April 17, 1945. H. MOURADIAN 2,373,906

CABLE SYSTEM FOR HIGH FREQUENCY TRANSMISSIONS

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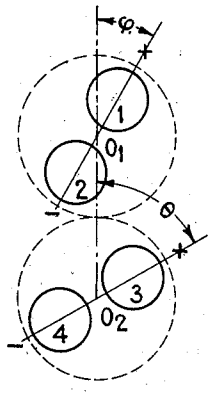


FIG. 1

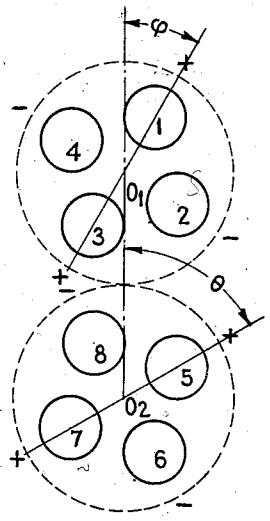


FIG. 2

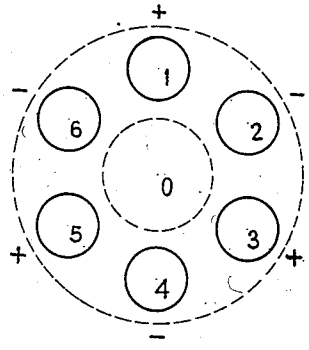


FIG. 3

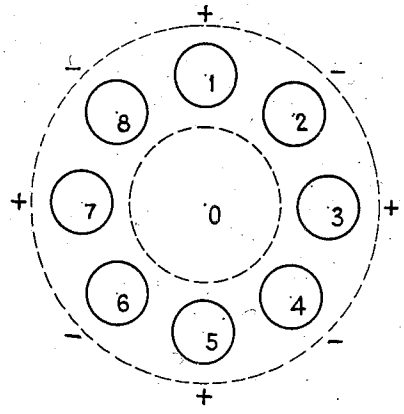


FIG 3-A

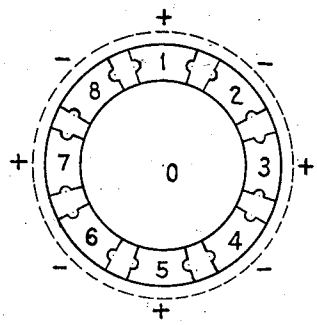


FIG. 3-B

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CABLE SYSTEM FOR HIGH FREQUENCY TRANSMISSIONS

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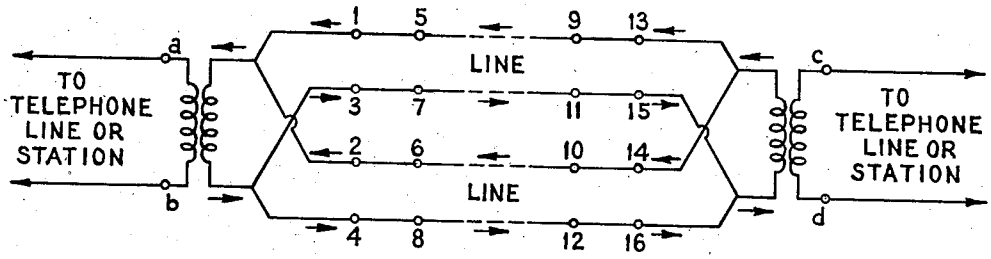


FIG. 4

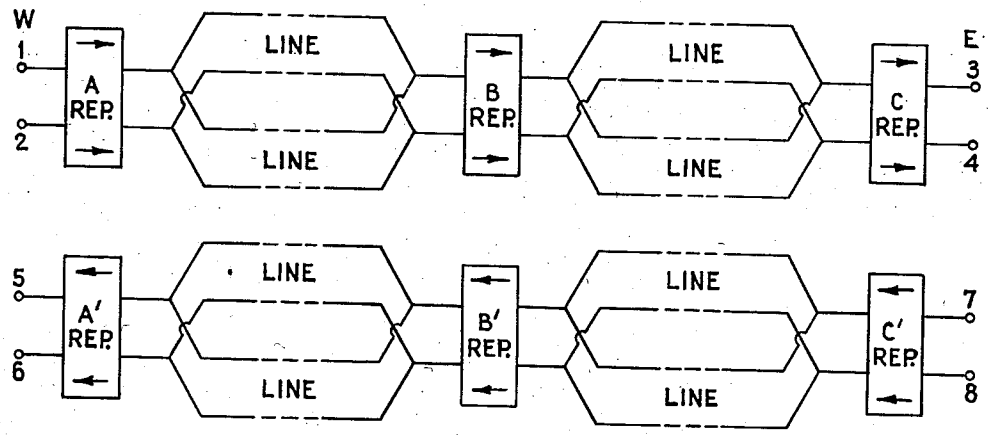


FIG. 5

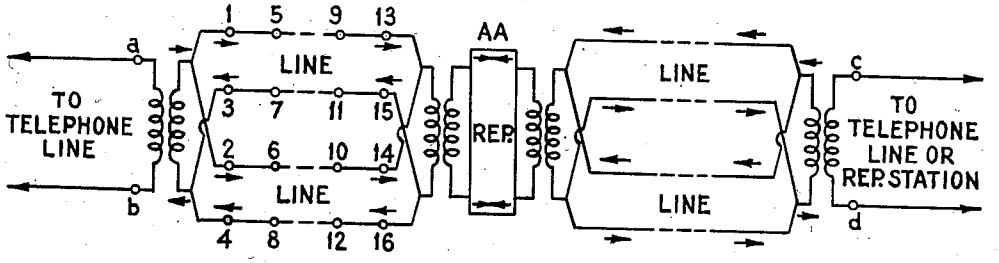


FIG. 6

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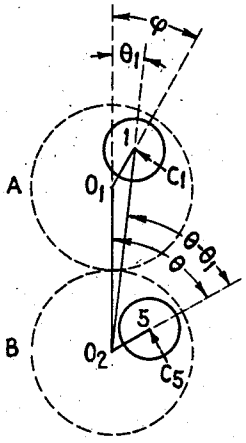


FIG. 7

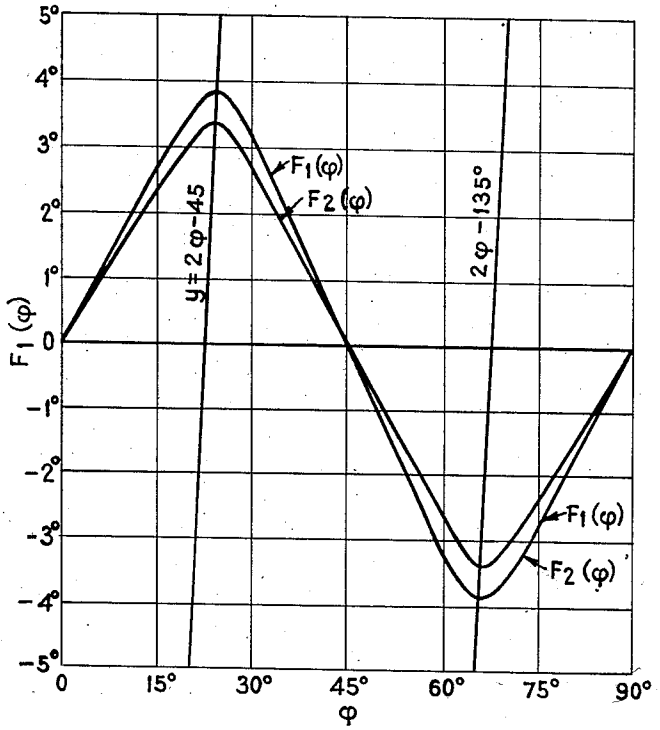


FIG 8

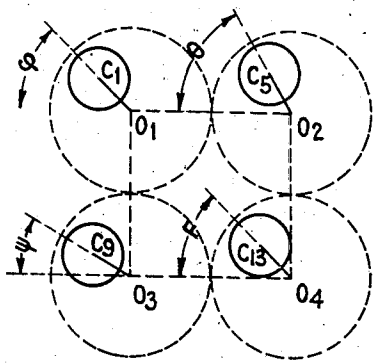


FIG. 9

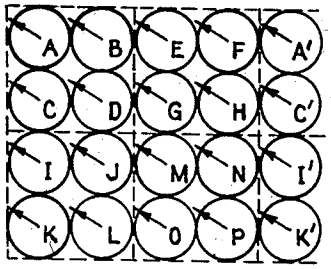


FIG. 10

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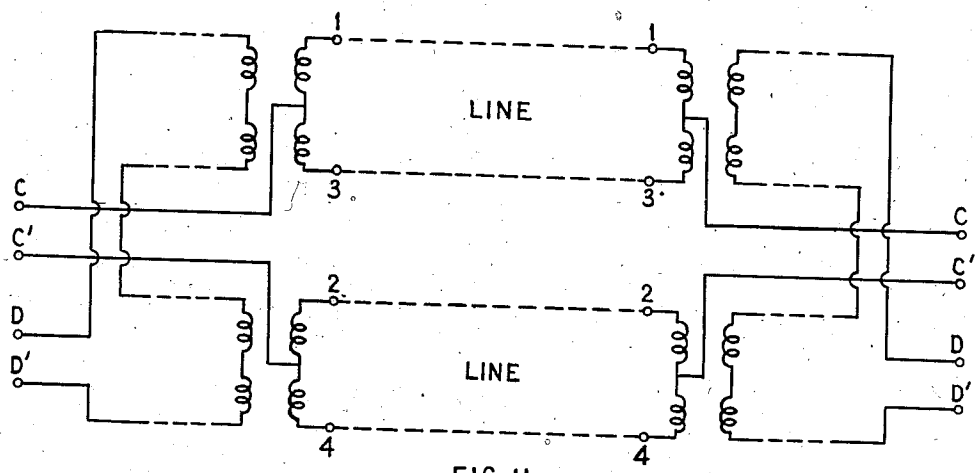


FIG. 11

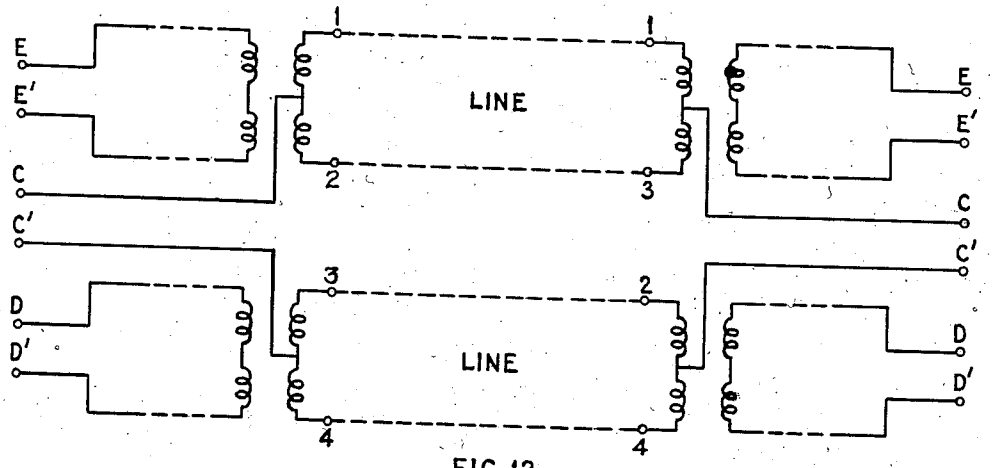


FIG. 12

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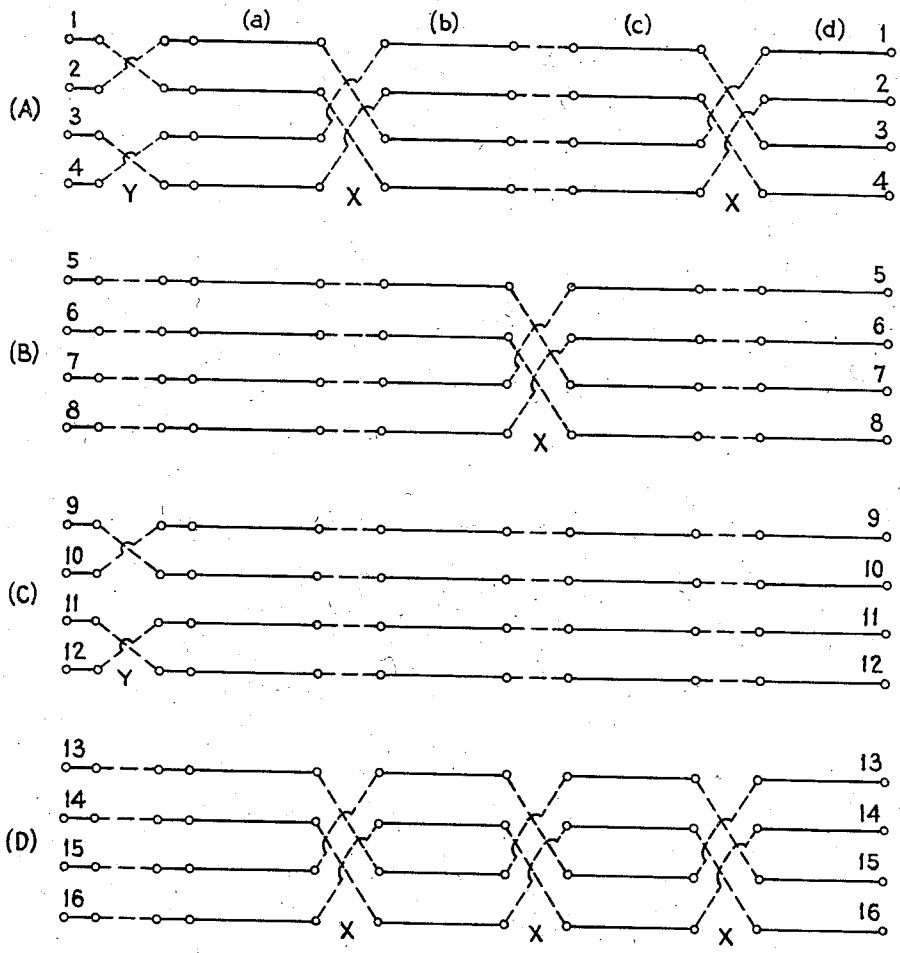


FIG. 13

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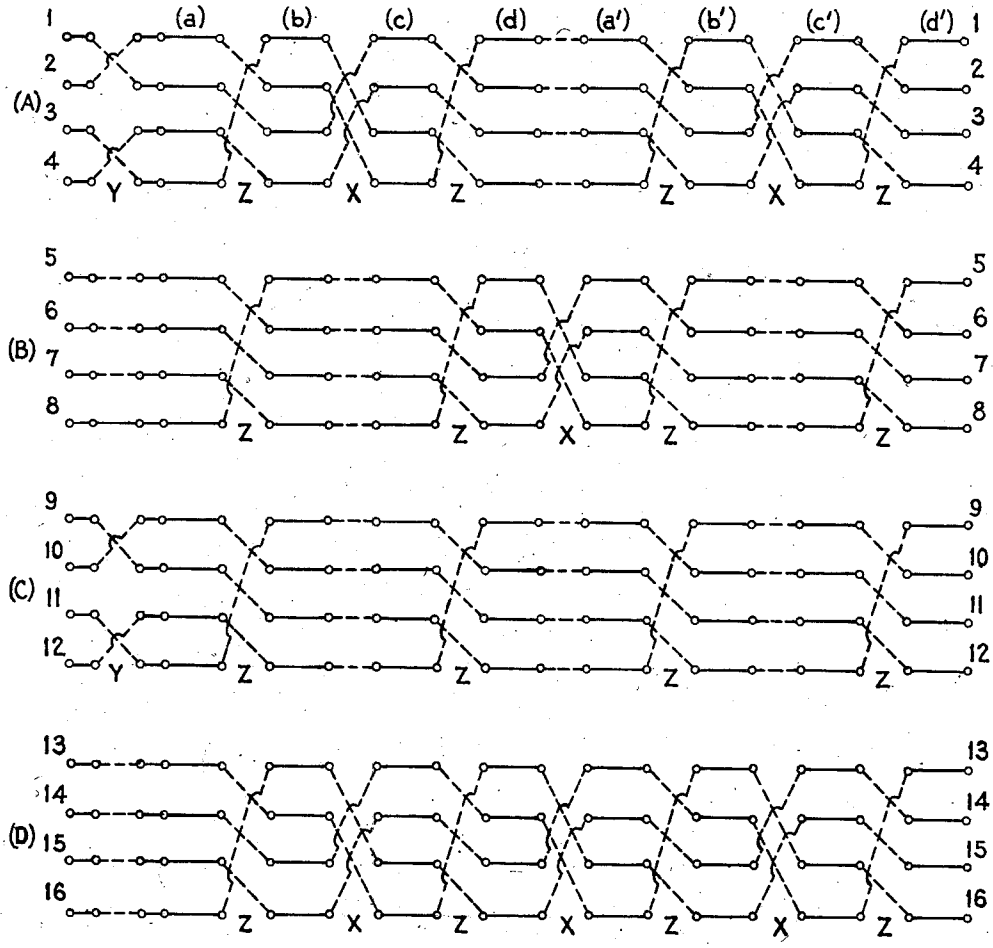


FIG.14

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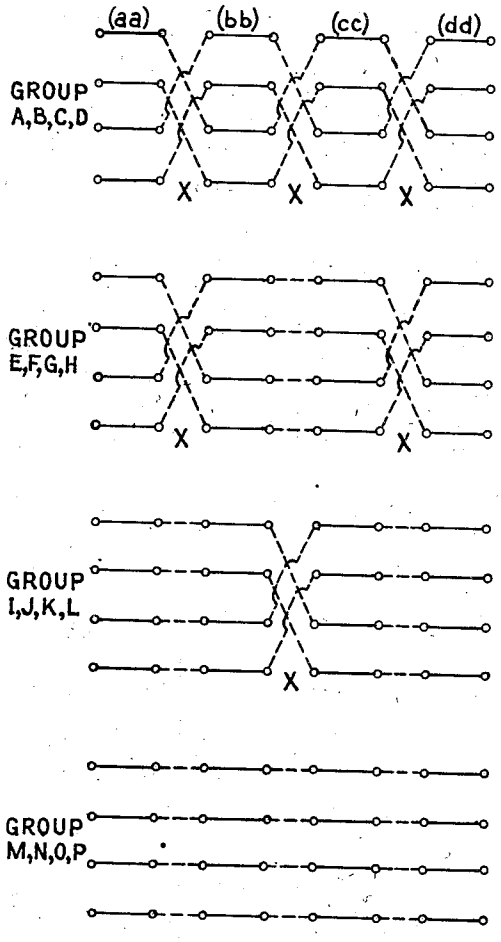


