately the desired cross-sectional configuration and proportion is first assembled. Suppose for specific example that the cable configuration is as shown in Fig. 5. Following technique well known in the art, measurements are made of the characteristic impedance of either coaxial unit, the characteristic impedance of the tertiary circuit comprising the two coaxial outer conductors on the one side and quads 8 and sheath 6 on the other, and the respective propagation constants of the tertiary circuit and of either coaxial unit. With the tertiary circuit then terminated at each end in its characteristic impedance as measured, the far-end cross-talk between the two coaxial circuits is measured in both phase and magnitude. From these data, the phase and magnitude of the first component of term 1 in Equation 8 can be computed by use of Equation 10.

To obtain the necessary data for computation of the other terms in Equation 8, an interaction cross-talk test is made. For this test two short lengths are joined, as shown schematically in Fig. 6, with all the conductors comprising the tertiary circuit as above defined continuous at the junction and with the tertiary circuit terminated at each end in the measured characteristic impedance. The coaxial circuits are interrupted at the junction and the "disturbing" and "disturbed" sections are terminated at their proximate ends in characteristic impedance and at their remote ends connected to the measuring apparatus as illustrated. The interaction cross-talk  $F_4$  for this case is

$$F_4 = \frac{\gamma_4 Z_{a2}^2 \beta^2}{4Z_{44}} \quad (12)$$

so that if it is measured in phase and magnitude the necessary data for the remaining terms of Equation 8 are calculable.

Knowing now the values of the several parameters in Equation 8, that equation can be solved to determine what the over-all cross-talk would be in a cable of any given length  $l$  having the cross-sectional proportions and electrical characteristics of the cable sections tested. A simple arithmetical calculation will now show in what sense and in what degree the surface transfer impedance  $Z_{a\beta}$  would have to be changed to bring the total cross-talk to the predetermined optimum value.

To translate the indicated change in the surface transfer impedance  $Z_{a\beta}$  into terms involving the thicknesses of the copper outer conductor and its ferrous over-layer, it is necessary to inquire into what the relation is between  $Z_{a\beta}$  and the various significant parameters of the cable cross-section.

It can be shown that the pertinent relation is given by the following equation for  $Z_{a\beta}$ :

$$Z_{a\beta} = \frac{Z_{a\beta 1} \cdot Z_{a\beta 2}}{Z_{\beta\beta 1} + Z_{a\beta 2}} \quad (13)$$

where

$Z_{a\beta 1}$  is the surface transfer impedance of the copper portion of the outer conductor,  
 $Z_{a\beta 2}$  is the surface transfer impedance of the ferrous over-layer,  
 $Z_{\beta\beta 1}$  is the surface self-impedance of the outer surface of the copper portion, and  
 $Z_{a\beta 2}$  is the surface self-impedance of the inner surface of the ferrous over-layer.

It will be evident from Equation 13 that the necessary change in the value of  $Z_{01}$  can be brought about by either a proportionate change in  $Z_{02}$  or of  $Z_{03}$  or of their product. Assuming for purposes of exposition that  $Z_{01}$  is to be modified, the necessary change in this factor can be effected by modifying the thickness of the copper portion of the outer conductors, for the two are interdependent as will appear from the following equation for the absolute value of  $Z_{01}$ :

$$Z_{01} = \frac{\sqrt{\mu}}{\sqrt{\pi g \alpha \beta} (\cosh \mu - \cos \mu)} \quad (14)$$

where

- $\mu$ =intrinsic inductance= $4 \times 10^{-9}$  henries/cm.  
 $g$ =intrinsic conductance in mhos/cm.= $5.8 \times 10^{-8}$   
 $\alpha, \beta$ =inner and outer radii in cms.  
 $f$ =frequency in cycles/sec.  
 $\omega = t\sqrt{2g\omega\mu}$   
 $t$ =thickness in cms.  
 $\omega = 2\pi f$ .

Equation 14 is applicable to integral copper tubes and with a high degree of accuracy to a longitudinal seam copper tube of the kind disclosed in the Seeley patent, supra. With the aid of the last equation, any indicated percentage change in  $Z_{02}$  or  $Z_{03}$  can be translated accurately into a corresponding equivalent change in  $t$ , the thickness of the outer conductor. Changes in thickness  $t$  will also affect  $Z_{01}$  but since  $Z_{02}$  is controlling due to the ferrous material, this change may be neglected. Since the inner diameter of an outer conductor is usually fixed by transmission requirements, changes in thickness  $t$  will affect, to some extent, the outside diameter. For any ordinary copper thicknesses, however, such a change will not appreciably affect any previously measured cable parameters. It should be understood too that the frequency  $f$  is the frequency at which cross-talk is most severe, viz., the frequency at the lower end of the signaling band.

