No. 171

The Institution of Post Office Electrical Engineers.

Multi-Circuit Carrier Telephony

E. M. RICHARDS, A.C.G.I., B.Sc. (Eng.), M.I.E.E.

and

F. J. D. TAYLOR, B.Sc. (Eng.)

A Paper read before the North Eastern Centre of the Institution on the 13th December, 1938, and at other Centres during the Session.

No. 171

The Institution of Post Office Electrical Engineers.

Multi-Circuit Carrier Telephony

E. M. RICHARDS, A.C.G.I., B.Sc. (Eng.), M.I.E.E.

and

F. J. D. TAYLOR, B.Sc. (Eng.)

A Paper read before the North Eastern Centre of the Institution on the 13th December, 1938, and at other Centres during the Session.

Multi-Circuit Carrier Telephony

INTRODUCTION.

Multi-circuit carrier telephony has recently made rapid progress, and for the last three years has been the means of providing a large number of new circuits to meet the growth of the long distance telephone traffic in the British Isles, and in a number of cases to provide circuits on comparatively short routes. Many articles and papers have been published on various aspects of the subject, but no inclusive account has been given. This paper, therefore, endeavours to give a broad survey of the subject and to indicate the present trend of development in this country. Cables and equipment for three-circuit aerial carrier systems, one audio plus four carrier circuit systems and twelve-circuit carrier systems are dealt with; particular applications or variations of these schemes are described, and the fields of use are indicated: the subject of coaxial cable circuits is mentioned only briefly as it has been fully dealt with elsewhere[1].

The reasons for the introduction of multi-circuit carrier telephony on an extensive scale are not far to seek. The general trade recovery of the past few years combined with telephone tariff reductions has resulted in a rapid increase in the demand for additional inland and international trunk circuits. The following table shows (*a*) the total number of inland long trunk circuits and (*b*) the number of circuits of 200 miles or more in length existing on 1st October in recent years.

Long trunks existing in	1934	1935	1936	1937	1938	1939
(*a*) Over 25 miles	4136	4719	5367	5820	6220	6800
(*b*) 200 miles or over	69	109	159	209	221	270

The increases from 1934 to 1939 are 64% and 291% respectively and the demand for circuits is still considerable. It would be difficult to attempt to meet the rate of development by providing long distance audio-frequency circuits, which would require many times the amount of material for external works compared with that required for multi-circuit carrier installations. Prior to the introduction of carrier telephony, about 80% of the first cost of trunk circuits was for cables and loading coils with 20% for station equipment. The use of multi-channel carrier circuits in non-loaded cables results in large savings on external works, and becomes economically sound on routes long enough for these savings not to be nullified by the increased cost of equipment and accommodation. More accommodation is required at terminal stations due to the need for modulating, demodulating and carrier-frequency generating equipment, whilst intermediate amplifier stations are required at intervals of 22 miles on a twelve-circuit carrier scheme as compared with about 50 miles on coil-loaded cable routes. The high cost of submarine cable manufacture and maintenance makes it particularly desirable to use carrier telephony to provide the maximum number of circuits on each submarine cable. Also, on the more congested routes, it is becoming increasingly difficult to find space for new submarine cables consistent with satisfactory conditions for repair; the use of cables providing a large number of carrier circuits will in some cases reduce the total number of cables required.

Considerable increase in the complexity of equipment has resulted from the use of multi-circuit carrier systems and is of importance from the manufacturing, installation and maintenance aspects; experience with the earlier systems has enabled a satisfactory technique to be evolved. Maintenance is referred to again later.

Present position in Great Britain.

The present (early 1939) position in this country is as follows:—

A number of multi-circuit carrier installations of various types is now in service in the British Isles.

A new trunk network between zone centres and, in some cases, between zone and group centres, is being built up by the provision of twelve-circuit carrier systems, using separate non-loaded, twelve-quad cables for each direction of transmission. The circuits obtained are supplementary to those provided by existing audio-frequency and single-circuit carrier equipment, but these latter will be used to an increasing extent for shorter distance circuits as the new network expands. Twelve-circuit carrier equipment is also being used to provide circuits on main submarine cable routes to Northern Ireland, Eire, the Channel Islands, France and Holland.

Group modulation is in use to translate the frequency bands from the twelve-circuit carrier equipment range (12 to 60 kc/s) to higher frequencies so as to provide additional circuits on the single-core concentric cables between Scotland and Northern Ireland, and a similar scheme is being planned for the Anglo-Dutch route; a field trial is well in hand to examine the possibilities of obtaining by this method 24 or more channels on each pair in the twelve-quad P.C.Q.T. carrier cables.

Carrier System No. 4 equipment (one audio + four carrier circuits) is being used to provide circuits as follows:—

(1) On existing cables which are deloaded or specially loaded (with 6 *m*H coils at 1000 yards spacing) for the purpose.

(2) Where transmission and crosstalk conditions permit, on existing submarine cables laid primarily for audio-frequency working.

(3) On new submarine cables laid for high-frequency working, in order to utilise the lower portion of the frequency spectrum.

No additional three-circuit aerial carrier equipment is being ordered. Coaxial cables have been laid for

---

[1] See Bibliography.

telephone circuits between certain zone centres; two of the four coaxial pairs in the cables are being used for telephony (one for each direction of transmission) and the other two tubes are available for the transmission of television programmes or for additional telephone circuits.

CABLES.

General.

The use of multi-circuit carrier telephony on cables necessitates either pairs lightly loaded at close spacing or non-loaded pairs in order to obtain transmission of a wide frequency band; in this and other countries both methods are in use. Considerable savings are effected by omitting loading coils, although a heavier gauge conductor may be used to reduce the higher attenuation of non-loaded pairs.

The use of non-loaded pairs also avoids interference due to cross-modulation in coils. Dielectric losses become more important at higher frequencies, but air-space, paper-core cable of normal pair type is satisfactory up to 150 kc/s at least. Skin effect in the wires has an appreciable effect in the range of twelve-circuit carrier frequencies, increasing the effective resistance and decreasing slightly the natural inductance, both these changes giving increased attenuation. A slight increase in attenuation also results from the losses in the lead sheath in achieving its function as a screen. Consideration of the above and other relevant factors has resulted in the use of 40 lb., non-loaded, star-quad, air-space, paper-core cable for twelve-circuit carrier working.

New types of cable.

With the development of multi-circuit carrier working which has taken place in the last three or four years, four new or modified types of cable have been developed and introduced. They have mostly been described in various articles, but their salient features and uses are given below.

1. Non-loaded, A.S.P.C., 12 quad, star quad, 40 lb. lead-sheathed cables for twelve-circuit carrier working, with a separate cable for each direction of transmission. Extra separation of the wires of a quad gives a nominal capacity of 0.057 microfarad per mile as compared with the usual value of 0.066 for audio type star-quad cables. This, combined with extra paper round the complete cable core, results in an overall sheath diameter for a twelve quad cable of 1.15 inches which is the same as for a 19 quad 40 lb. (or a 12 quad 70 lb.) audio-frequency cable. Two such cables, with rubber wax covering as a protection against corrosion or electrolysis where necessary (giving an overall diameter of 1.30 inches), are drawn together into one 3¼ inch duct way. More than two different quad lays are used (to improve crosstalk), and limits in microhenries are specified for the magnetic couplings. The increase in the thickness of the wrapping round the complete cable core is from 0.02 to 0.05 inch; this is advantageous in reducing the effect on crosstalk and attenuation of eddy currents in the lead sheath. This type of cable is now used extensively for zone-to-zone and some zone-to-group circuits: being of a simple construction it is easy to repair and jointers need no special training.