FIG. 15

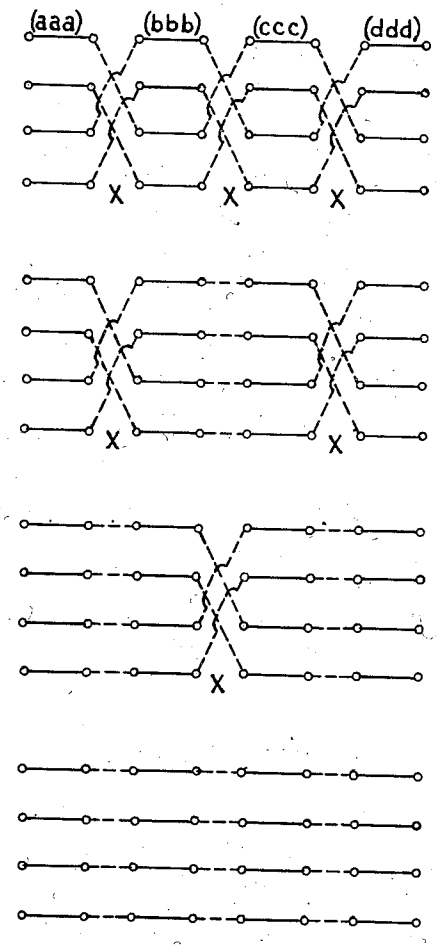


FIG. 16

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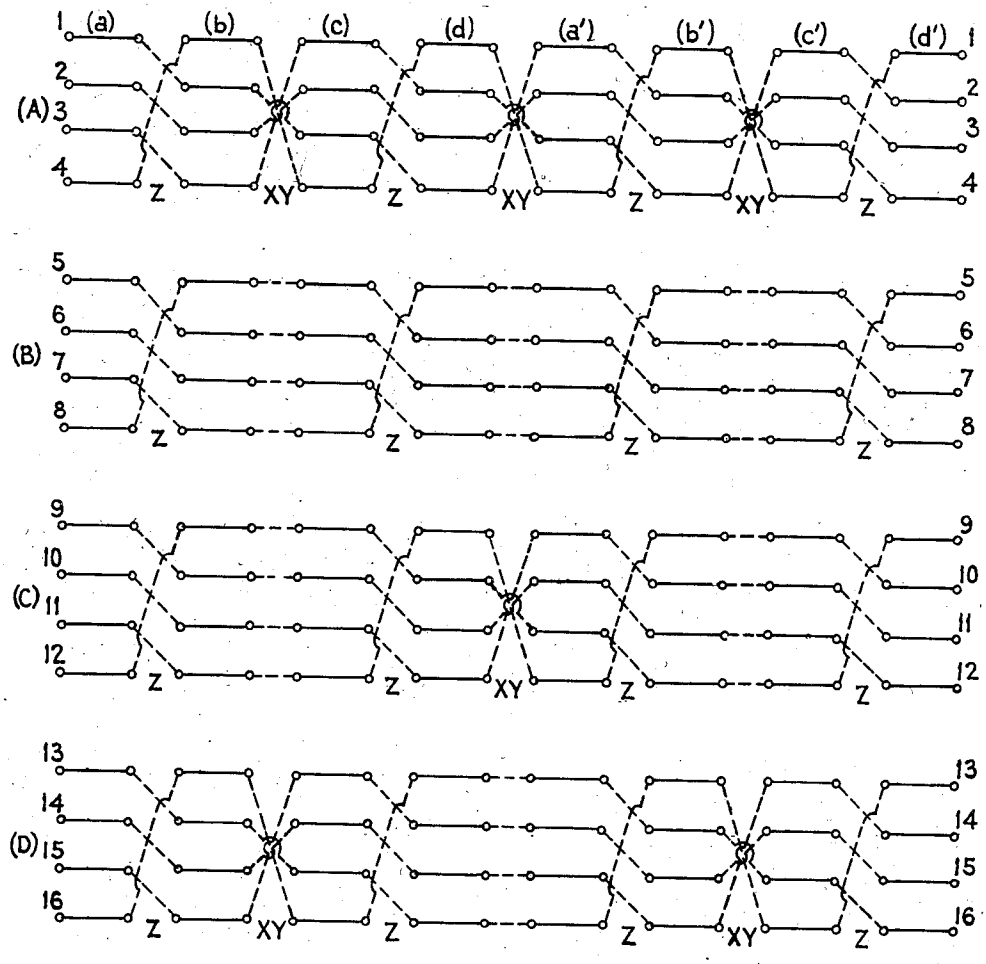


FIG. 17

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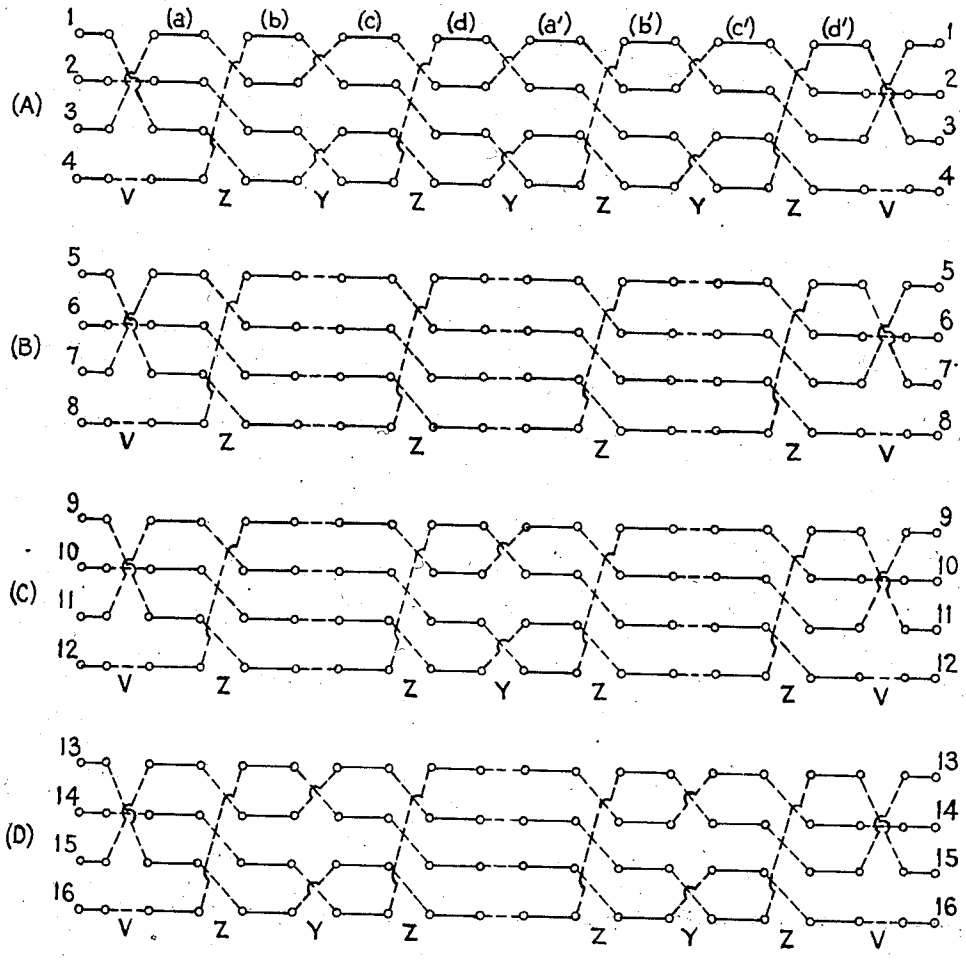


FIG. 18

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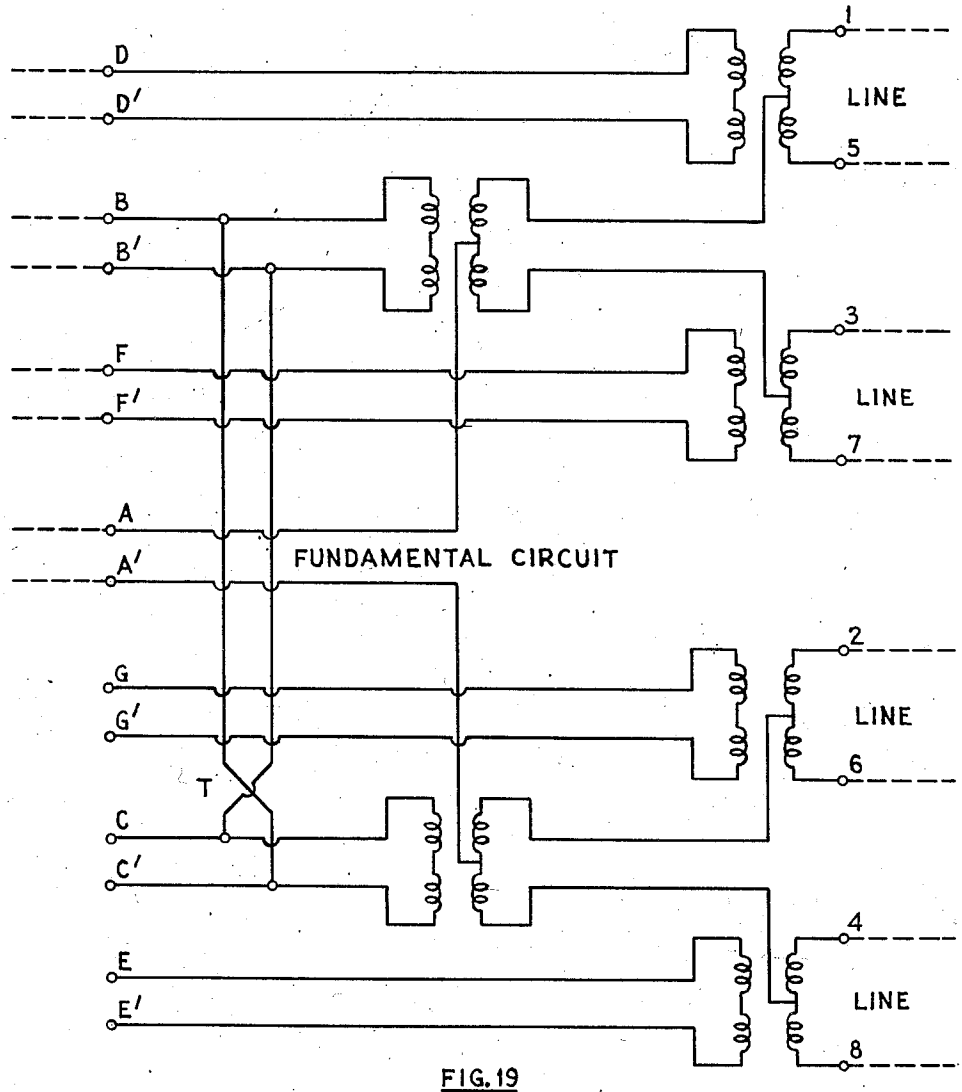


FIG. 19

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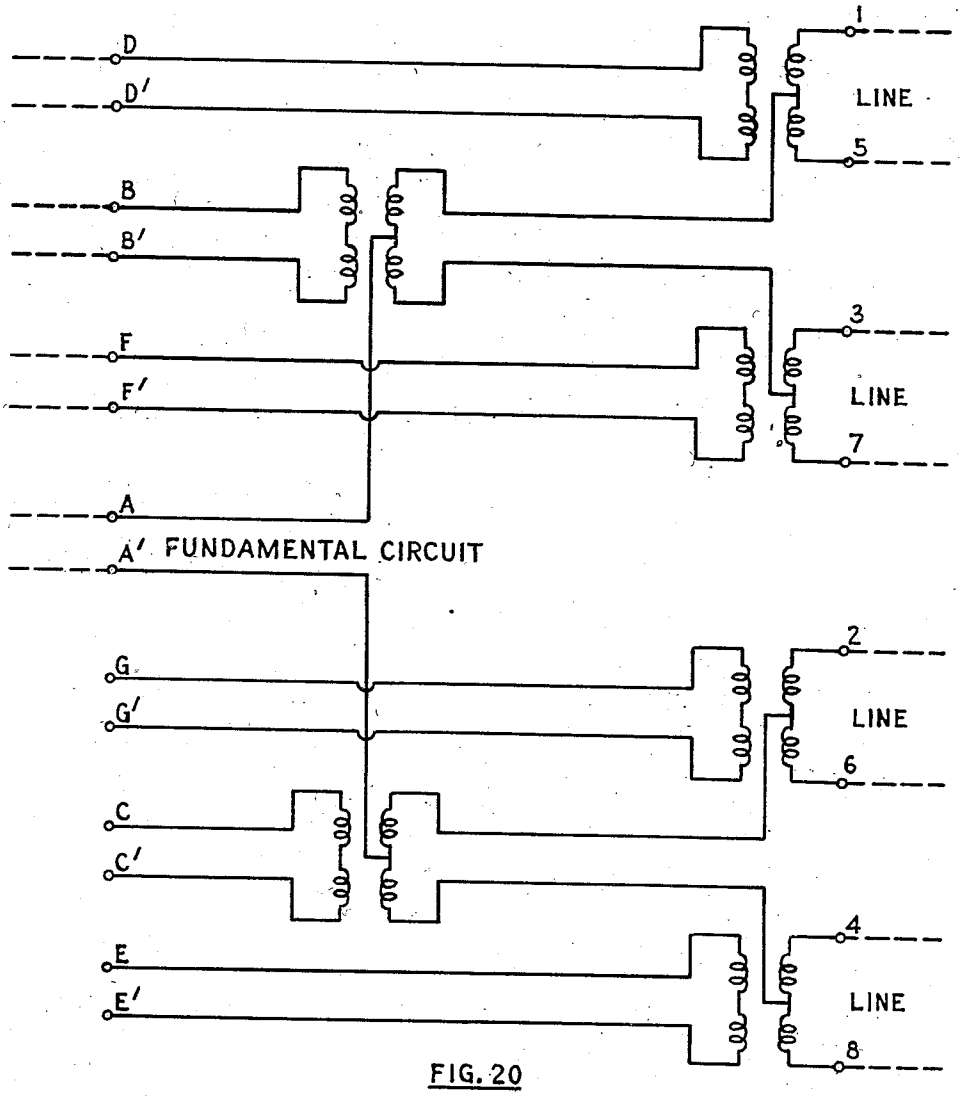


FIG. 20

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Patented Apr. 17, 1945

2,373,906

UNITED STATES PATENT OFFICE

2,373,906

CABLE SYSTEM FOR HIGH FREQUENCY TRANSMISSION

Hughes Mouradian, Philadelphia, Pa.

Application February 25, 1943, Serial No. 477,159

20 Claims. (Cl. 179—78)

This invention relates to a method of and describes the means required for eliminating inductive interference between adjacent circuits, particularly those in close vicinity to each other, such as those in cable.

In the early stages of the development of the telephone art, line circuits consisted, as well known, of single wires grounded at both ends. With the use of line circuits of this type, noise and overhearing were unbearable. As stated by General J. J. Carty—"A wire was strung from Boston to Lawrence, about 26 miles, on a telegraph line. Anybody listening on that telephone wire could hear all the telegraph messages. It was, as though, we had a drum corps and each drummer began drumming a separate tune." The first important forward step consisted in the invention and use of the metallic circuit.

Alexander Graham Bell was awarded, on July 29, 1881, U. S. A. Patent 244,426 describing the basic principles of the metallic circuit. It was pointed out by the inventor, in a deposition taken before the Commissioner of Patents that the improvements he had devised were:

1. To place the direct and return wires close together, and to place around them a common cover or envelope of such thickness that the telephone wires should always be so very much nearer to one another than they were to any other adjoining wires.
2. To twist the direct and return wires around one another, so that they should be absolutely equidistant from the disturbing wires.

The two-wire metallic circuit of the type just described has been the basic backbone of all telephone circuits. Additional improvements have been introduced by the use of different lengths of twist for adjacent pairs, and by the use of special manufacturing measures and installation procedures which have had for their objective the still further reduction of both the residual mutual capacity unbalances and inductive reactive unbalances between adjacent pairs.

The next step in the art, consisting in the introduction of the phantom circuit was a step in reverse in so far as mutual unbalances were concerned. The problems of the telephone engineer in overcoming cross-talk, babble, noise, etc. were greatly increased by the introduction of the phantom circuit. However, the economical advantages of being able to obtain, by phantoming, an additional circuit at no additional cost for line conductors, more than compensated the disadvantages of the increased difficulties involved, in the way of overcoming mutual interference between telephone circuits. It is important to call attention here to the fact that the phantom circuit uses 4 wires, just as one of the several systems disclosed in the present specifications, but while the particular arrangement known as the phantom circuit or "quadded" cable arrangement resulted in an increase of mutual interference conditions as above stated, the particular form of 4-wire arrangement hereinafter described has exactly the opposite property of decreasing the mutual interference.

The difficulties, above referred to, brought about by the introudction of the phantom circuit were alleviated by the use of capacity unbalance testing methods during the installation of the phantom, "quadded" or "duplex" type cables. With the advent, however, of the use of higher frequencies in the art, particularly with the introduction of carrier methods for cable transmission (range of 12,000 to 140,000 cycles per second), it became necessary to give up entirely the use of phantom facilities, and to separate incoming and outgoing messages by providing two separate cables, one for each direction of transmission, in order to reduce mutual interference to tolerable limits. In addition to the steps just indicated, extremely intricate special balancing methods are at present required, each carrier circuit being balanced against every other carrier circuit, to reduce mutual interference to a point satisfactory for commercial use. A very clear and adequate exposition of the difficulties involved and the methods used at present in overcoming these difficulties will be found in the following symposium of papers, all of which appeared in 1938 A. I. E. E. Transactions.

1. A Carrier Telephone System for Toll Cables, by C. W. Green and E. I. Green (pages 227–236)
2. Cable Carrier Telephone Terminals, by R. W. Chestnut, L. M. Ilgenfritz and A. Kenner (pages 237–244)
3. Crosstalk and Noise Features of Cable Carrier Telephone Systems, by M. A. Weaver, R. S. Tucker, and P. S. Darnell (pages 250–261)

The last paper deals in some detail with the difficulties of cross-talk and babble with the present day type K cable carrier system and is therefore of direct interest in conjunction with the consideration of the invention disclosed in the present specification.

In the field of radio applications also, where the frequencies used are expressed in megacycles, the interference between the wiring of input and output terminals of amplifiers and modulators has been so great as to require radical modifications in the design of these amplifying or modulating

tubes in order to avoid "singing" or howling, by keeping the input and output circuits as far apart as possible, actually at opposite poles.

I have discovered that the difficulties experienced with the present day two-wire and four-wire metallic circuits can be overcome, if use is made of multi-conductor systems of wires for each two-way signalling circuit, said wires being arranged on the periphery of a cylindrical core, with positive (+) and negative (—) polarities succeeding each other around said periphery in sequence, thereby producing a partly neutralized electromagnetic and electrostatic field in space, provided further "corresponding elements" in adjacent similar systems of wires are set at predetermined angles with reference to the line connecting together the center of said first system of wires to the center of said similar systems as fully described in these specifications. I find that the minimum number of wires required to produce the partly neutralized field is four (4). The advantages of the new system, first disclosed in these specifications, increase rapidly with the number of wires provided for each two way circuit.

To produce a neutralized field, in the specific ways described fully hereunder in the present specifications, the various wires of the same two-way system have to occupy fixed space relationships to each other, in contradistinction, to cite an example, of the present day "quadded" cable system, wherein the wires of the quad continuously change their respective positions with reference to each other. This structural characteristic is well defined in the original U. S. A. Patent 863,969 for a cable of the quadded type, the first claim of which reads:

"A method of making telephone and telegraph cable cores, which consists in twisting together pairs of individual conductors with a constant length of lay from end to end of each twisted pair, and again twisting the twin conductors in pairs but with a different length of lay."

A second main objective of the present invention is to secure the improved type of transmission circuit for high frequency use in closely packed wiring, as a superimposed carrier circuit upon the same wires which can be arranged for simultaneous use as voice frequency circuits or even a second carrier system. Thus the fundamental carrier circuit itself can be obtained at no additional cost for line conductors, when these can be used for voice frequency circuits between intermediate points.