The procedure hereinbefore outlined for the optimum design of a cable with respect to far-end cross-talk can be applied to the case where near-end cross-talk is the limiting factor. In the latter case the equation for total near-end cross-talk  $N_t$  corresponding to Equation 8 for far-end cross-talk is as follows:

$$N_1 + N_2 = N_t = \frac{Z_{02}}{2Z} \left[ \left( \frac{1}{Z_{03}} - \frac{1}{4Z_{04}} \cdot \frac{\gamma_1^2}{\gamma_1^2 - \gamma^2} \right) \frac{1 - e^{-2\gamma l}}{2\gamma} + \frac{1}{4Z_{04}} \cdot \frac{\gamma_1^2}{\gamma_1^2 - \gamma^2} \left( \frac{1 - 2e^{-(\gamma_1 + \gamma)l} + e^{-2\gamma l}}{2\gamma_1} \right) \right] \quad (15)$$

In a section where the tertiary circuit is electrically long, Equation 15 reduces to

$$N_t = \frac{Z_{02}}{2Z} \left[ \left( \frac{1}{Z_{03}} - \frac{1}{4Z_{04}} \cdot \frac{\gamma_1^2}{\gamma_1^2 - \gamma^2} \right) \frac{1 - e^{-2\gamma l}}{2\gamma} + \frac{1}{4Z_{04}} \cdot \frac{\gamma_1^2}{\gamma_1^2 - \gamma^2} \left( \frac{1 + e^{-2\gamma l}}{2\gamma_1} \right) \right] \quad (16)$$

and when  $l$  is electrically short, it reduces to

$$N_t = \frac{Z_{02}}{2Z} \left[ \frac{l}{Z_{03}} - \frac{\gamma_1}{4Z_{04}} \cdot \frac{l^2}{2} \right] \quad (17)$$

which is the same as for far-end cross-talk in very short lengths as given in Equation 10.

Implicit in the foregoing analysis and instructions for the design of a cable system is the assumption that throughout the system in the length  $l$  there are no repeaters in the coaxial circuit or in the tertiary circuit and that all of the circuits are electrically smooth. In practice, of course, repeaters are inserted in all of these

circuits if they are long enough to require such devices. In calculating the overall cross-talk in a long repeatered system, therefore,  $l$  represents the length of the repeater section and separate account is taken of the manner in which cross-talk sums up in successive repeater sections.

It is to be observed too that the foregoing equations for near-end and far-end cross-talk assume that the tertiary circuit is terminated in characteristic impedance at each end of length  $l$ , that is, at each repeater point in the case of a repeatered system, whereas in practice it may be desired, for one reason or another, effectively to short-circuit all other signaling circuits and the lead sheath of the cable to the outer conductors of the coaxial pairs at each repeater point. Except for the short circuit, of course, the adjoining sections of tertiary circuit would provide the assumed termination. Where far-end cross-talk is the controlling factor, however, one may disregard the manner of terminating the tertiary circuit in view of the relatively great length of a repeater section and the fact that significant contributions to the total cross-talk are made throughout the section. Where near-end cross-talk is the controlling factor, on the other hand, the fact that the significant contributions to the total near-end cross-talk are largely confined to one end of the repeater section makes the proximate termination somewhat more important. Account may be taken of the short-circuit termination of the tertiary circuit if greater accuracy is desired by employing the following equation in lieu of Equation 16.

$$N_t = \frac{Z_{02}}{2Z} \left[ \left( \frac{1}{Z_{03}} - \frac{1}{4Z_{04}} \cdot \frac{\gamma_1^2 - 3\gamma_1^2\gamma^2}{(\gamma_1^2 - \gamma^2)^2} \right) \frac{1 - e^{-2\gamma l}}{2\gamma} - \frac{1}{4Z_{04}} \cdot \frac{\gamma_1^2\gamma^2}{(\gamma_1^2 - \gamma^2)^2} \left( \frac{1 + e^{-2\gamma l}}{\gamma_1} \right) \right] \quad (18)$$

Similar expressions may be derived for cases in which only part of the tertiary is shorted or open.

Ordinarily the far-end cross-talk summation from one repeater section to another is one of practically direct addition inasmuch as all of the repeaters have substantially the same phase shift and the propagation characteristics of the coaxial circuits are substantially identical. One way that has been proposed for preventing this direct addition of far-end cross-talk is to transpose one of the signaling circuits with respect to the other in each repeater section or in successive groups of sections. These transpositions may be effected by phase reversing transformers as disclosed in M. E. Strieby Patent 1,950,127, March 6, 1934, or by inserting an extra, phase reversing amplifier stage in one of the systems at repeater points. If, as would ordinarily be the case, all or part of the tertiary circuit is continuous past the transposition point, it will carry tertiary circuit currents from one side of the transposition to the other and thereby carry interaction cross-talk into the next section, thus nullifying in part the effectiveness of the transposition.