2. Concentric type, paragutta dielectric submarine cable with 508 lb. per nautical mile central conductor, and 852 lb. per nautical mile return conductor, the latter in the form of a tube of copper tapes. (See Figs. **1** and **2**.) This type of cable, which is suitable for deep sea work, has been laid between the following places:—

(i) England to Holland; two cables in 1937.
(ii) Eire to N. Wales; one cable in 1937 and another in 1938.
(iii) Northern Ireland to S. Scotland; two cables in 1937.
(iv) England to Channel Islands; one cable in 1938.

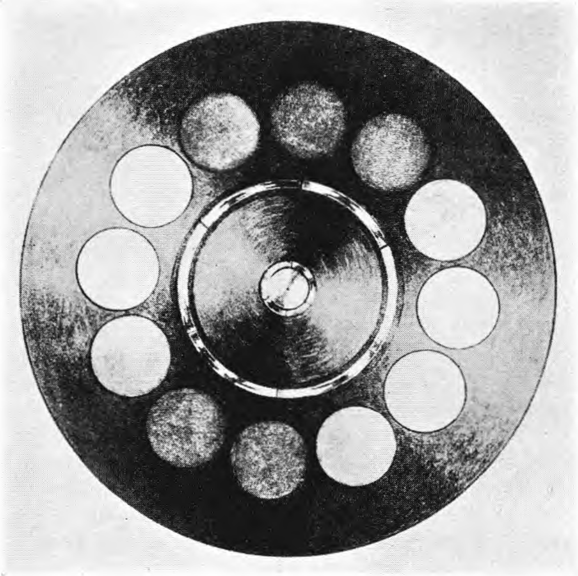


FIG. **1**.

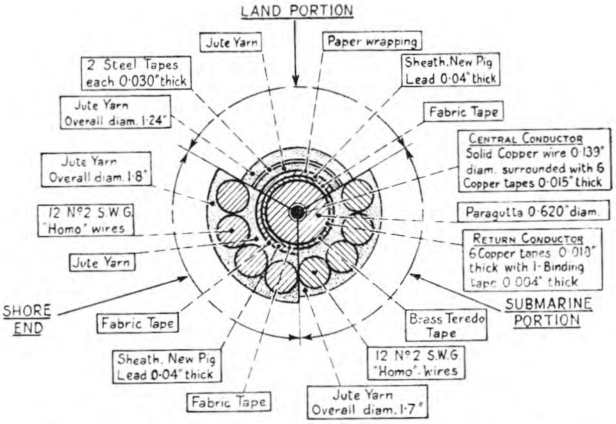


FIG. **2**.—CONCENTRIC TYPE PARAGUTTA DIELECTRIC CABLE.

Crosstalk between concentric cables improves with increase in frequency; this factor, combined with the low attenuation due to the heavy gauge conductor and low capacity, renders this type of cable suitable for the higher frequencies required by multi-circuit carrier working. The number of circuits obtainable is governed by the length of the cable.

A separate cable may be used for each direction of transmission [as in cases (i), (ii), and (iii) above] or two different frequency bands on one cable may be used to provide channels in opposite directions, *i.e.*, grouped-frequency working [as in case (iv) above]. The use of the same type of cable for several routes has considerably simplified the problem of the convenient storage of spare cable for repairs.

3. Coaxial type cable with dielectric mainly of dry air. This type of cable is being used for multi-circuit carrier telephony, with a separate coaxial pair (see Appendix No. 1) for each direction of transmission and to provide for the transmission of television programmes. It has been fully dealt with elsewhere[1].

4. One-pair, screened, low-capacity cable with dielectric mainly of dry air. One type actually in use (see Fig. **3**) has kinks in the copper conductors at intervals of two inches to support each conductor in a paper tube: successive kinks are in planes at right angles to one another and the two paper tubes are twisted in the usual way. The construction provides a maximum of air dielectric and wide separation between the conductors; this results in low capacity, low dielectric losses, high inductance and consequently lower attenuation. Each pair is screened by a spiral of copper tapes which is covered by a lead sheath to form a complete cable. A wide range of frequencies may be employed due to the adequate screening and the low losses. This balanced-pair type cable, unlike the unbalanced coaxial or concentric type cables which have one conductor earthed, is also satisfactory from the point of view of screening (*i.e.*, crosstalk and interference) down to very low audio-frequencies and hence is suitable for music transmission and for television transmission (which requires frequencies practically down to zero) without group modulation of the complete band of frequencies. A single cable of this type was laid on several routes in London in 1937 for television purposes[2], and two cables of this type were laid in S. Scotland and in Northern Ireland on the Belfast-Stranraer carrier route in 1937 for telephone circuits[3].

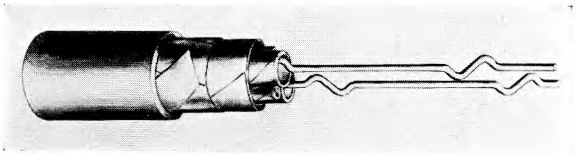


FIG. **3**.

Crosstalk and noise.

The subject of crosstalk has been dealt with elsewhere[4], but a number of primary considerations and factors affecting it are considered briefly here.

The problem of crosstalk between circuits is more difficult with carrier than with audio-frequency working; interference on external cables and internal wiring is greater at higher frequencies, lower received levels than with audio-frequency circuits are usually employed (giving greater level differences) and there is also interference in valves, transformers, and other components which carry more than one circuit. Intelligible crosstalk, " babble " and noise must be kept at a sufficiently low level.

Near-end and far-end crosstalk.

To avoid the limitations of two-wire working, all audio-frequency trunk circuits are now provided on a four-wire basis; the " go " pairs and " return " pairs in many cases are segregated into separate cable groups to improve crosstalk. The same principle has been adopted for carrier circuits. Between pairs which transmit in the same direction (*i.e.*, within a group), far-end crosstalk causes interference[5]; between pairs which transmit in opposite directions (*i.e.*, between groups) near-end crosstalk (and reflected far-end crosstalk) causes interference.

The use of the maximum length amplifier spacing consistent with reasonable amplifier design and the use of normal transmitting levels entails low receiving levels and a large difference in level at repeater stations between " go " and " return " groups, particularly at higher frequencies at which the cable attenuation is greater. As interference is also worse at higher frequencies, very good separation or screening between groups is essential. Hence for Carrier System No. 4 (one audio plus four carrier circuits) on existing cables the " go " and " return " groups are separated by a number of pairs carrying audio-frequency circuits, and for Carrier System No. 5 (twelve-circuit carrier system) separate lead sheathed cables are used; the latter provide electrostatic screening, and the electro-magnetic shielding is also good, particularly at higher frequencies. The lowest receiving level on an audio-frequency cable is about –25 db. relative to 1 milliwatt whilst on a twelve-circuit carrier cable it is at present about –55 db. Hence for a signal-to-noise ratio of 70 db. on a repeater section a near-end crosstalk value of 130 db. between cables is required. The values actually specified are 135 db. for 95% of all combinations and 125 db. for all combinations, at a frequency of 60 kc. In some cases this has necessitated the fitting of a sheet metal screen between the " go " and " return " cable test-tablets to reduce their contribution to the crosstalk. Measured values of near-end crosstalk between cables at 60 kc/s vary from about 130 to 155 db. and upwards.