All of the various objectives of the present invention will be more clearly understood by reference to the following description taken in connection with the accompanying drawings in which Fig. 1 indicates two present day two-wire metallic circuits in close vicinity to each other; Fig. 2 indicates one form of the proposed system for high frequency conductors using just four wires for a two-way circuit; Fig. 3 indicates a second form of the proposed system of high frequency conductors using six (6) wires for a single two-way circuit, in alternative positive and negative sequences, the seventh and central wire being a filler only; Fig. 3A indicates a third form of the proposed system of high frequency conductors using eight (8) wires for a single two-way circuit in alternative positive and negative sequences. The void shown in the center of Fig. 3A would be occupied by filler wires devoted to low frequency systems. Fig. 3B indicates a fourth form, as a general conception for a high frequency conductor, in which a hollow core conductor is divided into an even number of segments, by means of intervening insulation. A single two-way circuit is constituted by bridging together all non-adjacent metallic segments into two conductors; Fig. 4 indicates the method of using a proposed system with four constituent wires in a two-way circuit arrangement; Fig. 5 indicates the method of using the proposed system with four constituent wires in a one-way circuit arrangement, a second set of four constituent wires being used in the opposite direction the combination representing the equivalent of the present day so-called "four wire system," as modified for high frequency use; Fig. 6 indicates the proposed system as applied to repeater circuits of the two-way type; Fig. 7 indicates two four-wire units, designated as A and B, with unit A making an angle of φ degrees and unit B an angle of θ degrees with the line O_1O_2 representing the line of centers of units A and B. Only one of the four wires in each unit is shown, i. e. wires 1 and 5 respectively, and the definition of the angles φ and θ is related to these two wires as shown; Fig. 8 represents the "distortion function" $F_1\varphi$ as a function of the angle φ, as fully explained in the specification; Fig. 9 shows a quartet of the four-wire units A, B, C, and D with centers O_1, O_2, O_3, and O_4, respectively with the centers C_1, C_5, C_9 and C_{13} of wires 1, 5, 9 and 13, defining the angles φ, θ, ψ and F. This drawing serves as a basis for the analytical determination of the angles which result in zero coupling between the quartet of units A, B, C and D; Fig. 10 shows the designations used in the specifications for an assembly of adjacent four-wire units; Fig. 11 indicates an arrangement whereby two two-way circuits can be derived from a set of four-wires, one two-way circuit terminated at terminals CC representing a high grade, high frequency carrier circuit, and a second two-way circuit superimposed upon the first terminated at terminals DD^1 with no mutual reactions between these two circuits, each using the same four wires; Fig. 12 indicates an arrangement whereby three two-way circuits can be derived from a single set of 4-wires, consisting of one fundamental carrier circuit actually using all four wires terminated at terminals CC^1 and, in addition, two two-way two-wire circuits, terminated at terminals DD^1 and EE^1 respectively; Fig. 13 indicates a set of transpositions to be installed during the manufacturing of the cable between successive equal lengths of cable to eliminate two-wire unbalances in a quartet of four 4-wire units; Fig. 14 indicates an alternative arrangement to that shown on Fig. 13, Fig. 15 indicates the additional pattern of transpositions required to extend the freedom from mutual interference on the two-wire combinations to a group of 16 4-wire units; Fig. 16 indicates the additional pattern required to further extend the freedom from interference to a group of 64 4-wire units; Fig. 17 indicates a system of transpositions to obtain freedom from interference between a second system of 4-wire circuits depicted as terminating at terminals DD^1 on Fig. 11 of the drawings, such circuits forming part of a group of four adjacent 4-wire units, such second system being actually additional to the fundamental 4-wire circuit terminated at terminals CC^1 on the same drawing; Fig. 18 indicates an arrangement of transpositions applicable to the case illustrated on Fig. 11 of the drawings, wherein a second 4-wire circuit is superimposed

upon the fundamental 4-wire circuit, with unbalances developed which are all of the same size and sign, as shown in detail on Table XIX of the specification. Figure 19 indicates the method required to derive a balanced 8-wire two-way circuit using either the arrangement of Fig. 3A or Fig. 3B of the drawings, said two-way circuit being terminated at AA', with wires 1 to 8 inclusive terminated in the particular manner as shown. Fig. 19 also shows how it is possible to derive a second auxiliary or additional 8-wire circuit terminated at BB' and two auxiliary 2-wire circuits terminated at DD' and FF'. Fig. 20 shows an alternative arrangement to that shown on Fig. 19 of the drawings, with an auxiliary 4-wire circuit terminated at BB' replacing the auxiliary 8-wire circuit of Fig. 19 of the drawings.

The present invention has for its main purpose the eliminating of or the reducing to a negligible minimum the following effects:

1. Crosstalk between circuits in the same cable.
2. Babble between circuits in the same cable.
3. Noise from outside sources of interference with communications including, among others, the following:
   (a) Noise from heavy static on open wire taps to cable circuits.
   (b) Noise from telephone and telegraph repeater offices.

Quantitative measurements have been carried out and reported by Weaver, Tucker and Darnell (A. I. E. E. Transactions, 1938, pages 250–259) on all these effects. The near-end cross-talk is so large at carrier frequencies that it has been found necessary to route outgoing and incoming messages in two different cables as already referred to. The carrier transmission arrangement used in present practice is illustrated in Fig. 3, page 240 of the paper by Chestnut, Ilgenfritz and Kenner (A. I. E. E. Transactions 1938). It may be noted that the outgoing message is delivered to the line at a level of +9 db. The received message, on a separate cable pair in a separate cable, is received from the line at a level varying between −37 db. and −59 db., depending upon the carrier frequency, for a repeater spacing of 17 miles. This arrangement was made practicable through the use of the special methods described in detail by Weaver, Tucker and Darnell in their paper already referred to. As these special methods, some quite intricate in character, have been quite clearly and adequately described by the above authors, they will not be outlined here. It may be sufficient here to remark that, as a result of the special methods used, it has been possible to reduce far-end crosstalk as follows:

	Summary—Crosstalk reduction; far-end crosstalk	
	14,000 cycles	60,000 cycles
	Db.	*Db.*
1 Crosstalk before poling or balancing	−78	−66
2 Crosstalk after poling or balancing	−88	−83.5
3 Reduction obtained	−10	−17.5

For a repeater spacing of 17 miles, the near-end crosstalk is greater than the far-end crosstalk by 21 db. at 14,000 cycles per second and 30 db. at 60,000 cycles. As the reductions obtainable by the methods heretofore used in the art with non-loaded pairs could not go beyond the limits indicated in the above summary, it was necessary in practice to resort to the use of two different cables for transmission in the two directions to avoid completely the near-end crosstalk which is, as just indicated, so considerably heavier than far-end crosstalk, even for a stretch of 17 miles between successive repeater stations.

The above very brief and elementary description shows how the art of communication by means of paper insulated cables, finds itself handicapped and limited when carrier transmission is made use of to increase the number of channels of speech over a given number of conductors. For a more thorough and complete understanding of these difficulties, reference may be made to the several original A. I. E. E. papers cited hereinabove in these specifications and to U. S. A. 2,336,627, granted to me for a "System for overcoming thermal agitation noise and inductive disturbance noises in carrier systems."

The present invention has, for one of its main purposes, the reduction of both near-end and far-end crosstalk to limits below those found possible to realize in the art when use is made of No. 19 B. & S. gauge cable conductors for transmission. It is nowise restricted, however, as will be amply clear by an understanding of the general principles developed hereinbelow in these specifications, to the use of No. 19 B. & S. gauge conductors.

I have indicated in a companion application, which recently matured into U. S. A. 2,336,627, granted to me, one arrangement whereby greater reductions in crosstalk, babble, etc., can be obtained than shown as practicable to secure at the present time in the "Summary—Crosstalk reduction," reproduced hereinabove. In this arrangement use is made of a circuit layout (see Fig. 4 of U. S. A. 2,336,627) in which equal amounts of crosstalk, both far-end and near-end, on two physical pairs, are made to cancel each other. The fundamental conception first disclosed in U. S. A. 2,336,627 can be carried out in at least two different ways, both using present day type cable facilities:

I. Use, for the two physical pairs required, the two side circuits of a phantom or duplex type cable conductors. The additional requirement is that instead of providing twists of different lengths for the two side circuits, as at present provided in the art, it is necessary on the contrary to provide the two side circuits with twists exactly of the same length. In this manner, it is possible to obtain relative exposures for each of the two side circuits which are equal to each other with respect to all other conductors in the same cable, thus satisfying a fundamental requirement of the invention.

II. Use, for the two physical pairs required, a so-called spiral-4 quad. The requirement that the two physical pairs should have the same length of twist is automatically satisfied by the spiral-4 construction. Adjacent spiral-4 quads would of course be provided with different lengths of twist.

Under both of the above arrangements, the elimination of crosstalk is obtained by providing that the inductive exposures of the two pairs, both of which are used simultaneously for transmission purposes as a single circuit in both directions, as described fully in U. S. A. 2,336,627 and as clearly shown on Fig. 4 of said patent, are made exactly the same by construction as nearly as practicable. In the present application, dis-

closure is made for the first time in the art of an arrangement whereby instead of developing equal exposure effects of the same sign, on two physical pairs (or 4 wires) and then eliminating these effects by opposing them to each other at terminal points as first disclosed in U. S. A. 2,336,627, systems of 4 wires (to mention only one specific application of the invention) are used which produce no inductive effects upon adjacent similar systems of 4 wires. I have discovered that such a result can be obtained if the following conditions are satisfied:

(*a*) The outgoing and return conductors, instead of being oppositely located to each other in the 4-wire system, are on the contrary adjacent to each other. On Fig. 2 of the drawings of the present specifications, current on conductor 1 finds its return on conductor 2 and the current on conductor 3 finds its return on conductor 4. This is indicated by the sequence of (+), (−), (+), (−) on Fig. 2 of the drawings. See also Fig. 11 of the drawings where in the fundamental circuit CC′ the instantaneously (+) currents flow through conductors 1 and 3, and the (−) currents through conductors 2 and 4. Thus, the angular displacement of the conductors carrying outgoing and return conductors in the present invention is 90° and not 180° for the 4-wire arrangement.

(*b*) The various systems of $2n$ wires in individual groups in the same cable are set at "predetermined angles" with reference to the lines connecting the respective centers of said $2n$ wire systems. Again referring to Fig. 2 of the drawings, the above means that the angles φ and θ of "corresponding elements" 1 and 5 of two adjacent 4-wire systems with reference to the line of centers O_1, O_2 of said system are taken equal to each other, the common value being determined in the specific manner first disclosed in the present specifications.

This point is made clearer by reference to Fig. 10 of the drawings, in which A represents any $2n$-wire system of the type first described in these specifications and similar balanced systems are designated by B, C, D, etc., stacked as shown. It will be noted that a set of arrows is also shown on Fig. 10, all such arrows being parallel to each other. The directions of the arrows with reference to the line joining the centers of units or systems A, B, E, F in the horizontal direction or A, C, I, K in the vertical direction indicate what is referred to as "predetermined angles" in the claims. Wires bearing the same numbering such as 1, or occupying the same relative positions in each of the $2n$-wire systems, are referred to as "corresponding elements" in the specification and in the claims. For instance, on Fig. 9 of the drawings, depicting a set of adjacent 4-wire systems, wires 1, 5, 9 and 13 are, by definition, "corresponding elements." In practice, such wires will be identified by special colored paper insulation or binders, or by any other suitable identifying marks.

The "predetermined angle" is again, by definition, the angle between a designated element such as wire 1 in a $2n$-wire system and the line joining the centers of a row of adjacent systems of similar type so computed that in effect said $2n$-wire system will have zero coefficient of inductive coupling with the adjacent $2n$-wire system in said row. The full meaning of this point will be clearer by reference to Fig. 9 of the drawings, which illustrates four adjacent similar systems, with their respective centers O_1, O_2, O_3 and O_4. The "predetermined angle" is the angle φ on that figure. I have found that the angles φ, θ, ψ and F should be parallel angles for the sake of practical construction and simplicity of design. However, other equally effective design arrangements are available, all of which are pointed out in the detail mathematical disclosures first made in these specifications.

(*c*) The wires, in any one $2n$-wire system, are not twisted together (as in present-day practice with paper insulated cables) but, on the contrary, are maintained parallel to each other at the "predetermined angles" already defined in some detail hereinabove, which produce "no coupling" or "no inductive effects" between adjacent $2n$-wire systems.

Since the freedom from interference is due in part, in the case of the present invention, to the use of pre-selected fixed relative locations of any one of the $2n$-wire systems with reference to all other similar systems, such freedom would be destroyed if these optimum relative locations were changed, as they would be in case the wires of the $2n$-wire systems were twisted. $2n$ wire spiralling may be used, but in this case, all $2n$ wire systems must have the same spiral length and corresponding elements be properly disposed.

When conditions *a*, *b* and *c* have been satisfied, no matter how short a length of the $2n$-wire system herein disclosed is taken into consideration, said $2n$-wire system will have "zero" coupling with similar immediately adjacent systems. Thus a proper foundation has been laid for the building of an inherently balanced system.

To summarize the above, it may be stated that the basic foundation of the invention consists, broadly, in constructing a cable with a multiplicity of separate cores, each core consisting of $2n$-wires, where n is an entire number greater than unity, such wires in each core being symmetrically disposed around the periphery of a perfect circle, as shown on Fig. 2, Fig. 3, Fig. 3A and Fig. 3B, all $2n$ wires of each separate core being used cooperatively to form a single speech or carrier circuit, all of said wires being maintained parallel to each other at predetermined angles. Each side of said single circuit would thus be formed of n wires. The wires designated as (+) are joined together to form one side of a "composite" conductor, the wires marked (−) forming the second side. The joining of said wires is best carried out at repeater points, though nothing prevents or precludes such combinations being made also at intermediate points. Fig. 11 and Fig. 12 show how this joining together would be carried out with a 4-wire system of the present invention, using wires designated as 1, 3, 2, 4 terminated as a single circuit at CC′. Fig. 19 and Fig. 20 show how the corresponding 8-wire system of the present invention, using wires 1, 5, 3, 7, 2, 6, 4, 8 would be terminated as a single circuit at AA′.

The testing of the wires for maintenance purposes is, however, most conveniently carried out if the points where the component wires of a $2n$-wire system are joined together are restricted to repeater points or to other points where specially provided terminating and testing facilities can be made available.

I have also discovered that where $2n$ wires are used in accordance with the provisions of the present specifications, the electrostatic and electromagnetic unbalance figures decrease very rapidly as n increases numerically. With just two wires, I find it is actually impossible to construct an inherently balanced system. Where 4 wires are used in the particular manner described hereinbelow, the largest unbalances between such 4-wire systems, i. e., between immediately adjacent systems (such as between units A and B or units A and C, as shown in Fig. 10 of the drawings) can be completely eliminated. However, small 4-wire residual unbalances are left between diagonally separated units of the order of 250 micro-microfarads per mile, which are eliminated if certain wires in each cable reel are provided with a transposition of the γ type as shown on Fig. 13 and Fig. 14 of the drawings. All other unbalances are of negligible order as shown hereinbelow. Where 8 wires are used, in the particular manner fully described hereinbelow, and as illustrated on Fig. 19 and Fig. 20 of the drawings, all unbalances are eliminated when separate cores, each consisting of 8 wires as per Fig. 3A are assembled together in accordance with Fig. 10 of the drawings. Thus, without making $n=\alpha$, which would automatically result in a zero electromagnetic and electrostatic field throughout space (but which would be quite impossible to realize in practice) it is possible to secure an inherently balanced cable system with an 8-wire layout as per Fig. 3A of the drawings, and an almost but not quite perfectly balanced system with a 4-wire layout as per Fig. 2 of the drawings.

Where the inductive couplings can be annulled as shown hereinbelow, both far-end and near-end crosstalk can be eliminated. Babble, which is the resultant crosstalk from a multiplicity of inducing sources in the same cable, will also cancel out. As to the other remaining aspects of the primary objective of the present invention, i. e., the elimination of "noise from outside sources of interference with communications," these will evidently also cancel out if all circuits in the same cable make use of the balanced type transmission system first disclosed in this specification.

In view of the outstanding fact that the building of an inherently balanced cable communication circuit requires a multiplicity of wires, which is a decided practical disadvantage, I have carried out investigations to determine whether the wires used for a balanced circuit could be utilized to secure additional or auxiliary communication circuits, thereby decreasing the primary costs of furnishing service by means of cable facilities, using high frequency carrier systems. The term "superimposed" circuit is frequently used in the art instead of auxiliary or additional circuit, as above stated. I have discovered that it is definitely practicable to secure such superimposed circuits, though these, I find, will be of poorer quality from the standpoint of crosstalk and babble than the fundamental inherently balanced circuits hereinbefore described. However, if these auxiliary circuits are restricted for use to the shorter haul traffic between points along the route of the cable, they would still meet the requirements of present-day telephone service. Under these conditions, all such superimposed circuits would be obtained at no additional cost for line conductors and thereby would greatly decrease the overall costs of providing speech facilities along the route of the cable. This point, forming the second main objective of the invention, is covered in considerable detail in so far as 4-wire balanced systems are concerned, in Tables XI to XIX, inclusive.

In the case of 4-wire systems, the auxiliary circuits are circuits DD', shown on Fig. 11, or circuits DD' and EE' shown in Fig. 12. It will be noted that the arrangement shown in Fig. 11 of the drawings for DD' is a 4-wire arrangement of the series type. It is clearly evident that the secondaries of windings 1, 3 and 2, 4 could be bridged in parallel instead of in series, and equivalent results obtained thereby. This alternative arrangement has not been illustrated in the drawings. In the arrangement shown in Fig. 12 of the drawings, actually two (2) 2-wire circuits have been derived which do not interfere in any way with the fundamental circuit CC' of the 4-wire type first disclosed in these specifications, nor do they interfere with each other.

In the case of 8-wire systems, as per Fig. 3A of the drawings, while six (6) additional circuits appear possible, actually the number of mutually non-interfering circuits is more strictly limited. The arrangement of Fig. 19 of the drawings shows, in addition to the fundamental 8-wire circuit AA', using all 8 wires 1 to 8, inclusive, the following mutually non-interfering superimposed or auxiliary circuits:

(a) A second 8-wire circuit terminated at BB'.
(b) A 2-wire circuit terminated at DD'.
(c) A 2-wire circuit terminated at FF'.

Alternative arrangements to circuits DD' and FF' are the circuits EE' and GG'. From the standpoint of best overall practical performance, it may be preferable in some cases to further restrict the above arrangement to the combination of circuits BB' and DD' or BB' and FF' as an alternative, thus obtaining 3 circuits as a total, including circuit AA' with the 8-wires, 1 to 8 inclusive.

The arrangement of Fig. 20 of the drawings is alternative to that illustrated by Fig. 19 of the drawings for an 8-wire arrangement. It includes, in addition to the fundamental circuit AA', the following mutually non-interfering superimposed or auxiliary circuits:

(a) A 4-wire circuit of the fundamental type, similar to that shown as terminated at CC' on Fig. 11 of the drawings.
(b) A 2-wire circuit terminated at DD'.
(c) A 2-wire circuit terminated at FF'.

Alternative arrangements to circuits DD' and FF' are the circuits EE' and GG'. Again, it may be preferable in some cases to restrict the 2-wire auxiliary circuits to either DD' or FF'. Attention is called to the need for providing the transposition T between BB' and CC' on Fig. 19 of the drawings, as otherwise the crosstalk between adjacent auxiliary 8-wire circuits would be intolerable instead of zero. This is due to the fact that the couplings produced on BB' and CC' by immediately adjacent similar circuits, are of equal and opposite sign and cancel each other if connected as shown.

The possibility of utilizing auxiliary circuits in addition to the fundamental circuit using $2n$-wires, is an important development from the standpoint of practical application of the basic principles first disclosed in these specifications. It should be noted that these auxiliary circuits, in order to meet the present-day requirements of a maximum of 1000 units of crosstalk between cir-

cuits in the same cable devoted to toll service, require the use of a pattern of transpositions as illustrated by the diagrams of Fig. 13 to Fig. 18, inclusive. These transpositions will be, in practice, provided at the splicing of the wires between successive cable reels. The working out and the application of such patterns of transposition, unless restricted to a few combinations, may become unmanageable, as well known to those versed in the art. I have, therefore, carried out investigations to determine ways and means for decreasing the inductive couplings between cable pairs and have discovered a general method for accomplishing the purpose just mentioned. The method consists in rotating all wires in each separate core consisting of $2n$-wires by an angle equal to

$$\frac{2\pi}{2n}$$

around the geometrical center of each separate core. Thus, where the fundamental circuit of $2n$-wires is actually a balanced 4-wire circuit, the angle of rotation is

$$\frac{360}{4}=90 \text{ degrees}$$

In the case of the 8-wire balanced system, the angle of rotation is 45°, etc. Such an arrangement can be best carried out during the manufacturing of the cable, since no complicated pattern of transpositions is involved, as all wires in the cable are treated alike.