In accordance with a feature of the present invention the interaction cross-talk between transposed sections of cable is suppressed by blocking the flow of tertiary circuit currents at the transposition point. The blocking means may constitute a virtual short circuit or open circuit in the tertiary for the currents of signal frequency which flow in the coaxial circuits but it may be so arranged as not to interfere sub-

stantially with the transmission of low frequency signal and control currents through the elements of the tertiary circuit constituted by quads 7, for example, as in Fig. 5. Where the transposition is effected at a repeater point the blocking of the tertiary circuit serves also to suppress undesirable local coupling between virtually the input and output circuits of the several repeaters.

Fig. 7 illustrates a cable system in which the tertiary circuit is blocked for signal frequencies at mid-repeater transposition points and at repeater points. Coaxial circuit 1 is represented as being electrically transposed midway between successive repeater points while throughout the same section coaxial circuit 2 is left untransposed. At each of the repeater stations and at each repeater point the sheath 3 is effectively connected to the outer conductors of the coaxial circuit; a metallic connection can be used for this purpose. Any other component of the tertiary circuit such as the quads or wire conductors represented by conductors 7 in Fig. 7 may likewise be effectively connected in the same manner as sheath 3, but if their usefulness for low frequency signaling and control purposes is to be preserved, they may be blocked to signal frequencies by frequency selective reactances such as shunting condensers 8, or series inductors 9 or by a combination of both arranged as a low-pass filter. With the tertiary circuit thus suppressed, interaction cross-talk between successive transposition sections is likewise suppressed and the full benefits of the transposition may be realized.

What is claimed is:

1. A multicircuit signaling system comprising a plurality of sources of different signals to be transmitted, a cable for the long distance transmission of said signals, said cable comprising a plurality of coaxial conductor pairs, each of said pairs comprising an inner conductor and a hollow outer conductor insulated from each other, means for applying the said different signals from said sources to respective ones of said coaxial pairs for long distance transmission there-through, each of said outer conductors comprising an inner layer of high conductivity and a contiguous over-layer such that the external surface self-impedance of said over-layer is many times as large as the external surface self-impedance of said inner layer, said cable comprising also a conductor external of said pairs and symmetrically related thereto, said external conductor having a resistance low compared with that of said over-layers, and the surface transfer impedance of said outer conductors with their respective over-layers being so proportioned that the predominant cross-interference coupling is of optimum value.

2. A combination in accordance with claim 1 in which said external conductor is in substantially continuous contact with said over-layers.

3. A cable system for the long distance transmission of high frequency signals over a plurality of circuits, the cable of said system comprising a plurality of coaxial conductor pairs for the transmission of said signals, each of said pairs comprising an inner conductor and a hollow outer conductor insulated from each other, each of said outer conductors having an inner layer of high conductivity and a contiguous over-layer such that the external surface self-

impedance of said over-layer is many times as large as the external surface self-impedance of said inner layer, said cable comprising also a conductor external of and symmetrically disposed with relation to said coaxial conductor pairs and insulated therefrom whereby a tertiary circuit is provided comprising said external conductor and said over-layers, the surface transfer impedance of said outer conductors with their respective over-layers being so related to the propagation characteristics of said tertiary circuit that the predominant cross-interference coupling between said coaxial conductor pairs is of optimum value.

4. A combination in accordance with claim 3 in which said over-layers are in substantially continuous contact with each other.

5. A cable system for the long distance transmission of different high frequency signals over respective circuits, the cable of said system comprising a plurality of coaxial conductor pairs for the transmission of said signals, each of said pairs comprising an inner conductor and a hollow outer conductor insulated from each other, each of said outer conductors having an inner layer of high conductivity comparable with that of copper and an over-layer of such material that the external surface self-impedance of said over-layer is many times as large as the external surface self-impedance of said inner layer, said cable comprising also a conductor external of and symmetrically disposed in relation to said coaxial conductor pairs and substantially coextensive therewith, said external conductor being disposed in substantially continuous electrical contact with said over-layers and having a resistance longitudinally of said cable that is low compared with that of said over-layers, whereby the direct cross-talk between said coaxial pairs is substantially neutralized by the interaction cross-talk through said tertiary circuit.

6. A combination consistent with claim 5 including a metallic sheath enclosing all of said coaxial pairs, said sheath being in substantially continuous mechanical contact with a plurality of said over-layers.

7. A cable system for the long distance transmission of high frequency signals over a plurality of circuits, the cable of said system comprising a plurality of coaxial conductor pairs for the transmission of said signals, each of said pairs comprising an inner conductor and a hollow outer conductor insulated from each other, said cable comprising also a conductor external of and symmetrically related to said coaxial conductor pairs and insulated therefrom whereby a tertiary circuit is provided comprising said external conductor and said outer conductors, means at a point along said cable for electrically transposing one of said pairs relative to another, and means at said point blocking the flow of tertiary circuit currents past said transposition point.

8. A combination in accordance with claim 7 in which at said transposition point said tertiary circuit is adapted for the through transmission of currents of audio frequency.

9. A combination in accordance with claim 7 comprising signal repeaters spaced apart along said cable and in which said transposition point is located between successive repeaters.

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