Far-end crosstalk between pairs within group is dealt with later.

Quad lays.

The lengths of the twisting pitches, or lays, of the quads in a cable have an important effect on the crosstalk. The use of equal lays for quads (or for pairs in a pair cable or a multiple-twin cable) makes the cross-talk worse, but it can be improved by separation. For economy in manufacture a minimum number of lays is desirable; hence, in coil-loaded cables it is usual to employ two values of quad lay per layer, adjacent quads having different lays.

[1, 2, 3, 4.] See Bibliography.

[5.] See Bibliography.

The lay is one of the most important factors affecting the magnitude of a complex magnetic coupling between two circuits through a third intermediary circuit. With equal lays the value of the coupling is larger, the real part becomes larger and the variation with frequency is also increased. All these factors render more difficult the improvement of the distant-end crosstalk by means of networks. The use of different lays for neighbouring quads reduces appreciably these difficulties. In the case of the Bristol-Plymouth experimental scheme[6] which employed two twin cables each having 19 pairs, a different lay was employed for each pair. Subsequently it has been found desirable to use a different lay for each quad in the 24 pair star-quad carrier cables.

Electromagnetic and electrostatic coupling.

The crosstalk between two circuits is given by the expression Crosstalk $= Kf\left(\frac{M}{Z} + EZ\right)$ where K is constant, f is the frequency, Z is the circuit impedance, M is the electromagnetic coupling factor and E is the electrostatic coupling factor. The crosstalk between two circuits may be considered to be due to the presence of mutual impedances (series elements) and mutual admittances (shunt elements). Mutual impedance results in an E.M.F. in series with the disturbed circuit and the resulting crosstalk is known as " impedance crosstalk," " electromagnetic crosstalk " or " magnetic crosstalk." The mutual admittance results in an E.M.F. in parallel with the disturbed line and is known as " admittance crosstalk," " electrostatic crosstalk "or " electric crosstalk."

The magnetic coupling between two circuits is influenced largely at higher frequencies by the presence of the lead sheath, and, to some extent, of the other conductors, both of these acting as intermediary coupling circuits by reason of the eddy currents induced in them by the disturbing circuit. These indirect couplings giving " indirect crosstalk " must be taken into account as well as the direct couplings. The effect of the lead sheath is minimised by using a thicker layer of paper than usual over the cable core, as stated above, so as to increase its distance from the lead sheath.

The coupling between two circuits through a third circuit such as the lead sheath is reduced according to an exponential law as the separation from the third circuit is increased. Hence it is the initial small increase in the separation which is most effective. Wuckel[7] has shown that the sum of the direct and indirect voltages from a disturbing circuit (1) induced in a disturbed circuit (2) in the presence of a third intermediary circuit (3) of impedance $R_3 + j\omega L_3$ is given by the formula

$$V = -I_1\left\{ j\omega m_{12} + \frac{\omega^2 m_{13} m_{23}}{R_3 + j\omega L_3} \right\}$$

where I_1 = current in circuit (1),
m_{12} = inductive coupling between circuits (1) and (2),
m_{13} = inductive coupling between circuits (1) and (3).

This is a complex quantity in which both the real and imaginary components are dependent on frequency. Hence in some cases a complex network is required to reduce the crosstalk. Broadly, it may be said that for a short length of cable, crosstalk due to electrostatic and electromagnetic couplings (*i.e.*, electric and magnetic crosstalk) increases approximately in proportion to the frequency, provided the circuit impedance remains constant. The circuit impedance of a non-loaded cable increases considerably at lower frequencies, and crosstalk due to capacitive coupling varies directly as the impedance of the circuits whilst the crosstalk due to inductive coupling is inversely proportional to the impedance. The combined result of using higher frequencies and non-loaded cable is that magnetic crosstalk becomes relatively a much more important factor in balancing carrier cables. Magnetic crosstalk is dependent solely upon the geometrical arrangement of the conductors.

Since the real components of the couplings are small, either capacitance or inductance may be used to reduce the unbalance. For complete balancing of direct crosstalk[4] at all frequencies a combination of resistance, inductance and capacitance would be required. Indirect crosstalk, *i.e.*, *via* a third circuit such as a phantom, which has a different phase change per unit length, limits the effectiveness of the balancing, since the currents do not all arrive at the receive end in phase ; hence a different network is required at different frequencies for the best results. In practice a compromise balance has to be used when appreciable indirect crosstalk is present.

Noise.

The transmitted current at any point of a circuit should not be allowed to fall below a power of about 65 db. above the combined power of resistance noise and valve noise. Assuming a normal transmitted power, this at once sets a limit to the maximum attenuation length of a repeater section of cable, and it is important to be able to calculate the level of power due to noise.

" Resistance noise " is due to the electronic movements present in all conductors which produce a " thermal agitation voltage."

The expression for this voltage is given by Johnson as

$$E^2 = 4kT\int_{f_1}^{f_2} R.\,df.$$

where E is the R.M.S. e.m.f. in volts produced between the frequency limits f_1 and f_2 at the terminals of a conductor of resistance R ohms ; k is Boltzmann's gas constant in joules per degree Centigrade and T is the absolute temperature of the conductor on the Kelvin scale.

Since the energy is produced by a random effect, it is distributed equally over a very wide range from audio to radio frequencies.

6, 7. See Bibliography.

4. See Bibliography.

If R is constant over the frequency range considered then

$$E^2 = 4kTR\,(f_2 - f_1)$$

$$\therefore\ \frac{E^2}{R} = 4kT\,(f_2 - f_1)$$ which is an equation having the dimensions of power. Hence the power is directly proportional to absolute temperature and to the frequency band width.

The value of k is 1.37×10^{-23} and if $T = 288°$ (*i.e.*, 15°C), then

$$\frac{E^2}{R} = 1.60 \times 10^{-20}\,(f_2 - f_1)\text{ watts.}$$

For a band width of 300 to 2,600 c/s the value of $\frac{E^2}{R}$ is 3.68×10^{-17} watts, which is 134.3 db. below a milliwatt; this is the noise level in each telephone channel per repeater section, if the channel band-width is 2,300 c/s.