All wires in each reel of cable would be provided with "$n-1$" rotations, where the fundamental circuit is a $2n$-wire system. I have designated by the symbol "Z" on the diagrams in Fig. 14, Fig. 17 and Fig. 18, the rotational arrangement or the transposition of the wires. Thus, wires 1, 2, 3 and 4 of the 4-wire inherently balanced system are transposed with wires 2, 3, 4, 1. If reference is made to Fig. 2 of the drawings, which shows the location of the wires in a single one of the separate cores in the cable, it will be seen that the change of positions of wires 1, 2, 3, 4 to 2, 3, 4, 1 is equivalent to what might conceivably be called a "barrel" type transposition. Thus wire 1 is connected to wire 2, etc., and such "transposition" is equivalent to a rotation of 90° around the center O_1 of the separate core consisting of wires 1, 2, 3, 4, since the angle subtended by wires 1 and 2, i. e., the angle O_1, 2 is 90°.

The "Z" type barrel transposition must be applied, during the manufacturing process, to equal lengths of cable. If, for instance, the cable reel ordered is 600 feet in length and the cable is of the 8-wire balanced type, all wires should be transposed in the manner already described by 45° every 150 feet, thus securing a complete half "barrel" for that particular reel of cable.

I have shown in some detail hereunder in these specifications, the effect of the application of the "Z" type transposition on all wires for the inherently balanced system as per Fig. 2 of the drawings. The reduction obtained in inductive couplings is of the order of 10 db. This reduction applies only to the auxiliary circuits—such as circuit DD' of Fig. 11 of the drawings or, to the two 2-wire circuits DD' and EE' of Fig. 12 of the drawings. This will be clear by reference to Tables XVI and XVII in comparing the unbalance figures under the third column marked Section *a* with those under the last column.

When use is made of the general method of reducing crosstalk between the inherently unbalanced auxiliary circuits by means of the "Z" type transpositions applied on all wires as above described, and such use is supplemented by the application of the "X" type transposition system in conjunction with the comparatively simple patterns indicated on Fig. 13 to Fig. 18, inclusive, it becomes feasible to develop auxiliary circuits which will be sufficiently well balanced to meet the requirements of present-day telephone service, provided further the length of such circuits is restricted in accordance with the indications given hereunder.

In the case of the 4-wire inherently balanced circuit of Fig. 2 of the drawings, where two auxiliary two-wire circuits are derived as per Fig. 12 of the drawings and the transposition patterns of Fig. 14, Fig. 15 and Fig. 16 are used, a balanced cable section will include 64 successively spliced reels. If, as is customary, the length of each reel is about $\frac{1}{16}$ of a mile, a balanced cable section will have a length of 6.4 miles, with the transpositions of the "X" type installed between reels at the cable splices. The arrangement just described will leave a maximum unbalance between the auxiliary 2-wire circuits of 10 micro-microfarads per mile. It will be noted, by reference to Tables XVI and XVII, that when use is made of the "Z" type transpositions as first disclosed in these specifications, the unbalance between 2-wire circuit 1, 3 of one unit, such as unit A, and the unbalance of a second 2-wire circuit, such as circuit 6, 8 of an adjacent unit is zero. Therefore, if we further restrict ourselves in the utilization of two-wire possibilities and arrange to use circuit 1, 3 in unit A and circuit 6, 8 in adjacent unit B or C, then in any sub-group of four adjacent units such as A, B, C, D, of Fig. 10 of the drawings, the only unbalances remaining will be those between diagonal units. Since, in the case of 4-wire balanced units as per Fig. 2 of the drawings, it is necessary to provide "Y" type transpositions as described hereinbelow and as pictured on Fig. 13 and Fig. 14 of the drawings, if these "Y" type transpositions are changed into the "XY" type, also as described hereunder in these specifications, then a cable reel can be manufactured and delivered for use in which all the unbalances will have been removed as between units of any one sub-group such as A, B, C, D or E, F, G, H as per Fig. 10 of the drawings. Under these conditions, either a single two-wire auxiliary circuit can be obtained with only 1 or 2 micro-microfarads unbalance per mile and therefore of better grade than the two two-wire circuits of Fig. 12 of the drawings, using the same number of cable reels in sequence to secure a balanced cable section as per patterns of Fig. 14, Fig. 15 and Fig. 16, or the length of the balanced section can be reduced by omitting the transposition pattern of Fig. 16 of the drawings.

The observations just made as regards the auxiliary two-wire circuits which can be obtained with a cable core as per Fig. 2 of the drawings apply with equal force to the auxiliary two-wire circuits DD' and FF' of Fig. 19 and Fig. 20 of the drawings, which are used when the various separate cores in the cable are arranged in accordance with Fig. 3A of the drawings.

Referring again to Fig. 11 of the drawings, the extent to which and the manner in which the 4-wire unbalances of the auxiliary 4-wire circuit terminated at DD' can be reduced are shown in Table XVIII and illustrated in Fig. 17 of the drawings. In the case of the 4-wire auxiliary circuit of Fig. 20 of the drawings terminated at BB'

I have found that an auxiliary circuit of this type can be derived which is almost of as high quality as the inherently balanced fundamental 4-wire circuit terminated at CC' in Fig. 11 of the drawings. This result can be accomplished if the two 4-wire auxiliary possibilities of Fig. 20 of the drawings, one terminated at BB' and the other at CC' are used alternately for immediately adjacent units in horizontally or vertically located 3-wire units. With such an arrangement, the mutual capacity unbalance between 4-wire units which are immediately adjacent is actually zero in any length of cable which includes two sections of equal length separated by a "Z" transposition.

In order to help in an understanding of the manner in which the difficulties due to capacity and mutual reactance unbalances are removed or reduced to negligible amounts with the 4-wire two-way system first disclosed in this specification, the following analysis for a two-wire circuit is presented as a basis of comparison. Fig. 1 of the drawings shows two adjacent No. 19 B. & S. gauge pairs. It is assumed that wires 3, 4 are subject to interference from wire 2. There will be two different effects, as well known, when an alternating current is allowed to flow in wire 2.

1. An induced current effect upon wires 3, 4 due to the reactance unbalance between the system of wires 2 and 3, 4.

2. A direct potential effect, due to capacity unbalance between the system of wires 2 and 3, 4.

The capacity unbalance effect is computed using the Pender-Osborne formula (Electrical World, vol. 56, p. 667, also Electricity and Magnetism by Pender, page 40, 1919 edition), giving the mutual capacity between two wires—

$$(1)\qquad C=\frac{.0447K}{\cosh=1\left(\frac{D}{2r}\right)}\ \text{microfarads per mile}$$

where

K=specific dielectric capacity
D=distance between centers of wires considered.
r=radius of wires.

The mutual reactance effect is computed using the following formula (see Bulletin of the U. S. Bureau of Standards, vol. 8, No. 1, p. 15) for the coefficient of mutual inductance between two wires, of length (l) separated by a distance (d)

$$M=2l\left(\log 2\frac{l}{d}-1+\frac{d}{l}\right)$$

The mutual inductance between wire 2 and a pair of wires 3, 4 where wire 3 and wire 4 represent the two sides of a metallic circuit with distances d_1 and d_2 from wire 2, respectively, is given by the following equation

$$M=2l\left(\log\frac{d_1}{d_2}+\frac{d_1-d_2}{l}\right)$$

If wires 3, 4 are twisted around each other, this is equivalent to stating that both wire 3 and wire 4 are rotating around a common center O_2. See Fig. 1 of the drawings for a visual illustration. Under these conditions when wires 3 and 4 interchange positions, both the capacity unbalance and the reactance unbalance figures change in sign. It is also evident that for each position of wires 3 and 4, as defined by the angle θ of Fig. 1 of the drawings, there will be a different capacity unbalance and a different reactance unbalance figure. The actual computations, when carried out both for wires 1 and 2, result in the following capacity unbalance figures for the system of wires 1, 2, 3, 4 in function of the angle θ, when the angle φ is taken equal to zero.

TABLE I

CAPACITY UNBALANCE IN MICROMICROFARADS PER MILE

Systems (1, 2)—(3, 4)

Angle θ	Capacity unbalance (1)−(3,4)	Mutual capacity (2)−(3,4)	Capacity unbalance (1,2)−(3,4)
0	5,770	−17,600	−11,830
30°	4,900	−14,060	−9,160
45°	3,910	−10,060	−6,750
60°	2,500	−7,050	−4,550
90°	0	0	0
120°	−2,500	+7,050	+4,550
135°	−3,910	+10,060	+6,750
150°	−4,900	+14,060	+9,160
180°	−5,770	+17,600	+11,830

The unbalance values for relative angles between the two systems of wires included in the range 180°–360° are symmetrical to those shown in the above table, with reference to $\theta=180°$. The corresponding data for inductive reactance is of similar type to that shown above for capacity unbalance.

The final values indicated in Table I, when plotted, show a form very similar to a cosine curve. An analysis carried out by Fourier's method showed that the following series could be used to represent the residual capacity unbalance figures between the systems of wires 1, 2 and 3, 4 in function of the angle θ defining the relative angle between these two systems.

Capacity unbalance of 1, 2—3, 4 equals

$$-(10{,}695\cos\theta+873\cos 3\theta+219\cos 5\theta+\ldots)$$

The (−) sign is used, since we assumed wire 2 to have a negative instantaneous voltage at the origin of time and this wire has the dominating influence over the system 3, 4 in view of its closer proximity for θ=zero. The analysis showed no sine components and no terms in even powers of θ in the cosine series. In terms of the fundamental component in cos θ, the succeeding higher order odd harmonics are quite small. Expressed in percentage of the maximum unbalance the above series can be put in the form—

$$(3)\quad \text{Capacity unbalance}=-11{,}830\ (.904\cos\theta+.0738\cos 3\theta+.0185\cos 5\theta+\ldots)$$

The above series development was worked out on the basis that wires 1, 2 were stationary and had no twist, while wires 3, 4 had a definite twist thereby bringing about a rotation of these wires with reference to wires 1, 2. Under these circumstances, for a variation of 180° in the value of θ for one-half of a cycle, the net capacity unbalance between the two systems of wires would be exactly equal to zero, provided further certain other physical factors could be kept absolutely constant, such as distance between each of the wires 1, 2 taken separately and each of the wires 3, 4 also taken separately. With only paper insulation loosely wound around each wire as separators, this is not quite so easy to provide. Furthermore it is not feasible to provide complete twists or half-twists between successive splices of cable on all pairs in said cable. Since, in addition to the above points, the cable contains more than two pairs and a limited number of twists lengths are available in cable manufacturing machinery, all pairs in a cable are provided with a

twist or lay, several such twist lengths being used for any cable. If, therefore, both wires 1, 2 and 3, 4 are provided with twists, then for any change in angle θ of wires 3, 4 there will be a corresponding change in the angle φ between the line of centers O_1O_2 and the line joining the centers of wires 1 and 2. For any change in the angle φ, a new table of unbalance values will hold similar to Table I and the simple conclusion that for a change of 180° in the value of θ a perfect balance will be obtained between the system of wires 1, 2 and 3, 4 will hold no longer. This point can be understood more clearly if reference is made to the variation of the distance between any one wire of the first system of wires, such as wire 1 and any other wire of the second system as a double function of both θ and φ. The complete expression for the distance D between wire 1 and wire 3 is given by the equation:

$$(4)\quad D^2=D_0^2+2r_1D_0(\cos\varphi-\cos\theta)+2r_1^2(1-\cos(\theta-\varphi))$$

where $D_0=O_1O_2$, $r_1=$ distance between the center O_1 and the center of wire 1 which is also the distance between the center O^1 and the center of wire 3. The distances between the other wires of the system 1, 2, 3, 4 can be obtained by suitable changes in the signs of the coefficients of $\cos\varphi$, $\cos\theta$, &c. It is important to note that if only $\cos\theta-\varphi$ had appeared in the expression for D^2 then the whole problem would be simplified into that of one system of wires rotating relatively with reference to the second system of wires considered as stationary. This is not, however, the case. Actually, in practice, as already pointed out, considerable difficulty is being experienced with the present day system of cable conductors with different lengths of twist on adjacent pairs, particularly when used for carrier purposes. This question will not be dealt with in any further detail here except to point out that the latest quantitative measurements on this subject will be found in the Bell System Technical Journal, Oct. 1939, in a paper bearing the title, "Experience in applying carrier telephone systems to toll cables" by W. B. Bedell, G. B. Ransom and W. A. Stevens. Table I.

The above outline of the present day cable arrangements has been given in order to make possible a clear understanding of the novel features of the invention as fully described hereinbelow. I find, as previously stated, that if the number of wires provided for a two-way circuit is increased from two to four and these wires are arranged, as shown in one form of the invention, on Fig. 2 of the drawings, and used as shown on Fig. 4 of the drawings, then under certain conditions which will be described in detail, there will be no coefficient of coupling between two adjacent two-way circuits, assuming each such two-way circuit to be formed of 4-wires, with polarities disposed alternately positive and negative. The four (4) wires would be disposed at the four corners of a perfect square. The four constituent wires of the two-way circuit would be insulated separately and then combined into a symmetrical 4-wire unit or quad arrangement as shown on Fig. 2 of the drawings. The four wires would be maintained at fixed space relations with reference to each other by means of a wrapping of paper or a string spirally applied or any other suitable insulating separators. Designating the constituent wires of one such system as 1, 2, 3 and 4, and those of an adjacent system as 5, 6, 7 and 8, then wires 1 and 3 in the first unit would represent, in combination, one side of a two-way circuit, as used for carrier purposes, and wires 2 and 4 would form the opposite side. Similarly, wires 5 and 7 would form one side and wires 6 and 8 the opposite side in the second unit. It is important to note that as we go around in the first unit starting with wire 1 and assuming wire 1 to have a positive potential at a given instant of time, then we have the following sequences in signs—(+), (−), (+), (−) for wires 1, 2, 3 and 4 respectively. Correspondingly, we have a similar set of sequences (+), (−), (+), (−) for wires 5, 6, 7 and 8 respectively. It is necessary in order to understand the invention, to work out the capacity unbalance between the four wires of one unit 1, 2, 3, 4, and the four wires of an adjacent unit such as 5, 6, 7, 8. Referring to Fig. 7 of the drawings, let O_1 represent the center of the first unit and O_2 the center of the second unit. Let C_1 represent the center of wire 1 and C_5 the center of wire 5. Let φ represent the angle made by O_1O_2 with O_1C_1 and θ represent the angle made by O_1O_2 with O_2C_5. I find that the most convenient way of defining the capacity between a fixed location for wire 1 and any variable location for wire 5 in the second unit, is to express said mutual capacity as a function of the angle $\theta-\theta_1$ shown on Fig. 7 of the drawings by the following Fourier series development.

$$(5)\quad C_{15}=C_0+C_1\cos(\theta-\theta_1)+C_2\cos 2(\theta-\theta_1)+C_3\cos 3(\theta-\theta_1)+C_4\cos 4(\theta-\theta_1)+\ldots$$

When the capacity C_{15} is expressed as a function of the angle $\theta-\theta_1$ and of its various harmonics, all sine terms disappear from the Fourier series development. This is due to the fact that the distance D_{15} between wires 1 and 5 is exactly the same whether $\theta-\theta_1$ has a positive or an equal negative value. This is almost self-evident and can be immediately checked by reference to the relation:

$$(6)\quad D_{15}^2=(C_1O_2)^2-2r_1(C_1O_2)\cos(\theta-\theta_1)+r_1^2$$

where r_1 represents the distance C_2O_2 $\theta-\theta_1$ changes sign, $\cos\theta-\theta_1$ does not change in sign and D_{15} retains its original numerical value. Therefore, the capacity C_{15} which depends directly upon the distance D_{15} also remains the same. If, for purposes of greater generality, the usual sine terms of a complete Fourier series development had been included in the above expression for C_{15} then if $\theta-\theta_1$ were changed in sign, all such sine terms would also change in sign, while all the cosine terms would retain their original value intact. Since, as just demonstrated, the numerical value of C_{15} will not change, under the assumption that $\theta-\theta_1$ has changed in sign without changing in numerical value, it follows that all sine terms in the Fourier series development have zero coefficients. It may be recalled here that the actual computed values of capacity relations between two adjacent cable pairs as depicted on Fig. 1 of the drawings and as expressed by Equation 3 does not contain any sine terms either. The above demonstration as to the underlying reasons for the absence of the sine terms in the Fourier series development in Equation 5 shows this condition to be a general one, provided capacity relations are defined and expressed in function of the angle $\theta-\theta_1$, the angle made by O_2C_2 with the straight line joining the center C_1 of wire 1 with the center O_2 of the second adjacent unit of 4 wires (see Fig. 7 of the drawings).

The following tables, Table II to Table V, in

clusive, indicate the computed values of the actual capacities between wires 1, 2, 3 and 4 with wires 5 and 7, when wire 5 is at its shortest possible distance from wires 1, 2, 3 and 4 respectively, and wire 7 is at its most distant location from the same wires. The situation just outlined holds when in Formula 5, $\theta-\theta_1=0$. The computations referred to have been carried out for two adjacent 4-wire units, built in accordance with Fig. 2 of the drawings, consisting of four 19 B. & S. gauge paper insulated conductors, the distance between adjacent units being equal to .16 inch and the distance between any one conductor and the geometrical center of its corresponding 4-wire combination equal to .0468 inch.