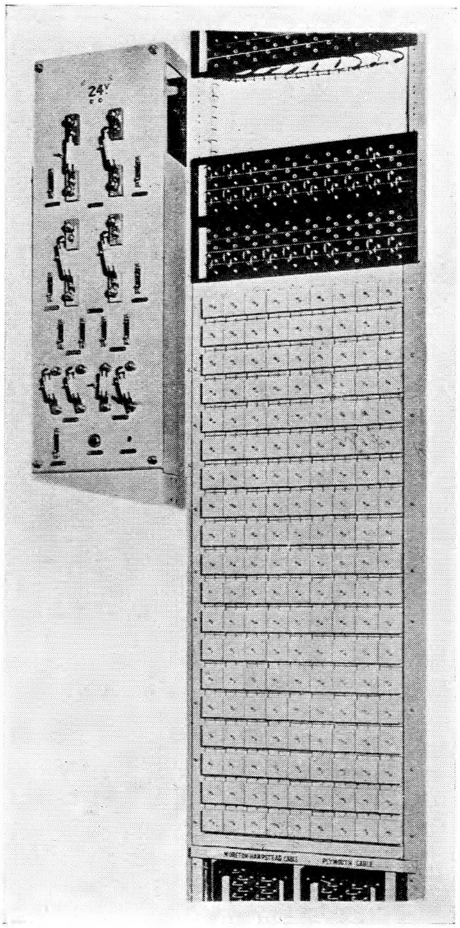


FIG. 4.

The accuracy of the formula, at room temperature and for a band-width up to 6,000 c/s, has been verified by measurement. It has also been verified that where the impedance of the grid circuit of the first valve is not a pure resistance, the use in the formula of the real part of the impedance gives a figure equal to that obtained by experiment.

Since the current in a valve from anode to cathode consists of the passage (from cathode to anode) of individual electrons differing in velocity, the flow across any inter-electrode plane is not constant for all small periods of time. This results in noise which is distributed over the frequency spectrum. There is no simple formula for the calculation of valve noise, but measurement has shown that for valves in normal use it is of about the same level as the resistance noise, and therefore the combined power of the two sources is about 130 db. below a milliwatt. Hence, for a signal-to-noise ratio of 65 db. on one repeater section, the received signal power should not fall below −65 db.

On twelve-circuit carrier systems a maximum of 22 miles has so far been fixed for repeater station spacing; this gives a specified attenuation length of 61.5 db., and with a sent power of +5 db. (relative to 1 *m*W) per circuit, the received power level is −56.5 db., which leaves a substantial margin over the calculated value of −65 db. Very few stations can actually be spaced at the maximum distance and the margin is correspondingly greater.

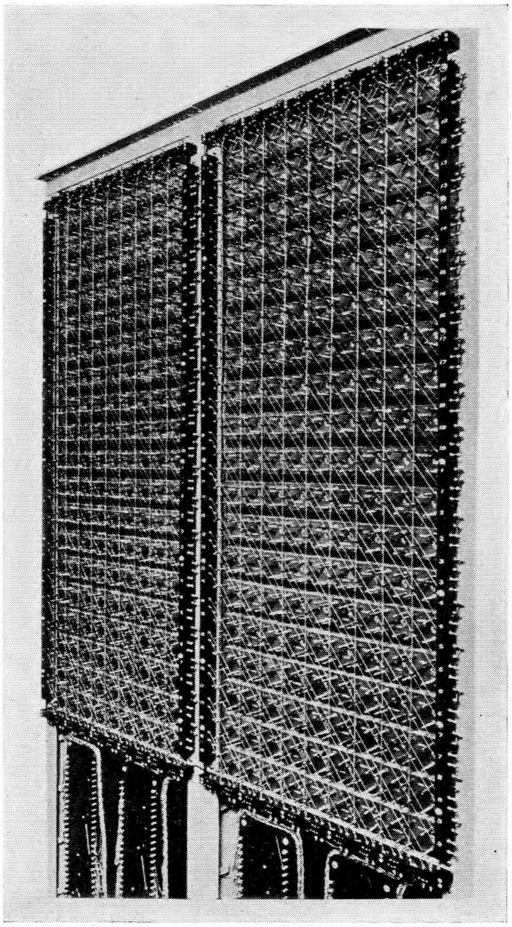
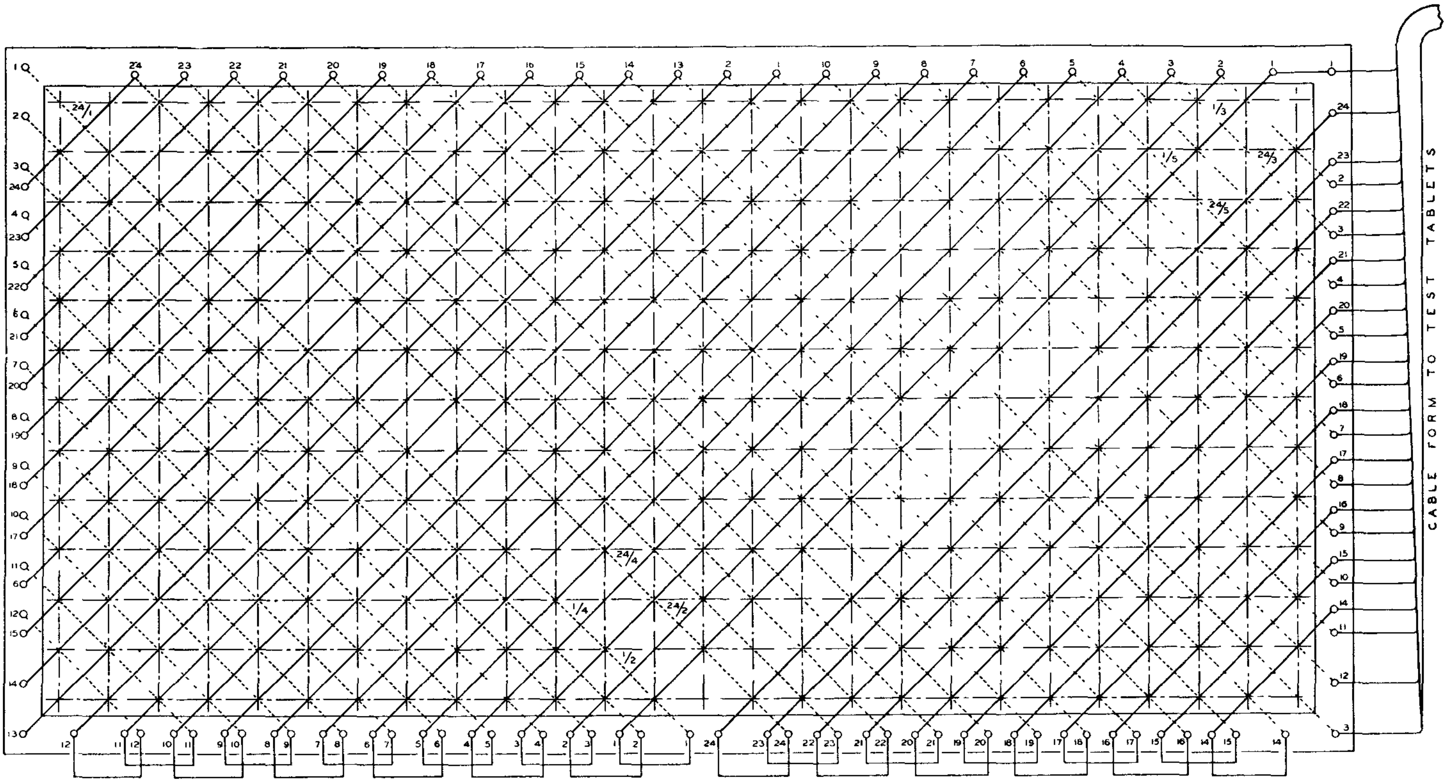


FIG. 5.



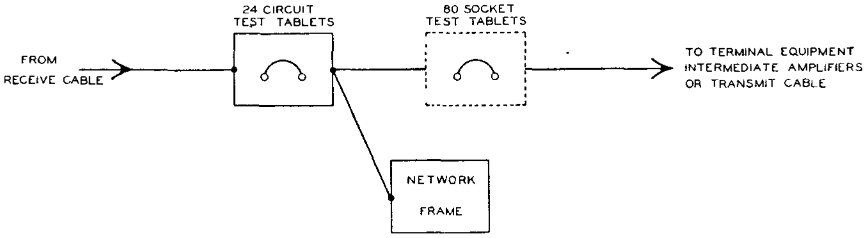


Fig. 6.—Far-end Crosstalk Balancing Networks. Schematic Wiring Diagram.

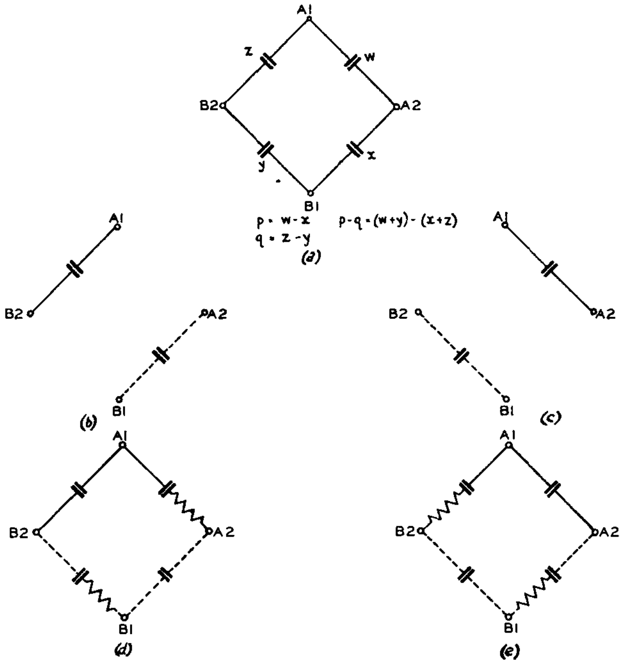


Fig. 7.—Connections of Far-end Crosstalk Balancing Networks. Alternative Connections are shown dotted.

Note :—A Resistance may also be required in Figs. (*b*) and (*c*).

In the case of audio plus four carrier circuit (" 1 + 4 ") equipment, for which the field of use is mainly on existing cables where the " go " and " return " circuits are in the same lead sheath, the limit to amplification is set, not by noise conditions, but by near-end crosstalk. The signal-to-crosstalk ratio for each repeater section is the near-end crosstalk less the repeater section attenuation at the frequency concerned, and on existing cables it is possible to arrange the grouping of " go " and " return " circuits so that near-end crosstalk is satisfactory on a repeater section of about 40 db. attenuation. The distant-end crosstalk, as in the case of twelve-circuit carrier cables, can be improved by balancing networks.

Where a standardised type of cable is in use and the minimum repeater station spacing is limited (as for example, in the case of a submarine cable), more circuits can be obtained by working to a higher frequency and therefore to a higher attenuation, if higher transmitted levels are used to keep the minimum received level above −75 db. A " high power " scheme considered for use on the Anglo-Dutch 1937 cables and transmitting a kilowatt to line is dealt with elsewhere in the paper.

With regard to extraneous sources of noise, cable pairs are sufficiently protected by the wires being balanced with respect to earth and by the screening action of the lead sheath.

Far-end crosstalk balancing.

It has already been stated that near-end crosstalk is made satisfactory on twelve-circuit carrier cables by the use of a separate cable for each direction of transmission; in the case of "1 + 4" type equipment on land cables laid for audio-frequency working, a similar result is obtained by using separate groups of quads for "go" circuits and "return" circuits (with separating quads where required). There remains in each case the problem of far-end crosstalk within a cable or group of quads.

The crosstalk is due to capacitance and inductance unbalance (neglecting the effect of leakance unbalance), and may be reduced by joining condensers or inductors between each combination of cable pairs which has crosstalk worse than the desired minimum. This method of reducing crosstalk has been used for audio-frequency circuits in Germany and elsewhere for many years and on some cables in this country, in place of test-selected joints. Its application to the reduction of far-end crosstalk only (between circuits having the same electrical constants) is considerably simplified because a balancing unit is required at only one point of the circuit: this is due to the fact that the crosstalk currents due to the various couplings between the circuits have the same distance to travel (viz., the total line length) and so at any particular frequency have the same phase change due to the cable, whilst the phase change due to the various crosstalk couplings is small; hence all the crosstalk currents are very nearly in phase at the receiving end and so may be balanced out by a network at that point. Also, since the far-end crosstalk between two circuits is the same at both ends (being due to precisely the same unbalances) the balancing unit may be at either end (or at any other point) of the repeater section.

On the first twelve-circuit carrier installations the networks were fitted in specially provided buildings situated at the mid-points (approximate) of the repeater sections; this was to avoid affecting the cable impedance presented to the equipment and the consequent reflection difficulties. If the network is placed at the receiving end of the cable it will itself constitute a path for any reflected energy to pass as near-end crosstalk into the disturbed circuit where it will add to the far-end crosstalk. An investigation into the effect of the terminal impedance on far-end crosstalk, when the networks are at the end of the repeater section, has shown that the degradation due

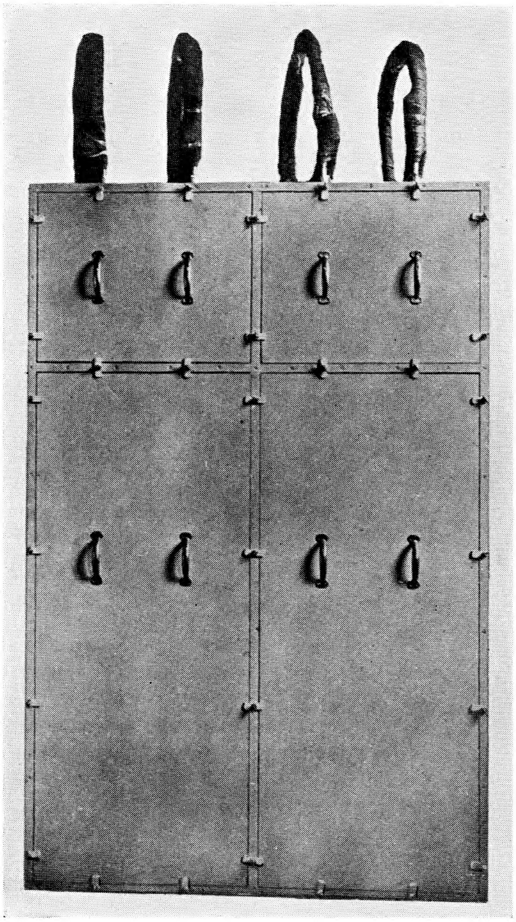


Fig. 8.