TABLE II

CAPACITY IN MICROMICROFARADS PER MILE OF WIRE 1

Angle φ	Wire 5	Wire 7	Difference
0°	29,651	24,387	5,264
15°	29,761	24,432	5,329
30°	30,097	24,580	5,517
45°	30,677	24,804	5,873
60°	31,545	25,135	6,410
90°	34,392	26,110	8,282
120°	39,454	27,538	11,916
135°	43,101	28,233	14,868
150°	46,775	28,938	17,845
180°	52,790	29,651	23,139
210°	46,775	28,938	17,845
225°	43.101	28,233	14,868
240°	39,454	27,538	11,916
270°	34.392	26,110	8,282
300°	31,545	25,135	6,410
315°	30,677	24,804	5,873
330°	30.097	24,580	5,517
345°	29,761	24,432	5,329
360°	29,651	24,387	5,264

TABLE III

CAPACITY IN MICROMICROFARADS PER MILE OF WIRE 3

Angle φ	Wire 5	Wire 7	Difference
0°	52,790	29,651	−23,139
15°	51,141	29,458	−21,683
30°	47,316	28,938	−17,845
45°	43,101	28,233	−14,868
60°	39,454	27,538	−11,916
90°	34,392	26,110	−8,282
120°	31,545	25,135	−6,410
135°	30,677	24,804	−5,873
150°	30,097	24,580	−5,517
180°	29,651	24,387	−5,264
210°	30,097	24,580	−5,517
225°	30,677	24,804	−5,873
240°	31,545	25,135	−6,410
270°	34,392	26,110	−8,282
315°	43,101	28,233	−14,868
330°	46,775	28,938	−17,845
345°	51,141	29,548	−21,683
360°	52,790	29,651	−23,139

TABLE IV

CAPACITY IN MICROMICROFARADS PER MILE OF WIRE 2

Angle φ	Wire 5	Wire 6	Difference
0°	34,392	26,110	8,282
15°	35,577	26,751	9,826
30°	39,454	27,538	11,916
45°	43,101	28,233	14,868
60°	46,775	28,938	17,845
90°	52,790	29,651	23,139
120°	46,775	28,938	17,845
135°	43,101	28,233	14,868
150°	39,454	27,538	11,916
180°	34,392	26,110	8,282
210°	31.545	25,135	6,410
225°	30,677	24,804	5,873
240°	30,097	24,580	5,517
270°	29,651	24,387	5,264
300°	30,097	24,580	5,517
315°	30,677	24,804	5,873
330°	31,545	25,135	6,410
360°	34,392	26,110	8,282

TABLE V

CAPACITY IN MICROMICROFARADS PER MILE OF WIRE 4

Angle φ	Wire 5	Wire 6	Difference
0°	34,392	26,110	−8,282
15°	32,751	25,570	−7,181
30°	31,545	25,135	−6,410
45°	30,677	24,804	−5,873
60°	30,097	24,580	−5,517
90°	29,651	24,387	−5,264
120°	30,097	24,580	−5,517
135°	30,677	24,804	−5,873
150°	31,545	25,135	−6,410
180°	34,392	26,110	−8,282
210°	39,454	27,538	−11,916
225°	43,101	28,523	−14,868
240°	46,775	28,938	−17,845
270°	52,790	29,651	−23,139
300°	46.775	28,938	−17,845
315°	43,101	28,523	−14,868
330°	39,454	27,538	−11,916
345°	36,577	26,751	−9,826
360°	34,392	26,110	−8,282

To secure a general relation for capacity unbalance between two adjacent cable units of the type described in these specifications as depicted on Fig. 2 of the drawings, and as used in the manner first shown on Fig. 4 of the drawings, we make use of the Fourier series development given by Equation 5 in the manner outlined below. The mutual capacities of wire 1 and wires 5, 6, 7 and 8 can be written down as follows, for any position of wire 5 defined by the angle θ, Fig. 5:

$$C_{15}=C_0+C_1\cos(\theta-\theta_1)+C_2\cos 2(\theta-\theta_1)+C_3\cos 3(\theta-\theta_1)+C_4\cos 4(\theta-\theta_1)+\ldots$$

$$C_{16}=C_0+C_1\cos\left(\theta-\theta_1+\frac{\pi}{2}\right)+C_2\cos 2\left(\theta-\theta_1+\frac{\pi}{2}\right)+C_3\cos 3\left(\theta-\theta_1+\frac{\pi}{2}\right)+C_4\cos 4\left(\theta-\theta_1+\frac{\pi}{2}\right)+\ldots$$

$$C_{17}=C_0+C_1\cos(\theta-\theta_1+\pi)+C_2\cos 2(\theta-\theta_1+\pi)+C_3\cos 3(\theta-\theta_1+\pi)+C_4\cos 4(\theta-\theta_1+\pi)+\ldots$$

$$C_{18}=C_0+C_1\cos\left(\theta-\theta_1+3\frac{\pi}{2}\right)-C_2\cos 2\left(\theta-\theta_1+3\frac{\pi}{2}\right)+C_3\cos 3\left(\theta-\theta_1+3\frac{\pi}{2}\right)+C_4\cos 4\left(\theta-\theta_1+3\frac{\pi}{2}\right)+\ldots$$

The above set of equations can be simplified into:

$$C_{15}=C_0+C_1\cos(\theta-\theta_1)+C_2\cos 2(\theta-\theta_1)+C_3\cos 3(\theta-\theta_1)+C_4\cos 4(\theta-\theta_1)+\ldots$$

$$C_{16}=C_0-C_1\sin(\theta-\theta_1)-C_2\cos 2(\theta-\theta_1)+C_3\sin 3(\theta-\theta_1)+C_4\cos(\theta-\theta_1)+\ldots$$

$$C_{17}=C_0-C_1\cos(\theta-\theta_1)+C_2\cos 2(\theta-\theta_1)-C_3\cos 3(\theta-\theta_1)+C_4\cos 4(\theta-\theta_1)+\ldots$$

$$C_{18}=C_0+C_1\sin(\theta-\theta_1)-C_2\cos 2(\theta-\theta_1)-C_3\sin 3(\theta-\theta_1)+C_4\cos 4(\theta-\theta_1)+\ldots$$

If wires 5, 6, 7 and 8 are used in the manner as first disclosed in these specifications, and as shown on Fig. 4 of the drawings, then wires 5 and 7 will have instantaneous potentials impressed upon them which will be of opposite sign to the instantaneous potentials impressed upon wires 6 and 8. The capacity unbalance between wire 1 and wires 5, 6, 7 and 8 of an adjacent two-way circuit will be given:

$$C(1)-(5,6,7,8)=C_{15}-C_{16}-C_{17}-C_{18}$$

Hence, inserting the values of C_{15}, C_{16}, etc. as above shown into the preceding equation:

(7) $C(1)-(5,6,7,8)=4C_2\cos 2(\theta-\theta_1)+4C_6\cos 6(\theta-\theta_1)+4C_{10}\cos 10(\theta-\theta_1)-\ldots$

It is interesting to note that the capacity unbalance of wire 1 with the system 5, 6, 7, 8 contains neither C_0 nor C_1. The full complement of unbalance equations involved is given by the following set, for wires 1, 2, 3, and 4, respectively:

(7) $C_1-(5,6,7,8)=4C_2^1\cos 2(\theta-\theta_1)+4C_6^1\cos 6(\theta-\theta_1)+4C_{10}^1\cos 10(\theta-\theta_1)+\ldots$

(8) $C_2-(5,6,7,8)=4C_2^2\cos 2(\theta-\theta_2)+4C_6^2\cos 6(\theta-\theta_2)+4C_{10}^2\cos 10(\theta-\theta_2)+\ldots$

(9) $C_3-(5,6,7,8)=4C_2^3\cos 2(\theta-\theta_3)+4C_6^3\cos 6(\theta-\theta_3)+4C_{10}^3\cos 10(\theta-\theta_3)+\ldots$

(10) $C_4-(5,6,7,8)=4C_2^4\cos 2(\theta-\theta_4)+4C_6^4\cos 6(\theta-\theta_4)+4C_{10}^4\cos 10(\theta-\theta_4)+\ldots$

Once the position of wire 1 in unit 1, 2, 3, 4 is set, the angles θ_1, θ_2, θ_3 and θ_4 can be immediately determined. For instance, the angle θ_1 is determined from the simple equation:

$$\sin\theta_1=\frac{r_1}{D_1}\sin\varphi_1$$

Where D_1 is the distance C_1O_2 of Fig. 7 of the drawings. The distance D_1 or C_1O_2 is given by:

(11) $$D_1^2=D_0^2+2r_1D_0\cos\varphi_1+r_1^2$$

where D_0=Distance O_1O_2.

Similar relations are obtained for sin θ_2, sin θ_3, etc. bearing in mind that

$$\varphi_2=\varphi_1+\frac{\pi}{2},\ \varphi_3=\varphi_1+\pi \text{ and } \varphi_4=\varphi_1+3\frac{\pi}{2}.$$

If we abbreviate the final unbalance relation between the systems of wires 1, 2, 3 and 4 and 5, 6, 7 and 8 by using the expression

$$C(1,2,3,4)-(5,6,7,8)$$

to represent said unbalance, then:

(12) $C(1,2,3,4)-(5,6,7,8)=C(1)-(5,6,7,8)+C(2)-(5,6,7,8)+C(3)-(5,6,7,8)+C(4)-(5,6,7,8)$

The unbalances just written down are obtained from Equations 7 to 10, inclusive.

For any one wire, such as wire 1, the capacity coefficients such as C_2^1, C_6^1 for the second and sixth harmonics respectively are obtained by Fourier's method. These coefficients actually vary with the position of wire 1 as defined by the angle φ and for each such position a separate Fourier analysis is involved. For each value of φ, furthermore, a separate Fourier analysis is required for each wire in the unit 1, 2, 3, 4. For $\varphi=0$, the following table indicates the several components of the capacity unbalance for each wire in the unit 1, 2, 3, 4 with reference to the system 5, 6, 7, 8, in m. m. f. per mile.

TABLE VI

HARMONIC COMPONENTS OF CAPACITY UNBALANCE OF SYSTEM 1, 2, 3, 4 WITH REFERENCE TO SYSTEM 5, 6, 7, 8

	Wire 1	Wire 2	Wire 3	Wire 4
C_2	416	829	3,503	829
C_6	$\frac{11}{12}$	$3\frac{5}{6}$	113	$3\frac{5}{6}$
C_{10}	$-\frac{13}{120}$	$\frac{11}{24}$	6	$\frac{11}{24}$

The above values are those required in conjunction with the application of Formulas 7–10, inclusive.

The particular advantage of the Fourier series development in the present case consists in the possibility it affords to express the capacity unbalances involved as continuous functions of θ. The importance of this point will be made clear hereinbelow.

It is of interest here to observe that the coefficient of cos 10θ is exceedingly small with reference to the coefficient of cos 2θ, and the coefficients of all higher harmonics will be smaller still and therefore are entirely negligible.

If the substitutions indicated in Equation 12 are carried out, bearing in mind Equations 7, 8, 9, 10, an expression is derived for the capacity unbalance between the two systems of wires 1, 2, 3, 4 and 5, 6, 7, 8, respectively, when used in the manner described hereinabove, which can be simplified into the following form:

$$C(1,2,3,4)-(5,6,7,8)=A_2\cos 2\theta+B_2\sin 2\theta+F(\varphi,\theta)$$

where

(14) $A_2=4C_2^1\cos 2\theta_1-4C_2^2\cos 2\theta_2+4C_2^3\cos 2\theta_3-4C_2^4\cos 2\theta_4$

(15) $B_2=4C_2^1\sin 2\theta_1-4C_2^2\sin 2\theta_2+4C_2^3\sin 2\theta_3-4C_2^4\sin 2\theta_4$

(16) $F(\varphi,\theta=A_6\cos 6\theta+B_6\sin 6\theta+A_{10}\cos 10\theta+B_{10}\sin 10\theta+\ldots$

The coefficients A_2, B_2, A_6, B_6 are all dependent upon φ and therefore in order to obtain the required capacity unbalance information, it becomes necessary to carry out the computations for a number of values of φ. As already pointed out the various harmonics of C_2 have coefficients which are quite small with reference to the coefficient C_2. The largest one, the sixth harmonic, has a coefficient which is less than 3.2% of the controlling coefficient which is C_2. The succeeding harmonics are so small as to be entirely negligible. If, therefore, we concentrate our attention upon the dominating term in cos 2θ and sin 2θ in Formula 13, we can show that the capacity unbalance between two adjacent 4-wire units such as 1, 2, 3, 4 and 5, 6, 7, 8 can be completely annulled, if the angle 2θ is so chosen that:

(17) $$A_2\cos 2\theta+B_2\sin 2\theta=0$$

Calling

$$\frac{A_2}{B_2}=\tan 2\theta_n$$

the above Equation 17 can be put in the following form:

(18) $$\sqrt{A_2^2+B_2^2}\sin 2(\theta+\theta_n)=0$$

Therefore, for any position of wires 1, 2, 3, 4 as defined by the angle φ, there will be a corresponding position of wires 5, 6, 7, 8 as defined by the angle θ_n such that there will exist no capacity unbalance between the above set of wires when used in the manner indicated on Fig. 4 of the drawings. I have called the angle θ_n of unit B the "neutralization angle" of said unit B when considered in conjunction with unit A set at the angle φ with reference to the line joining the centers of units A and B.

It will be noted by reference to Equation 18 that as a matter of fact, for any angle φ of unit A there are actually four positions of unit B which result in zero coupling between the wires

of said units, as defined by the following angles θ of unit B:

1. $\theta+\theta_n=0$
2. $\theta+\theta_n=90°$
3. $\theta+\theta_n=180°$
4. $\theta+\theta_n=270°$

The various angles θ_n are, as clearly evident from the above, separated from each other by 90°.

The type of computations, very briefly sketched hereinabove, were carried out for a number of values of the angle φ, defining the position of wires 1, 2, 3, 4. While the computations are lengthy and tedious, they are perfectly straightforward. I find that the relation between the angle φ of unit A and the angle θ defining the position of wires 5, 6, 7, 8 in an adjacent unit B, which results in zero capacity unbalance between these two units is a straight line inclined at a 45 degree angle, starting at $\theta=-45$ degrees for $\varphi=0$ (see Equation 19) with a periodic superimposed function $F_1(\varphi)$ of low amplitude crossing the straight line at intervals separated by an angle of 45 degrees. The period of this superimposed function, which is illustrated on Fig. 8 of the drawings, is 90 degrees. This function $F_1(\varphi)$ has an important bearing upon the solutions, and the possibilities of solution, to the general problem of obtaining cable or wire arrangements with zero coupling between the wires of these cable arrangements. I have called this function $F_1(\varphi)$—the "distortion function" as illustrated on Fig. 8 of the drawings. The higher the amplitude of the particular $F_1(\varphi)$ function involved, the greater is the difficulty of obtaining mutually non-reactive circuits. Fortunately, for the case of the arrangement of Fig. 4 of the drawings, the highest amplitude of the function $F_1(\varphi)$ for horizontally or vertically adjacent units is 3° 51', which represents the value finally obtained when account is taken not only of the terms included in Equation 18 but all other harmonics as expressed by Equation 17.

The general relation between θ and φ, which results in zero coupling between units A and B when used as shown on Fig. 4 of the drawings, is given analytically by Equation 19:

$$\theta=-45°-\varphi+F_1(\varphi) \tag{19}$$

The "distortion function" (see Fig. 8) has a numerical value equal to zero for $\varphi=0$, $\theta=45°$, $\varphi=90°$, etc. Broadly speaking once a position of complete neutralization is reached, a positive change in the angle of one unit can be compensated by a change in the opposite direction for the position angle θ of the adjacent unit. The following table indicates the numerical values of $\sqrt{A^2+B^2}$ and θ_n for nine (9) consecutive values of φ.

TABLE VII

AMPLITUDES AND NEUTRALIZATION ANGLES ADJACENT UNITS—HORIZONTAL OR VERTICAL

φ	$\sqrt{A^2+B^2}$	θ_n
	M. m. f.	
0°	10,544	−45° 0′ 0″
15°	9,476	−56°29′26″
22½°	8,398	−62°53′ 1″
30°	6,944	−71°50′ 5″
45°	6,356	−90° 0′ 0″
60°	6,944	−108° 9′55″
67½°	8,398	−117° 6′59″
75°	9,476	−123°30′34″
90°	10,544	−135° 0′ 0″

The above values of $\sqrt{A^2+B^2}$ repeat themselves in cyclic variations for increments of φ, $\varphi=90°$. The consideration of the data shown on Table VII hereinabove and reproduced on Fig. 8 of the drawings, combined with the facts developed hereinbelow show, that if we were dealing with a number of 4-wire units arranged in a single layer in the form of a ribbon between two points in space, then there would be an infinite number of ways in which a completely neutralized system of 4-wire units could be obtained. A preferred form, for such cases, is secured by making $\theta=\varphi$, in Equation 19. This means that all units in the single layer ribbon would be set in parallel to each other. Under the assumption just made, we obtain:

$$2\varphi=-45°+F_1(\varphi)+m\frac{\pi}{2} \tag{20}$$

or

$$\varphi=-22°30'+\frac{1}{2}F_1(\varphi)+m\frac{\pi}{4}$$

where m may take the values 0, 1, 2, etc. The value of φ required is readily obtained by finding the intersection of the straight line $2\varphi-45$ with the curve $F_1(\varphi)$ given on Fig. 8 of the drawings. The value thus obtained is $\theta_n=+24°25'$ for $m=1$. There are, in all, eight (8) different neutralization angles which are obtained by assigning to m in Equation 20 the values $m=1$, $m=2$, etc.

In practice, where cabling is involved, wires must be considered as set up in several layers. This condition, I find, presents some real complications, and I have indicated hereunder the complete solutions to the problems involved. I have taken as a specific example multiple layers of 4-wire units, arranged in rectangles or squares. This is just one of many possible forms in which 4-wire units may be assembled. The particular procedure indicated hereinbelow for the first time in the art, can be used to develop proper angles of neutralization for any type of cabling or assembling together of 4-wire units. Several new sets of "neutralization angles," must be considered in addition to the one considered in the case of a single layer. I have worked out and shown in Tables VIII and IX the values of the neutralization angles for the following two cases:

Table VIII—Neutralization angles between diagonally adjacent units.

Table IX—Neutralization angles between horizontal or vertical units separated by an intervening unit.

Reference may be made to Fig. 10 of the drawings for the physical relationships involved. In the case of Table VIII the separation involved is $\sqrt{2}D_0$, where D_0 is the distance between centers of two horizontally or vertically adjacent units. In the case of Table IX, the separation involved is $2D_0$.

TABLE VIII

AMPLITUDES AND NEUTRALIZATION ANGLES—DIAGONALLY ADJACENT UNITS

φ	$\sqrt{A^2+B^2}$	θ_n
	M. m. f.	
0°	1,162	−45° 0′ 0″
15°	1,107	−57° 20′ 37″
30°	973	−72° 6′ 30″
45°	902	−90° 0′ 0″
60°	973	−107° 53′ 30″
75°	1,107	−117° 39′ 23″
90°	1,162	−135° 0′ 0″

TABLE IX

AMPLITUDES AND NEUTRALIZATION ANGLES—UNITS SEPARATED BY ONE HORIZONTALLY OR VERTICALLY INTERVENING UNIT

φ	$\sqrt{A^2+B^2}$	θ_n
0°	183	−45° 0′ 0″
15°	179	−57° 46′ 45″
30°	162	−72° 35′ 43″
45°	153	−90° 0′ 0″
60°	162	−107° 24′ 17″
75°	179	−117° 13′ 15″
90°	183	−135° 0′ 0″

Comparing the data shown on Tables VII, VIII and IX, it is important to note:

1. The rapid decrease in the "typical unbalance" figures as shown in the second column in these tables. For example, the increase in distance from D_0 to $\sqrt{2}D_0$ brings about a drop from 10,544 m. m. f. per mile to 1,162 m. m. f. per mile, and an increase in distance from D_0 to $2D_0$ brings about a drop from 10,544 to only 183. These represent decreases, as expressed in decibels, of 19 db. and 35 db., respectively.

2. The "neutralization angles" are practically the same whether the separation is D_0, $\sqrt{2}D_0$ or $2D_0$. See Fig. 8 of the drawings.

The coefficients of typical unbalance, as noted in the tables, are of some importance, as the mutual interference between two four-wire units is directly proportional to said coefficients of typical unbalance as indicated by Equation 18, in case the 4-wire units are not arranged with reference to each other at the particular angle θ_n which completely "neutralizes" the mutual interference between the two units.

3. The typical unbalance of the 4-wire unit, with reference to a similar adjacent unit, is actually less than that between two adjacent 19 B. & S. gauge conductors. This will be clear by reference to Table I.

Considering the situation, as represented by Fig. 9 of the drawings, wherein four adjacent units are designated as A, B, C and D, it is necessary to recall that no difficulty whatsoever is experienced in so arranging the relative angular positions of units B and C with reference to unit A, so that there will exist no "coupling" coefficient of mutual interference between A and B or A and C, respectively. In fact, the number of arrangements which can be used is infinity. However, there are definite restrictions that have to be observed in the particular dispositions of the various 4-wire units in order to reduce the mutual interference between diagonally located units, A and D, also B and C, to zero. I have discovered that there are a limited number of arrangements which will achieve the following specific results:

(*a*) No mutual interference between adjacent units aligned in a vertical or horizontal row, i.e. between A and B or A and C.

(*b*) No mutual interference between any units located in a vertical or horizontal row, whether they are separated with one or more intervening units.

(*c*) A very small minimum coupling coefficient, for any given stretch of cable between successive splices, of equal absolute numerical value between diagonal units A and D, also between B and C.

(*d*) The small minimum residual unbalance between diagonal units for a given length of cable can be annulled on a succeeding section of cable of equal length by suitable transposition of wires at the junction of two consecutive lengths of cable.

It must be evident that with the possibilities of satisfying all four requirements *a*, *b*, *c* and *d* as set forth hereinabove, an ideal solution has been obtained for the construction of high frequency transmission channels with zero coupling coefficient between these channels. Taking up in sequence the various points mentioned above, the possibility of satisfying the requirement of paragraph *a* has been demonstrated by Equation 18. The possibility of satisfying the requirement of paragraph *b* has also been established in the review of the ribbon type single layer cable.

Considering next the conditions to be satisfied for zero coupling between adjacent units when these are located as shown on Fig. 9 of the drawings and calling φ, θ, ψ, and F the angles made by units A, B, C and D, respectively, as defined on said Fig. 9 of the drawings, the conditions of balance between units A and B also between A and C, require:

$$\theta = -(45+\varphi) + F_1(\phi) + m\frac{\pi}{2} \tag{21}$$

$$\psi 90 = -(45+\varphi-90) + F_1(\varphi-90) + n\frac{\pi}{2} \tag{22}$$

It must be borne in mind that the period in the cycle variation of the function $F_1(\varphi)$ is 90° and that the same function is symmetrically opposed with reference to the 45° point, i. e. we can write:

$$F_1(\varphi) = F_1(\varphi-90) = F_1(\varphi+90) \tag{23}$$

$$F_1(45-\varphi) = -F_1(45+\varphi) \tag{24}$$

(See Table VII for basic data.)

Since φ is included in both Equations 21 and 22, we establish a relation between θ and φ, as follows, bearing in mind Equation 23.

$$\theta = \psi + (m-n-2)\frac{\pi}{2} \tag{25}$$

In the above equation m and n are arbitrary entire numbers.

Thus, in order to avoid inductive interference between units A and B as well as between A and C, the angle θ of unit B must be set either parallel to or at right angles to the angle ψ of unit C.

The conditions required to satisfy zero coupling between unit B on one hand and units A and B on the other hand are given by:

$$\varphi - 180 = -(45+\theta-180) + F_1(\theta-180) + m^1\frac{\pi}{2} \tag{26}$$

$$F - 90 = -(45+\theta-90) + F_1(\theta-90) + n^1\frac{\pi}{2} \tag{27}$$

Eliminating θ between Equations 26 and 27, a necessary relation is obtained as follows:

$$F = \varphi - (m^1-n^1+2)\frac{\pi}{2} \tag{28}$$

In the above relation, as previously in Relation 25, m^1 and n^1 represent arbitrary entire numbers.

We see again that to obtain zero coupling between B and A and between B and D, the angle F of unit D must be either parallel to or at right angles to the angle φ of unit A. We complete the survey of balance conditions for the square A, B, C, D with an equation exactly similar to Equation 25, when we write down the condition for freedom from interference between D and B also D and C.

In view of all the points brought out above, it follows that once we decide upon the angle φ, we can obtain complete neutralization between units A and B by choosing the proper value of θ for unit B from Equation 21 and by aligning unit C in parallel to θ (or at right angles thereto), we eliminate inductive couplings between A and C. From Equation 28 we deduce the conclusion that to secure zero coupling between units B and D it is sufficient and necessary to align unit D with an angle F parallel to (or at right angles to) the angle φ of unit A. If the angles φ, θ, ψ and F have been chosen in accordance with the above, then there will also be no coupling between units C and D. Thus we have one degree of freedom left in the choice of φ.

In the consideration of the balance conditions between units A, B, C and D on the basis of horizontal or vertical relationships, we gave no weight to the diagonal situations AD and BC. In order to obtain zero coupling between units A and D, we must have:

(28a)

$$F-45=-(\varphi-45+45)+F_2(\varphi-45)+r\frac{\pi}{2}$$

where r is an arbitrary entire number and $F_2(\varphi-45)$ is a superimposed function, similar to the function $F_1(\varphi)$, and is illustrated on Fig. 8 of the drawings. In view of a Equation 28, the following relation is obtained:

(29) $$2\varphi=45+F_2(\varphi-45)+m\frac{\pi}{2}$$

where m is an arbitrary entire number.

Correspondingly, the requirements for zero coupling between units B and C, which are located in diagonal relationship to each other, is given by the following:

(29a)

$$\psi-135=-(\theta-135+45)+F_2(\theta-135)+s\frac{\pi}{2}$$

where s=arbitrary entire number.

In view of Equation 25 relating together ψ and θ, we can eliminate ψ from the requirement as just set forth and we obtain an equation completely defining θ.

(30) $$2\theta=45+F_2(\theta-135)+(s+m-n)\frac{\pi}{2}$$

The simultaneous elimination of inductive couplings between AD as well as between BC would require either equality between φ and θ or a difference between φ and θ, which would be equal to a multiple of 45°, as will be made clear by comparison of Equations 29 and 30. While, as previously pointed out, we have the freedom to choose φ in order to obtain zero couplings between A and B, A and C, B and D, C and D, we have no freedom of choice about making $\theta=\varphi$. The relation between θ and φ, has to meet the requirement set forth by Equation 21. We can, if we wish, take $\theta=\varphi$ without, however, trying to satisfy Equations 29 and 30. If we do this, we get the following value for θ or φ, as obtained from Equation 21:

$$2\varphi=-45+F_1(\varphi)+m\frac{\pi}{2}$$

For convenient solution, we take $m=1$ and find for φ the value $\varphi=24°\ 25'$. There are, in this case, seven other solutions, which are obtained by adding multiples of 45° to the value just determined of $\varphi=24°\ 25'$. This value of φ—i. e. $\varphi=24°\ 25'$ will not satisfy either Equation 29 or Equation 30 and therefore it is not possible to annul all six mutual induction couplings involved in the consideration of the four units A, B, C and D. I find, however, that if the condition $\theta=\varphi$ is satisfied, then the deviation from absolute zero of the residual unbalances between units A and D on one hand and B and C on the other will be equal to each other. This is, obviously, a very definite advantage, in that, with any other arrangement either one or the other of the residual unbalances would be greatly in excess of the unbalance obtained when we make $\theta=\varphi$. The actual solution for Equations 29 and 30 results in a value of $\varphi=\theta=20°\ 48'$. The values of $F_2(\varphi-45)$ and $F_2(\varphi-135)$ are obtained from Table VIII. As the solution for obtaining zero coupling for AB, AC, BD and CD resulted in $\varphi=24°\ 25'$, we see immediately that the angle of unbalance for the diagonally located units AD and BC is equal to $24°\ 25'-20°\ 48'=3°\ 37'$. A glance at the figures given in Tables VII and VIII shows that a deviation of one degree from the neutralization angle in the case of horizontally or vertically adjacent units results in a capacity unbalance 8 times greater than for diagonally located units. It appears preferable therefore to plan for the complete neutralization of the couplings AB, AC, BD and CD by means of proper alignment of the elements or units A, B, C and D and find other means for reducing further or annulling the couplings between AD and BC. If, therefore, we accept the solution $\varphi=24°\ 25'$ which results in zero coupling between horizontally or vertically adjacent units, then the values of the angles for units A, B, C and D will be given by:

TABLE X

Unit	Angle of zero coupling
A	24° 25′
B	24° 25′
C	24° 25′
D	24° 25′

The above values take into account not only the predominating second harmonic but the sixth harmonic as well, all other harmonics being negligible in their effect. If only the second harmonic is taken into account the "neutralization angle" so obtained is 20′ larger.

When the angle φ of unit A is set at 24° 25′, the angle required at unit D to avoid coupling between these two units is obtained from Equation 28a and found equal to 17° 26′. By reference to Table VIII and bearing in mind that the applicable angle in Table VIII for the present case is $(45°-\varphi)$, we obtain the capacity unbalance equation for the combination of units AD as given by $1{,}056 \sin 2(F-F_n)$, which in the present case is equal to:

(31) Capacity unbalance=
$1.056 \sin 2\ (24°\ 25'-17°\ 26')=255$ m. m. f. per mile

Correspondingly, we obtain for the combination of diagonally located units B and C, with unit B set at an angle of 24° 25′ (see Table X), and using Equation 29a, the following "neutralization angle" ψ_n which would result in zero coupling between units B and C:

(32) $$\psi_n=-(\theta+45)+F_2(\theta-135)+(s+3)\frac{\pi}{2}$$

where

$\theta=24°\ 25'$

$\psi_n=20°\ 35'-3°\ 9'=17°\ 26'$

The capacity unbalance in the case of diagonally located units B and C is therefore exactly the same as for units A and D, i. e. is equal to 255 m. m. f. per mile, being given by Equation 31.

The residual unbalance of 255 m. m. f. per mile for the diagonally located units AD as well as BC is therefore far below the value of the "typical unbalance" figure per mile of circuit of two adjacent physical pairs in No. 19 B. & S. gauge cable of 11,830 micromicrofarads per mile (see Table XI). It is actually 33 db. below the typical unbalance figure of 19 B. & S. gauge cable pairs of the present art.

I find, further, that with the arrangement as fully disclosed hereinabove it is possible to completely eliminate all unbalances between horizontally or vertically adjacent units and one of the two diagonally located units, i. e. either AD or BC, but not both. But in such a case the combination which remains unbalanced is about twice as great as when both diagonal combinations are so chosen as to result in equal unbalances of the same amount and the same sign of —255 m. m. f., as above developed.

I have discovered also that it is possible to eliminate completely the small residual unbalance of 255 m. m. f., by the following procedure. The arrangement worked out hereinabove and shown on Table X is one wherein all four units A, B, C, D, are stacked exactly in parallel to each other. Suppose, we take unit B, and give it a 90° advance. The angle θ of this unit thus becomes 114° 25′. We will show that the residual unbalance of this unit with reference to the diagonally located unit C changes its sign, though retaining its amplitude of 255 m. m. f. We note by reference to equation 32 that ψ_n has decreased by just 90°, as the function $F_2(\theta-135)$ has a cyclical period of 90° and does not change in numerical value, if θ is increased by 90°. Hence ψ_n is now equal to 17° 26′—90° or —72° 34′. Putting this value of ψ_n into the unbalance Equation 33:

(33) —Capacity unbalance=
1056 sin $2(\psi-\psi_n)$1056 sin 2(24° 25′—72° 34′)=
—255 m. m. f.

This shift in the angle of unit B does not in any way change the balanced condition between the horizontally or vertically adjacent combinations AB, AC, etc., as definitely shown hereinabove. It follows, therefore, that if we take two sections of cable of equal length and in one section arrange the units A, B, C and D as shown in Table X, and in the succeeding place unit B with an advance of 90° in its angle O, then the combination of the two sections of cable in series will provide zero coupling between units B and C. By following the same procedure for unit D, in alternatively succeeding sections of cable, the residual unbalance of the diagonally located units A and D can also be completely eliminated. Thus all unbalances whether as between adjacent units or diagonally located units can be completely eliminated by suitable stacking or aligning of the elements A, B, C and D. I have discovered several other ways of eliminating the unbalances between diagonally located units, once the unbalances between adjacent units have been eliminated, some of which are described in detail, hereinbelow.

There remains the question whether any appreciable residual unbalances will develop between units in a row, one unit apart, such as between units A and E, or A and I, etc. To determine this point, reference is made to Table IX. To obtain zero coupling between units A and E, for instance, we must satisfy the relation:

$$\theta = -(\varphi+45)+F_3(\phi)+m\frac{\pi}{2}$$

The values of periodic function $F_3(\phi)$ are obtained from Table IX. Now, for ϕ=24° 25′, indicated in Table X, and taking m=1

$$\theta=20°35'+F_3(24°25')=20°35'+2°45'=23°20'$$

Where θ=the angle made by unit F with the line connecting the centers of units A and E. The capacity unbalance equation between the units A and E is given by:

168 sin 2(24°25′—23°20′)=166 sin 2°30′=7 M. m. f.

It will be noted that the residual unbalance is negligibly small. Even this practically negligible unbalance can be eliminated by using the procedure outlined in some detail hereinabove in conjunction with diagonally located units. It will also be noted that all other combinations in a layout of cable pairs, such as pictured on Fig. 10 of the drawings will have unbalances less than 7 m. m. f. per mile, and therefore deserve no further consideration.

It has been pointed out already that there are actually eight (8) different arrangements, similar to that shown on Table X, which will provide equivalent solutions—each of the eight arrangements being obtained by advancing the angle indicated on Table X by 45° steps.

The above complete solution was given for a specific size of wire, i. e. No. 19 B. & S. gauge, and for a specific arrangement using 4-wire units, as illustrated on Fig. 2 and Fig. 9 of the drawings. The arrangement used in actual cable make-ups will naturally differ from the one shown on Fig. 9 of the drawings. Depending upon the number of circuits provided in any given cable, there will be different angular positions between the different 4-wire units in the same or successive layers of cable. The method described hereinabove is, however, absolutely general in principle and furnishes a complete guidance as to the procedure to be followed in case the angular relations between centers of 4-wire units are different from 0°, 45° or 90° such as pictured by the layout shown on Fig. 9 of the drawings. The solution worked out in some detail, hereinabove, made use of 4-wires in the manner shown on Fig. 2 of the drawings. Several alternative arrangements of wires illustrating the general principles of the invention are shown on Fig. 3 and Fig. 3A of the present drawings. The principle followed is always the same, i. e. successive wires of the same unit or two-way transmission channel are given opposite polarities. In Fig. 3, the center wire, designated O, is merely a filler and the six (6) surrounding wires form the real unit. Instead of a single 19 B. & S. gauge wire for the center filler, it would be feasible to use a pair of #22 B. & S. gauge wires, and this pair could then be used for telephone communication purposes at speech frequencies. In Fig. 3A, the true carrier frequency unit is formed of eight (8) wires, around a central core of wires which would be devoted to ordinary speech frequency use. The number of wires which could be placed in the central core space will naturally depend upon the size or gauge of the wires therein placed. From a purely theoretical viewpoint, the greater the number of wires used to form the high frequency or carrier unit, the smaller will be the "distortion function," and the smaller the residual unbalance which must be

taken care of in one way or another. Considering for instance, the arrangement of Fig. 3A which uses 8 wires around a central core the corresponding $F_1(\varphi)$ function for such a system would have a period of 45° instead of the 90° for the arrangement of Fig. 2 of the drawings. When use is made of such a unit in the form of a cable or wiring between two points as illustrated on Fig. 9 of the drawings, then the unbalance between adjacent as well as between diagonally located units would be exactly equal to zero, if an angle of 22° 30′ (instead of the angle of 24° 25′ of Table X) were to be used. This can be proved very easily. Thus, without going into the use of a very large number of wires, but restricting ourselves to just eight (8) wires we can secure the theoretically ideal solution of zero coupling under all conditions, if the cable make-up is of the type depicted on Fig. 3A of the drawings. However, it is a distinct advantage to use as large a number of wires as eight (8) for a single circuit. I have, therefore investigated more exhaustively the 4-wire arrangement of Fig. 2 of the drawings, and have succeeded in showing that for this arrangement the "typical unbalance" can also be reduced to zero, if certain procedures are followed as fully described hereinabove.

A more general solution to the problem of a system of high frequency conductors in cable layout which is inherently free from inductive interference from adjoining systems is depicted in Fig. 3B. The arrangement here uses a hollow cylindrical structure, with an even number of segments successively designated as (+) and (−) insulated from each other. All of the segments marked (+) would be connected together to form one conductor and all of the segments marked (−) would be connected to form a second conductor. The main difficulty with this system is its mechanical rigidity.

The elimination of unbalances, as developed hereinabove, in these specifications is based upon a new system in the cable art, i. e. that of maintaining fixed space relationships between the interfering sets of wires so calculated as hereinabove set forth as to result in zero couplings between the interfering set of wires in said cable. It would also be practicable to secure a reduction in unbalances by providing adjacent systems of 4-wire units with special twists. It would be necessary to provide these twists with different lengths, and a least four and more probably six (6) different lengths of spiral twists would be required. As previously indicated and as shown in equation 4 the coupling factor between two systems of 4-wires depends not only upon the relative angle of rotation θ-φ, but also upon the angles φ and θ as well. As indicated by practical experience with the use of different length of twists in present day cables it is to be expected that the results obtainable with different lengths of spiral twist, even though as many as six (6) different ones were provided for the 4-wire units of Fig. 2 of the drawings, will be no better than now obtained with such use with present day cables. As brought out in the reference already cited (A. I. E. E. Transactions—Crosstalk and noise features of cable carrier telephone systems, pages 250–261), it is actually necessary to balance every pair used for carrier purposes against every other pair. If 50 carrier pairs were used, there would be 49 balancing coils connected to each pair hence a total of 1225 coils would be required on all pairs in the 50 pair complement. In view of the present day unsatisfactory experience with carrier cables set up on the basis of the different number of twists in such cables it is evident that the system described for the first time in these specifications is definitely superior in that the maximum unbalance developed per mile of circuit is 33 db. below that obtained with present day two-wire cables, and this maximum unbalance (only on diagonally located 4-wire units) can be completely eliminated in the simple matter disclosed hereinabove or illustrated on Fig. 13 of the drawings.

Even if no further use were made of the 4-wires required with the system illustrated on Fig. 2 of the drawings to secure a single carrier circuit, it would still prove of greater advantage than the present day system. This last system also makes use of 4-wires, but two of these four wires have to be located in one cable sheath for traffic in one direction and the remaining two in a second cable sheath for traffic in the opposite direction. Furthermore, considerable expenditures in the way of balancing each pair against every other pair in the cable, when used for carrier purposes, and of providing special costly balancing panels to eliminate unavoidable residual random in balances are required. See A. I. E. E. references previously mentioned.

To summarize all of the above points, an arrangement which would provide different lengths of twist for adjacent 4-wire units, would necessarily destroy the favorable balance conditions which, as shown, result in zero coupling between such units. Large random unbalances are developed by the method of different lengths of twist and reliance is then placed upon finding unbalances of opposite sign and by opposing these to each other cancel them out. But, as shown by experience, only partial success is obtained in this manner. Nothing prevents us, however, from following the principle of fixed space relations for definite lengths of cable and introducing between such lengths, transpositions of the type required where it is necessary to eliminate any unbalances not eliminated by the method of fixed optimum space relationships. A transposition, under the conditions outlined, would be equivalent to a full twist. This procedure is outlined more in detail hereinbelow.

The second objective of the present invention, as previously stated, is to show that if certain additional measures are taken as fully described hereinbelow, it will be possible to make use of the same 4-wires used for carrier purposes to secure one of the following additional combinations of circuits:

(*a*) A second carrier circuit.
(*b*) A second speech frequency circuit.
(*c*) Two carrier or two speech frequency circuits.

It is thus possible, in addition to all the advantages above mentioned, to effect considerable savings in copper investment, if the required measures are taken to obtain either one of the three alternatives *a*, *b* and *c* mentioned hereinabove. The second carrier circuit under alternative *a*, while theoretically it can be made completely free from mutual induction, will not be quite as good as the fundamental carrier circuit of Fig. 2 of the drawings. The reason for this lies in the fact that it is obtained by balancing large positive unbalances in one cable section with equally large negative unbalances in a succeeding cable section. In cases of this type, as well known in practice, random deviations are likely to creep in. For the reason just indicated,

the use of alternative *b* might be preferable in certain cases. If arrangement *c* is adopted, and steps taken to obtain two speech frequency circuits, such circuits would be available for short haul traffic at repeater stations. The 4-wire carrier circuit wired in accordance with Fig. 2 of the drawings, in the case just mentioned i. e., *c*, would be obtained at no additional cost for line conductors, since it would be a superimposed circuit. In practice, the need for short haul circuits alone would in many cases justify the installation of the cable and the carrier circuit would be obtained at no additional cost for copper conductors, if the particular system of carrier transmission first disclosed in these specifications is used.

Fig. 11 of the drawings shows the arrangement required in case either alternative *a* or *b* is used. Fig. 12 of the drawings shows the arrangement required in case alternative *c* is used. It might be mentioned here that in case either alternative *b* or *c* is chosen, it would be feasible to provide loading coils for the speech frequency circuits without interfering with the carrier circuit. When use is made of the arrangements shown on Fig. 11 and Fig. 12 of the drawings, a fundamental carrier circuit is made available at terminals CC as indicated and this circuit is definitely free from objectionable crosstalk as fully described hereinabove. I have, in a companion application, S. N. 437,012, now matured into U. S. P. 2,336,627, described in some detail the particular advantages of the system using four (4) wires, when connected in the particular manner fully described in said application for carrier transmission purposes. I am not therefore describing these advantages herein, as reference may be made to my said companion application for a complete statement of said advantages.

Where, for any reason, it is necessary to use two one-way channels for carrier transmission purposes an arrangement using eight (8) wires, wired in accordance with Fig. 5 of the present drawings can be used. This figure represents a slight modification of the arrangement shown on Fig. 5 of my previously filed companion application S. N. 437,012, now matured into U. S. P. 2,336,627, already referred to. This modification allows the normal use of the eight (8) line conductors, in addition to the use as a carrier transmission channel, for obtaining four (4) two-way speech frequency circuits or two (2) four-wire speech frequency circuits of the present art wired in accordance with Fig. 2 of the drawings of my companion application S. N. 437,012.