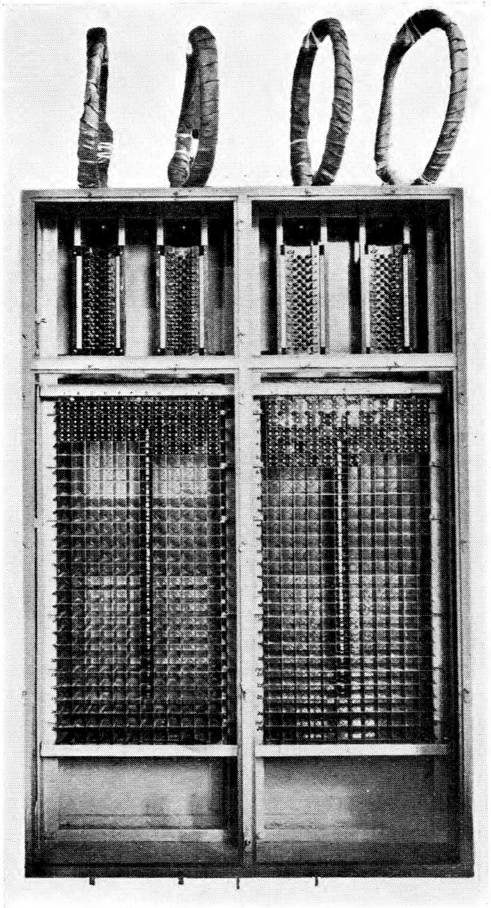


Fig. 9.

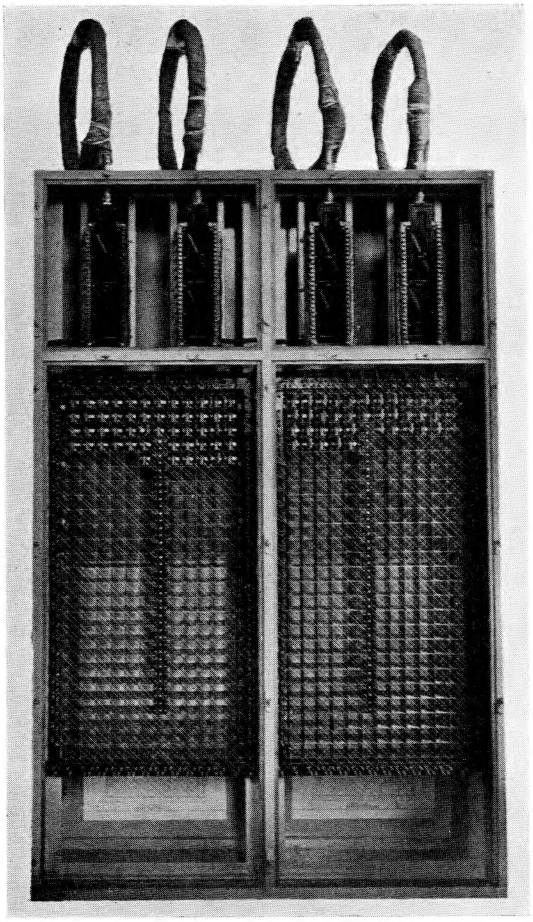


Fig. **10.**

to the networks being at the end is less than 2 db. Hence it is now the practice to fit the networks at the receiving end of every repeater section, *i.e.*, at a low level point. This applies to both twelve-circuit and to " 1 + 4 " type carrier installations.

As already stated, either capacitance or mutual inductance may be used for balancing ; the former is at present used in this country since it is a simpler arrangement. For reasons indicated previously, crosstalk currents may be due to complex quantities and therefore it is sometimes necessary to use a complex balance (*i.e.*, resistance and capacitance) instead of the comparatively pure reactance provided by a condenser.

The balancing procedure for twelve-circuit carrier cables is accordingly as follows:—

Balancing by test-selected jointing is carried out on each cable in the usual way ; Appendix No. 3 gives a brief outline of this procedure as used by two manufacturers, together with some typical results. Far-end crosstalk on each complete repeater section of cable is then reduced by joining in circuit and adjusting as required the far-end crosstalk networks. The total number of networks required to balance each pair against every other pair is $\frac{n(n+1)}{2}$ where " $n + 1$ " is the number of pairs in the cable. For the 24 pair cables in use for twelve-circuit carrier equipment the number is 276, and the frame containing the networks is designed to accommodate this number.

A brief description follows of the frames and networks provided by the manufacturers.

Distant-end crosstalk balancing network frames.

Messrs. S.T. and C. type.

Figs. **4** and **5** show front and rear views respectively of the frame with condensers and wiring. Adjustable differential air condensers each enclosed in a screening box are used ; they are mounted on mild steel strips, and the connection tags at the rear are soldered to the uninsulated, 19 gauge, tinned-copper cross wires. The latter are joined to terminals at the top and bottom of the frame whence cable forms lead to the internal side of the 24-circuit test tablet on both the " up " and " down " cables. The cross wires are thus in the transmission path ; they are arranged as shown in Fig. **6** so that a network can be connected between any two pairs.

Using the normal nomenclature [as shown in Fig. **7**(*a*)] for capacitance between pairs, the unbalance to be reduced between each pair is $(p - q) = (w + y) - (x + z)$. Hence either x or z may be increased if $(p - q)$ is positive ; this is shown in Fig. **7**(*b*). If $(p - q)$ is negative, either w or y may be increased as shown in Fig. **7**(*c*). The use of differential condensers enables them to be connected to the cross wires (*e.g.*, B2, A1 and A2) in the factory and capacity may be inserted to increase z or w as required by adjustment after installation. In those few cases where resistors are required they are inserted on site, the chemical type being used.

If installed in an unheated hut the network frame and cable test tablets are enclosed in a cabinet with tightly fitting covers having rubber packing. Fig. **8** shows the external appearance which is similar for frames of all three manufacturers. The covers have containers for silica gel packets. This maintains the insulation resistance of the networks in the unheated buildings and so enables initial cable fault localisation tests to be made from the repeater stations: it also reduces the risk of leakance unbalance on the networks affecting the crosstalk.

Messrs. Siemens Brothers type.