In view of all the above cited facts, it is clear that the carrier frequency channel, obtained in the manner shown, requires no additional investment in line conductor costs, except such small increments in cable manufacturing costs due to the necessity of careful aligning of the cable conductors.

In order to show that the second objective of the present invention can be achieved in accordance with Fig. 12 of the drawings, i. e. the possibility of using cable conductors in the manner first disclosed in these specifications for two speech frequency circuits while superimposing a carrier circuit upon these same voice frequency circuits can be realized, we still have to show that the voice frequency circuits using two-wire combinations in 4-wire units aligned in accordance with Fig. 2 of the drawings will have sufficiently low inductive couplings with similar circuits in the same assembly or cable. Referring to Fig. 7 of the drawings, with units A and B set at the angles indicated in Table X, the capacity unbalances between the various 2-wire combinations in these two adjacent units are, I find, as follows.

TABLE XI

ADJACENT HORIZONTAL UNITS

Designation of 2-wire circuits		Capacity unbalances per mile
(A)	(B)	
		M. m. f.
(1, 3)	(5, 7)	−8, 517
(1, 3)	(6, 8)	+5, 963
(2, 4)	(5, 7)	+5, 963
(2, 4)	(6, 8)	+2, 586

The 2-wire unbalances, shown in Table XI, may be eliminated as between adjacent units A and B, A and C, D and B or D and C by means of the transpositions of the type indicated as "X" on Fig. 13 of the drawings. These type "X" transpositions are inserted, as shown, on diagonally located units A and D between two successive cable lengths *a* and *b*. We still have to consider the two-wire unbalances between diagonally adjacent units A and D, also B and C in a combination of four adjacent units A, B, C and D. The unbalances of the type just referred to are given in the following Table XII, for units A and B.

TABLE XII

ADJACENT DIAGONAL UNITS

Designation of 2-wire circuits		Capacity unbalances per mile
(A)	(D)	
		M. m. f.
(1, 3)	(13, 15)	−2, 868
(1, 3)	(14, 16)	−1, 704
(2, 4)	(13, 15)	−1, 704
(2, 4)	(14, 16)	+1, 127

We eliminate all unbalances between the two-wire combinations in units A and D by providing a type "X" transposition in unit D, between cable sections *b* and *c*. Equal unbalances between units B and C are eliminated by type "X" transposition in unit B, as shown, between cable sections *b* and *c*. It must be clearly evident that the type "X" transpositions, which are effective in eliminating the two-wire circuit unbalances shown in Tables XI and XII have no effect whatsoever upon the 4-wire carrier circuit unbalances. Since with the system using four (4) wires for a fundamental carrier transmission channel, we had a four-wire residual unbalance left of 255 m. m. f., as between diagonal units A and D, also B and C, we eliminate these unbalances by providing a type "Y" transposition as shown on Fig. 13 of the drawings on units A and C. An equally satisfactory arrangement would be to provide these same type transpositions on units B and D, in place of units A and C.

If the work of placing the transpositions as shown on Fig. 13 of the drawings on sections *a*, *b*, *c* and *d* is carried out during manufacture, each cable reel delivered to the user can be made free of all the important two-wire circuit unbalances, except as to small random deviations. All of these transpositions are provided specifically to eliminate two-wire unbalances only, and in order to build up speech frequency 2-wire circuits of satisfactory type. The problem, how-

ever, is not yet completely solved. We have to look into all other mutually inductive relationships, in the assembly of 4-wire units, as between two-wire circuit combinations. It will be recalled that the capacity unbalance between two 4-wire units separated by one intervening unit, when used on a 4-wire basis, is just 7 m. m. f. per mile, a negligibly small figure. This is the great advantage of the particular 4-wire arrangement first disclosed in these specifications. Once, as already shown, the couplings between adjacent units have been adjusted to zero in the specific manner disclosed hereinabove, it is unnecessary to concern ourselves with the existence of other units at greater distances, in so far as 4-wire couplings are concerned. Unfortunately, a similar situation does not hold true for 2-wire combinations, when separated by an intervening 4-wire unit such as between unit A and unit E. The capacity unbalances between 2-wire combinations 1, 3 and 2, 4 in unit A and 21, 23 and 22, 24 in unit E separated from unit A by the intervening unit B is given by the following Table XIII.

TABLE XIII

HORIZONTAL UNITS SEPARATED BY ONE INTERVENING UNIT

Designation of 2-wire circuits		Capacity unbalances per mile
(A)	(E)	
		M. m. f.
(1, 3)	(21, 23)	−869
(1, 3)	(22, 24)	+694
(2, 4)	(21, 23)	+694
(2, 4)	(22, 24)	+375

The above unbalances are fairly large nor are the unbalances between diagonal units separated from each other by an intervening diagonal unit negligible either. As an example, suppose we take the case of units A and M and consider the unbalances between circuit combinations (1, 3), (2, 4) in unit A with (41, 43), (42, 44) in unit M which is separated from unit A by the intervening diagonally located unit D. These unbalances are indicated in the following Table XIV.

TABLE XIV

DIAGONAL UNITS SEPARATED BY ONE INTERVENING UNIT

Designation of 2-wire circuits		Capacity unbalances per mile
(A)	(M)	
		M. m. f.
(1, 3)	(41, 43)	−353
(1, 3)	(42, 44)	−234
(2, 4)	(41, 43)	−234
(2, 4)	(42, 44)	+178

We can, by repeating the procedure indicated on Fig. 13 of the drawings, eliminate the unbalances shown both on Table XIII and Table XIV. Thus, by providing the "X" type transpositions at properly chosen locations on sixteen consecutive cable sections of equal length, we can secure two-wire circuits in 4-wire units separated by one intervening unit. either diagonally, vertically or horizontally, which are mutually non-interfering with each other. It is interesting to note that we need not concern ourselves with the couplings of units which are separated by two intervening units such as A and F or A and P. They will have zero coupling coefficients by construction. The arrangement required is actually shown on Fig. 14 of the drawings. Section *aa, bb,* etc. on that drawing represent the entire combination of cable sections *a, b, c, d,* of Fig. 13 of the drawings with their associated transpositions. As noted on that drawing, the same type of transposition is provided on units A, B, C and D, on units E, F, G, H, etc. However, when the number of intervening 4-wire units is an odd number, such as 3, we still have to contend with inductive coupling coefficients. The following table indicates the two-wire unbalances between circuits (1, 3) (2, 4) of unit A, and (51, 53) (42, 54) of another unit A^1 separated from unit A by the intervening units B, E and F.

TABLE XV

HORIZONTAL UNITS SEPARATED BY THREE INTERVENING UNITS

Designation of 2-wire circuits		Capacity unbalances per mile
(A)	(A^1)	
		M. m. f.
(1, 3)	(51, 53)	−145
(1, 3)	(52, 54)	+138
(2, 4)	(51, 53)	+138
(2, 4)	(53, 54)	−35

If, as assumed, the two-wire circuits are restricted to short haul traffic use, a present day standard of 1000 units of crosstalk can be realized. The lengths of the two-wire circuits would have to be restricted to 50 miles, or one full length voice frequency repeater section. The detail analysis given in Tables XI to XV inclusive illustrates better than any generalization, the difficulty of obtaining two-wire circuits sufficiently free from crosstalk for satisfactory commercial use. The various transpositions indicated on Fig. 13 of the drawings repeated four (4) times would thus follow a definite pattern and would include sixteen (16) four-wire units. The pattern would be repeated for a second group of sixteen (16) 4-wire units and so on until all units are completely taken care of. To provide even higher grade 2-wire facilities, from the standpoint of freedom from crosstalk, would also be possible by extending the pattern of "X" type transpositions to include sixty-four (64) 4-wire units in a single transposition group or layout.

I have discovered a more effective alternative method of reducing crosstalk couplings than the one just outlined. I find that if the wires in the 4-wire units, such as 1, 2, 3, 4 for unit A, 5, 6, 7, 8 for unit B, etc., are all given a 90° rotation, either right handed or left handed, then the crosstalk couplings throughout the entire cabling system are all greatly reduced. Such a rotational arrangement as indicated by the transposition designated as "Z" on Fig. 14 of the drawings. To illustrate a specific result, if two sections of units A and B, designated as cable section *a* and *b* on Fig. 14 of the drawings, are joined together by a transposition of the "Z" type, then the four possible inductive couplings between the wires in units A and B, i. e. (1, 3)—(5, 7), (1, 3)—(6, 8), (2, 4)—(5, 7) and (2, 4)—(6, 8) change respectively as shown in the following Table XVI.

TABLE XVI

ADJACENT HORIZONTAL UNITS

Designation of 2-wire circuit		Capacity unbalances per mile		
(A)	(B)	Section (*a*)	Section (*b*)	Sections (*a* and *b*)
		M. m. f.	*M. m. f.*	*M. m. f.*
(1, 3)	(5, 7)	−8, 517	+2, 586	−2, 965
(1, 3)	(6, 8)	+5, 963	−5, 963	−0
(2, 4)	(5, 7)	+5, 963	−5, 963	−0
(2, 4)	(6, 8)	+2, 586	−8, 517	−2, 965

It will be observed that the maximum 2-wire unbalances between the systems 1, 3 and 2, 4 of unit A and the systems 5, 7 and 6, 8 of unit B have been greatly reduced, about 10.3 db. This will be evident by comparing the figures in the first column with the figures in the final or third column. I find further that this is a universal property in that it extends throughout the entire system of 4-wire units no matter what their physical separation or their geographic situation with reference to each other. For instance, in the case of the 2-wire couplings between units A and E which are given in Table XIII, the maximum two-wire coupling is reduced from 868 m. m. f. per mile to 246 m. m. f. per mile. The reduction in this case is about 11 db. in the maximum values. A second point of real importance consists in the fact that this large reduction in inductive couplings is obtained regardless of the type of assembly of the 4-wire units, whether in the form of squares as illustrated on Fig. 10 of the drawings or in any other imaginable type. This is borne out directly by the fact that the inductive couplings along diagonally located units such as A and D, or B and C, are also affected in the same manner and to the same approximate degree as are the inductive couplings between horizontally or vertically located units such as A and B, or A and C. This important point is made quite clear by reference to Table XVII which shows the effect of the 90° rotation, imposed by means of the "Z" type transposition on all pairs in the cable, upon diagonally adjacent units A and D.

TABLE XVII

DIAGONAL UNITS (A) AND (D)

Designation of 2-wire circuit		Capacity unbalances per mile		
(A)	(D)	Section (*a*)	Section (*b*)	Sections (*a* and *b*)
		M. m. f.	*M. m. f.*	*M. m. f.*
(1, 3)	(13, 15)	−2, 868	+1, 127	−870
(1, 3)	(14, 16)	−1, 704	+1, 704	0
(2, 4)	(13, 15)	−1, 704	+1, 704	0
(2, 4)	(14, 16)	+1, 127	−2, 868	−870

It will be noted that the reduction in the value of the maximum inductive couplings in the case of diagonally located units A and D is equal to 9.6 db. An exactly equal reduction takes place in connection with the couplings between units B and C. I find that this property is absolutely general, as previously stated, and hence independent of the angle between the centers of any two 4-wire units considered and the respectively conjugate elements in each such 4-wire unit. Thus, the improvement due to the procedure of providing a 90° rotation to the wires in all 4-wire units in any cable assembly between two successive cable sections, results in an improvement over the respective maximum couplings, of 9–11 db. Such an improvement is possible only because two pairs are used, in the particular structural arrangement already described, and therefore represents a forward step in the art from the standpoint of the possibility such step affords in obtaining a reduction in inductive couplings.

The arrangement of Fig. 13 of the drawings can also be used, after a "Z" transposition is inserted midway between each cable section, such as *a*, *b*, etc. as outlined above. Such an arrangement would require 32 successive cable sections to realize complete elimination of all 2-wire inductive couplings and the 4-wire couplings between diagonally adjacent units, for a system comprising sixteen (16) four-wire units. If the layout shown on Fig. 14 of the drawings is realized during the manufacturing of the cable reel, and the transpositions are inserted between equal lengths of cable, then all important 4-wire as well as 2-wire unbalances between adjacent units A, B, C and D will have been removed. The transposition pattern shown on Fig. 14 of the drawings provides mutually non-interfering 2-wire circuit arrangements, under six (6) different mutual relations as between 2-wire circuits considered in the combinations AB, AC, AD, BC, BD, and CD. By applying the same underlying procedure, using therefore thirty-two (32) successive cable sections, the feature of zero coupling can be readily extended to include all mutual inductive relations between units A, B, C, D (shown on Fig. 14 of the drawings) as well as E, F, G, H—I, J, K, L and M, N, O, P. The pattern used for the groups A, B, C, D—E, F, G, H, etc., would be the same as shown on Fig. 14 of the drawings. Four similar sections, each arranged in accordance with Fig. 14 of the drawings would be provided, with additional transpositions between these sections as indicated on Fig. 15 of the drawings. To simplify the drawings each succession of cable sections as represented by Fig. 14 of the drawings is shown on Fig. 15 of the drawings by the designations *aa*, *bb*, etc., since on said Fig. 15 we are only concerned with the transpositions between sections. It will be noted that only "X" type transpositions are shown and that all units belonging to the same subgroup (such as units A, B, C, and D) are provided with the same intersectional transpositions as shown. With the arrangement illustrated on Fig. 14 and Fig. 15 of the drawings, all couplings between units A to P inclusive, sixteen (16) in all, are reduced to zero. The highest residual unbalance left will be that between unit A and a unit A^1 belonging to a second group of sixteen (16) units similar to the first group of units A to P, inclusive. This residual unbalance is equal to 55 m. m. f. per mile, which is readily obtained from the data shown on Table XV. Thus, the use of the "Z" type transpositions on all pairs in the cable reduces the maximum residual 2-wire unbalance from 145 m. m. f. (see Table XV) to just 55 m. m. f. per mile. It will be evident to those versed in the art that the procedure hereinabove outlined can be carried out to the point of including, for instance, sixty-four (64) 4-wire units in a single complete pattern, instead of sixteen (16) as considered heretofore, in which case the highest residual unbalance is reduced to about 10 m. m. f. per mile. Thus, while it is necessary to provide a multiplicity of 90° and 180° transpositions to obtain the two additional 2-wire circuits (1, 3 and 2, 4 in unit A, 5, 7 and 6, 8 in unit B, etc.), the

pattern required is definite and comparatively simple to provide. In case it is desired to include sixty-four (64) 4-wire units in a single transposition pattern, thus reducing all 2-wire unbalances in the cable make-up to less than 10 m. m. f. per mile, the arrangement shown on Fig. 16 of the drawings, is used, wherein the designation *aaa*, *bbb* etc., include the entire pattern of transpositions on Fig. 13 and Fig. 15 or Fig. 14 and Fig. 15, shown on said drawings. I have discovered several alternative equally satisfactory arrangements for eliminating 2-wire inductive couplings, but none of these appear to possess particular advantages over those illustrated on Fig. 13, Fig. 14, Fig. 15 and Fig. 16 of the drawings. I have not, however, described these in order not to clutter further the specification and the drawings.

DERIVATION OF TWO 4-WIRE CIRCUITS FROM ONE SET OF FOUR WIRES

All of the descriptions and illustrations as above outlined refer to the case where two 2-wire circuits are developed which represents case C as previously referred to in these specifications. It is also possible to use all four wires in any one of the units A, B, C, D, etc., to obtain a second 4-wire circuit terminated at terminals DD¹ as shown on Fig. 11 of the drawings, which would be additional to the basic 4-wire circuit, highly immune to inductive influences, terminated at terminals CC¹, also as shown on Fig. 11 of the drawings. I have discovered a number of arrangements which satisfy the requirement of the fundamental problems involved. I am describing hereinbelow only a few of these, in order not to clutter unduly the specifications and the drawings. Fig. 17 shows one of these arrangements and Table XVIII shows the results obtained from the standpoint of capacity unbalance expressed in micromicrofarads, per mile, for the six (6) combinations involved in any group of 4-wire units such as A, B, C and D.

The unbalances shown in columns 3–9 of the above table are the unbalances which obtain when proper account is taken of the effect of the associated transpositions with the various sections *a*, *b*, *c*, etc., as shown on Fig. 17 of the drawings.

The 4-wire unbalances between units A and D, also between units B and C, which are equal to 255 m. m. f. per mile, are also eliminated by the "XY" transpositions as shown on Fig. 17 of the drawings.

The first heading in the above table indicates the 2-wire combinations (1, 3)–(5, 7) etc. Where, as here assumed, circuits 1, 3 and 2, 4 will be connected together in series combination to form a single 4-wire circuit, and correspondingly circuits 5, 7 and 6, 8 will also be connected in the same way to form a second 4-wire circuit, the capacity unbalance we are interested in is that between the two finally resulting 4-wire circuits 1, 2, 3, 4 and 5, 6, 7, 8, respectively, and is given by the sum of the four unbalances shown in the ninth or final column, designated as S_3. The figures indicated under heading Sec. S_1 represent the unbalance per mile for the sum of sections *a*, *b*, *c*, and *d*. The figures indicated under heading Sec. S_2 represent the unbalance per mile for the sum of sections a^1, b^1, c^1 and d^1. (See Fig. 17 of the drawings.) The figures indicated under heading Sec. S_3 represent the unbalance per mile for the sum of sections *a*, *b*, *c*, *d* and a^1, b^1, c^1, d^1. As will be seen from an examination of the figures shown under heading S_3, the final capacity unbalance between circuits 1, 2, 3, 4 and 5, 6, 7, 8 is equal to zero. The same result hold true for the final unbalances of the 4-wire combinations between sections A and C, A and D, B and C, B and D, C and D.

The arrangement shown on Fig. 16 of the drawings but without the transpositions (1, 3), (5, 7), etc., at both ends of the layout is one that results in equal unbalances of the same sign on all

TABLE XVIII

UNITS (A), (B), (C), (D), IN COMBINATIONS

Designation of 2-wire circuit		Capacity unbalances per mile in m. m. f.						
(A)	(B)	Sec. *a*	Sec. *b*	Sec. *a*+*b*	Sec. *c*+*d*	Sec. S_1	Sec. S_2	Sec. S_3
1, 3	5, 7	−8,517	+2,586	−2,965	0	−1,492	−1,492	−1,492
1, 3	6, 8	+5,963	−5,963	0	+2,965	+1,492	+1,492	+1,492
2, 4	5, 7	+5,963	−5,963	0	+2,965	+1,492	+1,492	+1,492
2, 4	6, 8	+2,586	−8,517	−2,965	0	−1,492	−1,492	−1,492
(A)	(C)							
1, 3	9, 11	+2,586	−8,517	−2,965	0	−1,492	−1,492	−1,492
1, 3	10, 12	−5,963	+5,963	0	+2,965	+1,492	+1,492	+1,492
2, 4	9, 11	−5,963	+5,963	0	+2,965	+1,492	+1,492	+1,492
2, 4	10, 12	−8,517	+2,586	−2,965	0	−1,492	−1,492	−1,492
(A)	(D)							
1, 3	13, 15	−2,868	+1,127	−870	−870	−870	0	−435
1, 3	14, 16	−1,704	−1,704	0	0	0	+870	+435
2, 4	13, 15	−1,704	−1,704	0	0	0	+870	+435
2, 4	14, 16	+1,127	−2,868	−870	−870	−870	0	−435
(B)	(C)							
5, 7	9, 11	+1,127	−2,868	−870	−870	−870	0	−435
5, 7	10, 12	+1,704	−1,704	0	0	0	+870	+435
6, 8	9, 11	+1,704	−1,704	0	0	0	+870	+435
6, 8	10, 12	−2,868	+1,127	−870	−870	−870	0	−435

The unbalances for the 2-wire combinations between units B and D are the same as those indicated for units A and C in the above table. The unbalances for the 2-wire combinations between units C and D are the same as those indicated for units A and B in the above table.