This differs from the type already described in three main respects:—

1. Instead of individual screening boxes for each condenser, a " nest " of compartments is provided, each one containing a network. The nest is made of tinned brass, 0.034 inch thick, and is constructed like an egg box. (See Figs. **9** and **10.**)
2. The variable condensers used have a ceramic dielectric of permittivity 80 ; the plates are of silver, fired on to the dielectric at a temperature of about 500°C. The I.R. of the con-

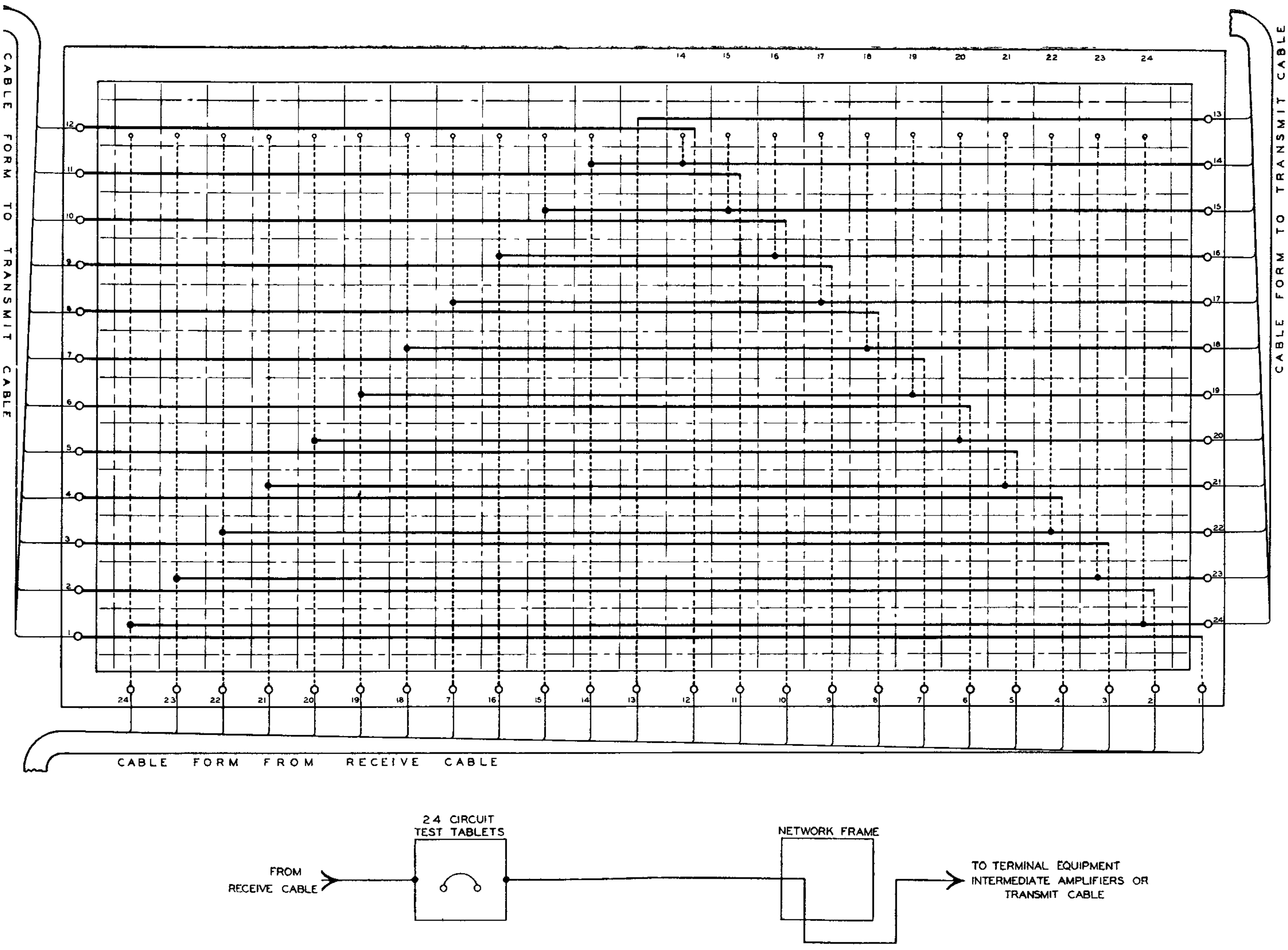


FIG. 11.—FAR-END CROSSTALK BALANCING NETWORKS. SCHEMATIC WIRING DIAGRAM.

densers is not lower than 50,000 megohms under laboratory conditions. As at present installed the condensers are not differential, and so two are fitted on each mounting for joining in the *z* or *w* position, the one not required being set to minimum value. The mounting can also carry on each side two " M " type T.C.C. condensers and a chemical resistor: hence large and complex unbalances can easily be dealt with.

3. There is one cable form only, taken to the top of the network frame from the receiving cable test tablets, the cross wiring being a tee from the transmission path.

The " 1 + 4 " type carrier equipment has been applied to the Liverpool-Glasgow (1934) cable with 30 pairs in both the " go " and " return " groups (and separator quads between) and to the Anglo-Belgian (1932) cable which has 30 pairs on each side of the diametric screen. For these and similar cases a frame has been designed to accommodate 30 pairs, *i.e.*, 435 networks. It is similar in design and construction to the type just described.

Messrs. G.E. Co. type.

In this case the cross wires are horizontal and vertical as shown in Fig. **11**. Fig. **12** shows the front view of a completely equipped frame. On the London-Cambridge route the networks are fitted on bakelite panels, but a later type of frame dispenses with these and uses steel strips. A differential air condenser is used ; it has no screen but is protected by a thin bakelite cover. Where necessary a resistor can be joined to the condenser terminals.

Fig. **13** shows the types of network used by the three manufacturers.

Network cabinets for repeater stations.

With the present practice of installing the balancing networks in repeater stations, completely air-tight cabinets are not required and a simpler cabinet for mechanical protection is provided.

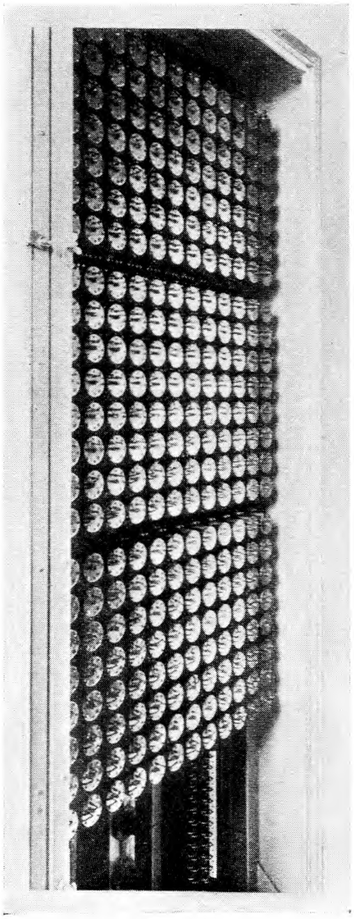


Fig. 12.