2-wire combinations of the same 4-wire unit, such as A or B, etc. This is shown in detail on Table XIX in the ninth or final column. This arrangement was originally developed by applicant on Fig. 1 of the drawings of his companion application S. N. 437,012. It will be noted that

on said Fig. 1, wires 1, 3 are transposed actually at the terminals of the circuits. When these same transpositions are provided at the ends of a single cable reel, as shown on Fig. 18 of the drawings of the present specifications, in conjunction with all the other transpositions associated with sections *a, be, c, d,* etc., it becomes possible to limit the maximum unbalance developed on any pair of a 4-wire unit, before eliminating it by opposing said unbalance to the equal unbalance but of opposite sign of the other pair of the same unit. Since filing his application S. N. 437,012, now matured into U. S. A. 2,336,627, applicant has discovered a number of arrangements some of which have been described and illustrated in the present specifications which result in zero unbalances on both pairs of a single 4-wire unit. He has also shown that he can obtain such a result with practically the same number of transpositions, per mile of cable, than with the arrangement previously discovered by him illustrated on Fig. 1 of S. N. 437,012 and Fig. 18 of the present specifications. The arrangements just referred to are illustrated on drawings Fig. 13, Fig. 14, Fig. 15 and Fig. 16 of the present specifications. This being the case, it is seen that it is possible to obtain with the same effort two circuits with the arrangements of Fig. 13, Fig. 14, Fig. 15, Fig. 16, where only one circuit can be obtained with the arrangement of Fig. 18 of the drawings. Furthermore, these two circuits are in addition to the excellent 4-wire fundamental circuit terminated at terminals CC^1 of Fig. 11 of the drawings. Thus, he has succeeded since filing his application S. N. 437,012 in developing arrangements which make it possible to secure three (3) circuits with only four (4) wires, instead of the single circuit with the same number of wires, as shown on Fig. 1 of the drawings of S. N. 437,012.

also between units B and C, are 255 m. m. f. per mile, are also eliminated by the "Y" transpositions as shown on Fig. 18 of the drawings.

It is important to recall here that the fundamental 4-wire circuit as terminated at terminals CC^1 of Fig. 11 of the drawings is continuously balanced, i. e. no matter how small a length of cable is considered the coupling between two adjacent horizontal or vertical 4-wire units is always equal to zero, while the comparatively small diagonal couplings AD and BC are taken care of by means of the transpositions installed during the manufacturing of the cable. These are represented by the "Y" transpositions of Fig. 13 and Fig. 18 of the drawings, by means of the "XY" transpositions of Fig. 17 of the drawings. The fundamental 4-wire circuit is superior in quality, as regards freedom from crosstalk and babble, for the reasons already indicated, to the two (2) 2-wire circuits obtained in the manner fully described hereinabove, and also to the derived second 4-wire circuit terminated in terminals DD^1, as shown on Fig. 11 of the drawings.

I have already pointed out that if eight (8) conductors are used to obtain a two-way carrier circuit in the manner illustrated on Fig. 3A of the drawings, then all capacity unbalances between all units in the cable including those between diagonal units, independently of the number of units intervening, will be eliminated, provided the common angle of these units is taken at 22° 30′. I find that in this ideal case, two sub-polygons, each a square, can be obtained which will be non-interfering with each other, as well as with the fundamental octagon. This situation, I find further, is absolutely general and can be stated in the following general terms. If the fundamental circuit is a regular polygon of $(2)^n$ conductors, then there can always be found two regular sub-polygons of $(2)^{n-1}$ conductors which are non-interfering not only with each other, but with the fundamental polygon also.

The method of terminating each of the component cores of a cable, each core consisting of 8 wires arranged as shown on Fig. 3A or Fig. 3B of the drawings is illustrated in Fig. 19 and Fig. 20 of the drawings. The method used allows the development, in addition to the fundamental 8-wire circuit terminated at AA′, of a number of additional circuits all mutually non-interfering with each other, using the same number of 8 wires. The numbering of the wires at the right-hand side of both Fig. 19 and Fig. 20 of the drawings

TABLE XIX

UNITS A, B, C, D, IN COMBINATIONS

Designation of 2-wire circuit		Capacity unbalances per mile in m. m. f.						
(A)	(B)	Sec. *a*	Sec. *b*	Sec. *a*—*b*	Sec. *c*—*d*	Sec. S_1	Sec. S_2	Sec. S_3
1, 3	5, 7	−8, 517	+2, 586	−2, 965	0	−1, 482	−1, 482	−1, 482
1, 3	6, 8	+5, 963	−5, 963	0	−2, 965	−1, 482	−1, 482	−1, 482
2, 4	5, 7	+5, 963	−5, 963	0	−2, 965	−1, 482	−1, 482	−1, 482
2, 4	6, 8	+2, 586	−8, 517	−2, 965	0	−1, 482	−1, 482	−1, 482
(A)	(C)							
1, 3	9, 11	+2, 586	−8, 517	−2, 965	0	−1, 482	−1, 482	−1, 482
1, 3	10, 12	−5, 963	+5, 963	0	−2, 965	−1, 482	−1, 482	−1, 482
2, 4	9, 11	−5, 963	+5, 963	0	−2, 965	−1, 482	−1, 482	−1, 482
2, 4	10, 12	−8, 517	+2, 586	−2, 965	0	−1, 482	−1, 482	−1, 482
(A)	(D)							
1, 3	13, 15	−2, 868	+1, 127	−870	−870	−870	0	−435
1, 3	14, 16	−1, 704	+1, 704	0	0	0	−870	−435
2, 4	13, 15	−1, 704	+1, 704	0	0	0	−870	−435
2, 4	14, 16	+1, 127	−2, 868	−870	−870	−870	0	−435
(A)	(C)							
5, 7	9, 11	+1, 127	−2, 858	−870	−870	−870	0	−435
5, 7	10, 12	+1, 704	−1, 704	0	0	0	−870	−435
6, 8	9, 11	+1, 704	−1, 704	0	0	0	−870	−435
6, 8	10, 12	−2, 868	+1, 127	−870	−870	−870	0	−435

The unbalances for the 2-wire combinations between units B and D are the same as those indicated for units A and C in the above table. The unbalances for the 2-wire combinations between units C and D are the same as those indicated for units A and B in the above table.

The unbalances shown in columns 3–9 of the above table are the unbalances which obtain when proper account is taken of the effect of the associated transpositions with the various sections *a, b, c,* etc., as shown on Fig. 17 of the drawings.

The 4-wire unbalances between units A and B,

corresponds to the numbering in the actual individual cable core of Fig. 3A or Fig. 3B of the drawings. While it would seem possible to develop as many as six (6) circuits with wires 1 to 8, inclusive, actually just four (4) circuits can be set up which will be sufficiently free from crosstalk to warrant their use. Of these four circuits one, that terminated at AA'', will be an inherently balanced and ideal 8-wire circuit. The two solutions indicated in Fig. 19 and in Fig. 20 of the drawings differ only in that a second auxiliary octagonal circuit is developed in Fig. 19, while a single active 4-wire auxiliary circuit is shown in Fig. 20. The second auxiliary octagonal circuit will be almost as good as the fundamental inherently balanced 4-wire circuit CC' of Fig. 11 and Fig. 12 of the drawings. The qualification "almost" is used for the reason that while circuit CC' as just referred to is completely balanced no matter how short a stretch of cable we take into consideration, the auxiliary 8-wire circuit is balanced only if the entire length of cable included in one cable reel is taken into consideration, provided further, each such reel has all its component 8-wire cores arranged for $(n-1)$ or 3 barrel type transpositions per cable reel. The entire cable in any reel is assumed divided into four exactly equal parts by the three "Z" type transpositions. Any random deviation in the equality of these four parts would introduce an unbalance. In Figure 20 of the drawings it is shown how two auxiliary 4-wire circuits can be developed and terminated at BB' and CC'. It appears preferable to use only one of these two circuits. By using a circuit BB' in one 8-wire core and a circuit CC' in a horizontally or vertically adjacent core, the mutual unbalance between two such immediately adjacent circuits can actually be made equal to zero in any single cable reel by the use of "Z" type transpositions applied to all wires in all individual cores in the cable. Hence, the auxiliary 4-wire circuit of Fig. 20 can be made almost as good, from the standpoint of freedom from inductive interference, as the fundamental 4-wire circuits designated as CC' in Fig. 11 and Fig. 12 of the drawings, both of which use the arrangement of wires of Fig. 2 of the drawings in each of the component cores of the cable.

In both of the terminating arrangements illustrated in Fig. 19 and Fig. 20 of the drawings, it would be possible to develop two 2-wire circuits satisfactory for short haul use. We have, in this respect, freedom of choice as between circuits DD' and FF' or circuits EE' and GG'. To indicate that all four (4) combinations of 2 wires cannot be simultaneously used, circuits EE' and GG' have not been shown as connected, while circuits DD' and FF' are so shown. If wires 1, 3, 5, 7 are used, in the case of the arrangement of Fig. 20 of the drawings, for the auxiliary 4-wire circuit, it is advisable to use 2-wire circuits DD' and FF'. If, on the contrary, wires 2, 4, 6, 8 are used for the auxiliary 4-wire circuit, then it is advisable to make use of the 2-wire circuits EE' and GG'. I have discovered that if we decide to restrict ourselves to a single 2-wire circuit, either DD' or FF', a 2-wire circuit can be developed which is better balanced than if use were made of both circuits DD' and FF'. It is necessary, in order to secure this desirable result, to use alternately for immediately adjacent units in horizontal or vertical rows (see Fig. 10 of the drawings) circuits DD' and FF'. For instance, if 2-wire circuit DD' is used in one 8-wire unit, then circuit FF' would be used in the immediately adjacent 8-wire units in vertical or horizontal rows. This arrangement can be used to develop zero unbalance between such adjacent units if the 2-wire circuits are considered for the entire length of a single cable reel, provided the 8-wire cores in such cable reel are provided with "Z" type transpositions in accordance with the indications hereinbefore outlined. Similar results are obtainable, of course, if the same restriction is accepted in the case of the 2-wire circuits of Fig. 12 of the drawings. It will be evident, by reference to Table XVIII, that the unbalances between horizontally adjacent 2-wire circuits are actually equal to 1482 mmf. per mile for the two sections *a* and *b* included in a single cable reel. The above restriction would therefore avoid the possible random deviations of this large unbalance of 1482 mmf. per mile, leaving unchanged, however, the 2-wire unbalances between diagonal units. Since, however, as already shown, there will exist a residual 4-wire unbalance of 255 mmf. per mile, as between diagonal units A and D, or B and C and it is necessary to provide "Y" type transpositions in the wires affected at terminals of a cable reel to avoid said residual unbalance, it will be possible, by changing the "Y" type transposition to the "XY" type to eliminate the 2-wire unbalances as well between the diagonally located units.

In the case of the octagonal arrangement of Fig. 3A and Fig. 3B of the drawings, the 8-wire capacity unbalance between immediately adjoining circuits is given by the following expression for the first term of a Fourier expansion:

$$\begin{aligned} &8C_4^1\cos 4(\theta-\theta_1)-8C_4^2\cos 4(\theta-\theta_2)+8C_4^3\cos 4(\theta-\theta_3)\\ &\qquad -8C_4^4\cos 4(\theta-\theta_4)+8C_4^5\cos 4(\theta-\theta_5)\\ &-8C_4^6\cos 4(\theta-\theta_6)+8C_4^7\cos 4(\theta-\theta_7)-8C_4^8\cos 4(\theta-\theta_8) \end{aligned}$$

Thus we have to deal with 8 times the 4th harmonic terms of the Fourier series development in this first term of the 8-wire capacity unbalance. It is interesting to note that the intercapacity coefficients C_0, C_1, C_2 and C_3 do not appear in the fundamental term of the 8-wire capacity unbalance. The second term in the Fourier series development is represented by 12th harmonic terms and the third term by 20th harmonic terms.

For immediately adjacent units of the octagonal type, the "typical unbalance," as previously defined, is about 9 db. lower than for adjacent units of the 4-wire type. For $\varphi=0$ the capacity unbalance for the adjacent 8-wire cores is given by the expression

$$\text{C. U.}=3{,}779\sin 4\ (\theta+22^\circ\ 30'\ 0'')$$

For $=11^\circ\ 15'\ 0''$, the corresponding unbalance is given by

$$\text{C. U.}=3{,}534\sin 4\ (\theta+30^\circ\ 6'\ 36'')$$

It will be noted that this 8-wire unbalance is considerably smaller than the 4-wire unbalance of 10,544 mmf. per mile, as shown on Table VII. It is furthermore clearly evident that the above unbalance becomes nil for $\theta=-22^\circ\ 30'\ 0''$ as already referred to hereinabove.

I claim:

1. In a cable system comprising a number of similar groups, a method of making telephone cable cores which consists in assembling the $(2)^n$ individually insulated conductors of each group, where n is some entire number greater than unity, around a cylindrical core, and maintaining said conductors in parallel relation to the axis of said cylindrical core and at fixed distances to each other.

2. In a cable system comprising a number of similar groups, a method of making telephone cable cores which consists in assembling the $(2n)$ individually insulated conductors of each group, where n is some entire number greater than unity, around a cylindrical core and maintaining said conductors in parallel relation to the axis of said cylindrical core and at fixed distances to each other.

3. In a cable system comprising a number of similar groups, a method of making telephone cable cores which consists in assembling the $(2)^n$ individually insulated conductors of each group, where n is some entire number greater than unity, around a cylindrical core, in a regular polygon, and maintaining said conductors in parallel to the axis of said core.

4. In a cable system comprising a number of similar constituent groups, a method of making telephone cable cores which consists in assembling the $(2)^n$ individually insulated conductors of each group (where n is some entire number greater than unity) around a cylindrical core in a regular polygon, and in aligning reference conductors in aforesaid groups at predetermined angles with reference to the line connecting the geometrical centers of said groups, substantially as described.

5. In a cable system as defined in claim 4, a method of making telephone cable cores which consists in transposing the conductors of each such groups on the basis of a predetermined pattern between successive equal lengths of cable, substantially as described.

6. A method of obtaining a two-way carrier circuit from a constituent group of the cable system defined in claim 3 which consists in combining the $(2)^n$ conductors in said group into just two composite conductors, each composite conductor consisting of $(2)^{n-1}$ conductors taken in alternate sequence around the cylindrical core of said group and connecting them in parallel at terminal points.

7. A method of obtaining a one-way carrier circuit from a constituent group of the cable system defined in claim 3 which consists in combining the $(2)^n$ conductors in said group into just two composite conductors, each composite conductor consisting of $(2)^{n-1}$ conductors taken in alternate sequence around the cylindrical core of said group and connecting them in parallel at terminal points.

8. A method of obtaining a two-way carrier circuit from a constituent group of the cable system defined in claim 4 which consists in combining the $(2)^n$ conductors in said group into just two composite conductors, each composite conductor consisting of $(2)^{n-1}$ conductors taken in alternate sequence around the cylindrical core of said group and connecting them in parallel at terminal points.

9. A method of obtaining a one-way carrier circuit from a constituent group of the cable system defined in claim 4 which consists in combining the $(2)^n$ conductors in said group into just two composite conductors, each composite conductor consisting of $(2)^{n-1}$ conductors taken in alternate sequence around the cylindrical core of said group and connecting them in parallel at terminal points.

10. A method of obtaining a two-way carrier circuit from a constituent group of the cable system defined in claim 4 which consists in combining the $(2)^n$ conductors in said group into just two composite conductors, each composite conductor consisting of $(2)^{n-1}$ conductors taken in alternate sequence around the cylindrical core of said group and connecting them in parallel at terminal points.

11. A method of obtaining a one-way carrier circuit from a constituent group of the cable system defined in claim 4 which consists in combining the $(2)^n$ conductors in said group into just two composite conductors, each composite conductor consisting of $(2)^{n-1}$ conductors taken in alternate sequence around the cylindrical core of said group and connecting them in parallel at terminal points.

12. In a cable system comprising a number of similar constituent groups with each such group consisting of $(2)^n$ individually insulated conductors (where n is some entire number greater than unity) assembled as a regular polygon around a cylindrical core, the method of obtaining a fundamental circuit and two superimposed circuits mutually non-intefering with each other in each such constituent group which consists in dividing each group of $(2)^n$ conductors into two subgroups with the conductors in each sub-group disposed as a regular sub-polygon of $(2)^{n-1}$ conductors, combining the conductors of each subpolygon into just two composite conductors, each composite consisting of a number of conductors taken in alternate sequence around said subpolygon, with said composite conductors connected to the terminals of the secondary of a phantom repeating coil group at terminal points with the composite conductors of the second subpolygon connected to the terminals of the second coil of said phantom group, the third and fundamental carrier circuit being secured by tapping the mid-points of the secondaries of said phantom group at said terminal points.

13. In a cable transmission system as defined by claim 12, the method of securing mutually non-interfering fundamental carrier circuits in different groups which consists in aligning reference conductors in each group at predetermined angles with reference to the line connecting the geometrical centers of such groups.

14. In a cable transmission system as defined in claim 12, the method of securing mutually non-interfering sub-polygonal circuits in different groups which consists in connecting conductors in successive equal lengths of cable through a predetermined pattern of transpositions.

15. In a cable transmission system as defined by claim 12, the method of securing a substantial reduction in the coefficients of mutual induction between sub-polygonal circuits in different groups which consists in connecting conductors in successive equal lengths of cable through a transposition equivalent to a rotation by an angle equal to π/n of all the conductors of said polygonal circuits in said groups.

16. In a cable system comprising a number of similar groups, as defined in claim 4, the method of obtaining two (2) mutually non-interfering circuits in each such group as a phantom coil group combination at terminal points, which consists in dividing each group of $(2)^n$ conductors into two sub-groups with the conductors in each subgroup disposed as a regular sub-polygon of $(2)^{n-1}$ conductors, combining the conductors of each such sub-polygon into just two composite conductors, each composite conductor consisting of a number of conductors taken in alternate sequence around said sub-polygon with said composite conductors connected to the terminals of the secondary of a phantom repeating coil group

at terminal points with the composite conductors of the other sub-polygon connected to the secondary of the second coil of said phantom group, connecting the two primary coils in series to form one derived circuit, the second and fundamental carrier circuit being secured by tapping the mid points of the secondaries of said phantom coil group at said terminal points.

17. In a cable system comprising a number of similar constituent groups, with each such group consisting of $(2)^n$ conductors (where n is an entire number greater than unity) assembled as a regular polygon around a cylindrical core, the method of securing mutually non-interfering fundamental carrier circuits in different groups, which consists in combining the $(2)^n$ conductors of each such group into just two composite conductors to form a fundamental carrier circuit, each composite conductor consisting of $(2)^{n-1}$ conductors taken in alternate sequence around said regular polygon, and aligning reference conductors in each group at predetermined angles with reference to the line connecting the geometrical centers of such groups, substantially as described.

18. In a transmission system as defined by claim 17, the method of securing a substantial reduction in the coefficients of mutual induction between superimposed circuits in different groups which consists in connecting conductors in successive equal lengths of cable through a transposition equivalent to a rotation by an angle equal to π/n of all the conductors in said groups substantially as described.

19. In a transmission system as defined by claim 17, the method of securing mutually non-interfering superimposed and fundamental circuits in different groups, which consists in connecting the conductors of each such group in successive equal lengths of cable through a predetermined pattern of transpositions, substantially as described.

20. In a cable system comprising a number of similar constituent groups as defined in claim 4, the method of obtaining two mutually non-interfering circuits in each such group as a phantom coil combination at terminal points, which consists in dividing each group of $(2)^n$ conductors into two sub-groups with the conductors in each sub-group disposed as a regular sub-polygon of $(2)^{n-1}$ conductors, combining the conductors of each such sub-polygon into just two composite conductors, each composite conductor consisting of a number of conductors taken in alternate sequence around said sub-polygon, with said composite conductors connected to the terminals of the secondary of said phantom coil group with the composite conductors of the other sub-polygon connected similarly to the secondary of the second coil of said phantom group, connecting the two primary coils in parallel to form a superimposed circuit with all $(2)^n$ conductors, the second and fundamental circuit being secured by tapping the mid-points of the secondaries of said phantom coil group, substantially as described.

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