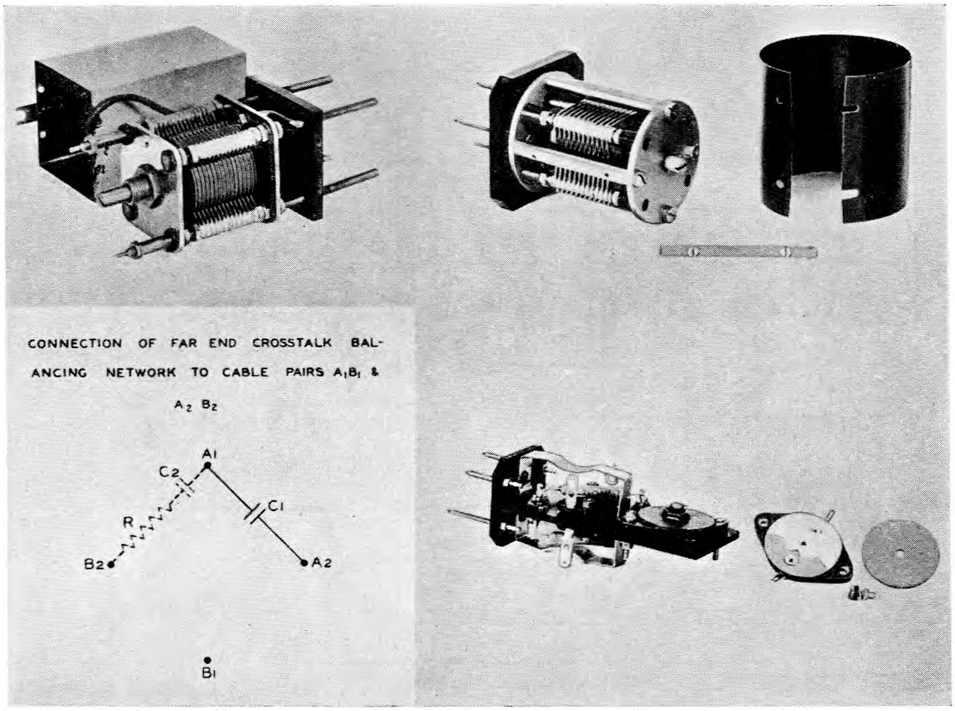


Fig. 13.—Far-end Crosstalk Balancing Networks.

EQUIPMENT.

Basic types.

The basic requirements of the equipment constituting a multi-circuit carrier group are as follows:—(i) a band of audio frequencies broad enough to ensure adequate intelligibility and quality must be raised to any desired position in the frequency spectrum, *i.e.*, modulated, (ii) a number of such modulated bands must be combined and transmitted on a common path without mutual interference and without undue attenuation or distortion, (iii) at the receiving station the modulated bands must be separated and restored to their original frequency form, *i.e.*, filtered and demodulated.

The basic form on which almost all modern systems are designed is described below. One end of such a basic "four-wire" circuit is illustrated in Fig. **14**. A circuit end of a particular type of equipment may or may not include all of the items indicated. Only one stage of frequency changing is shown, but, in certain cases, more than one stage is used.

Audio frequencies may pass first *via* a low-pass filter the function of which is to restrict the band-width to be modulated to somewhat less than the channel band-width available. Should audio frequencies of values in excess of the carrier frequency separation be modulated, frequencies lying within adjacent channel bands would be produced, *i.e.*, inter-channel interference would result.

Inter-channel interference is also reduced by the use of a voltage limiter which is usually placed at the input of the low-pass filter (if provided). A limiter prevents peak voltages in the speech waveform from reaching the modulator where they would tend to cause (*a*) over-modulation of the carrier voltage and (*b*) overloading of the common line amplifiers. It further ensures that, in the event of a circuit becoming unstable, the oscillatory currents cannot build up

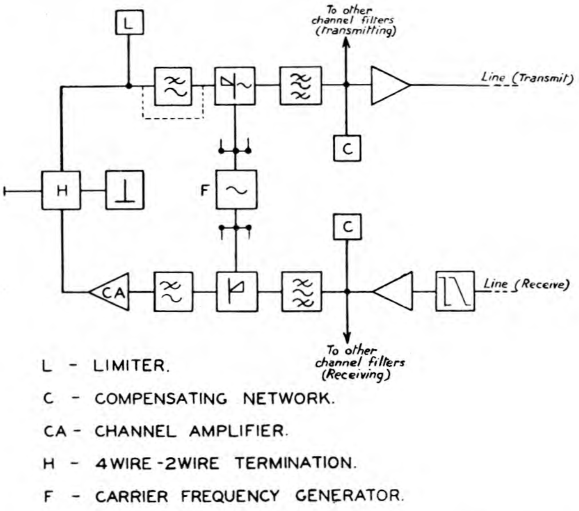


Fig. 14.—Schematic of Typical Four-wire Carrier Circuit End.

to such a magnitude as to overload the line amplifiers. The types of voltage limiter in common use function on the following principle: to voltages lower than a pre-determined level the limiter appears as a high impedance across the line, but to voltages in excess of that level its impedance is very low and the voltage applied to the modulator is reduced accordingly. Two types of voltage limiter are in general use; they are of the neon tube and dry plate rectifier types, and are illustrated in Figs. **15** and **16**. Sometimes the inherent limiting action of a modulator is utilised and the employment of separate limiters avoided.

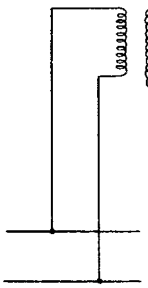


Fig. **15**.—Neon Tube Limiter.

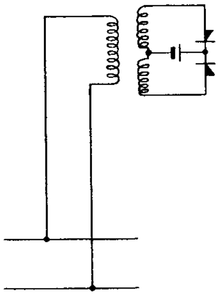


Fig. **16**.—Rectifier Limiter.

In the case of the neon tube its impedance is high unless its " striking " voltage is reached, when the impedance drops to a low value. The step-up ratio of the transformer, across the secondary of which the neon tube is placed, is so adjusted that the tube " strikes " when the voltage at which limiting is desired is applied at the input terminals. The limiting voltage can be adjusted only by altering the transformation ratio.

In the rectifier type of limiter, two rectifiers in series opposition are back-biased (by means of a potential obtained usually from a potentiometer across the L.T. supply circuit) to such a value that the forward as well as the backward impedance is high. If the peaks of the applied A.C. voltages are in excess of the bias voltage the forward impedance of the rectifiers drops to a low value for the duration of the peaks, and the required shunting condition is obtained. This form of limiter has the advantage that the transformer need have only a small step-up ratio (this is, therefore, a smaller and cheaper transformer) and that the limiting voltage can be altered by adjusting the rectifier biasing voltage.

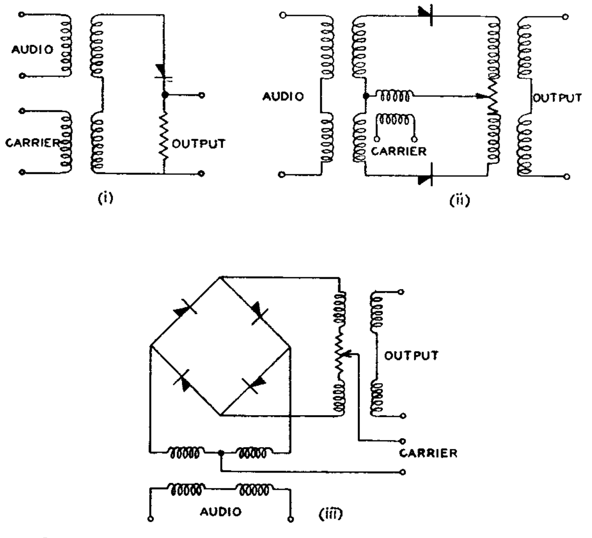


Fig. **17**.—Three Types of Modulator Network.

After being subject to limiting and filtration, speech frequencies pass to the modulator. There are many forms of modulator, but they invariably consist of a network of non-linear impedance elements to which the carrier and modulating voltages are applied. They are usually so designed that the carrier voltage itself is suppressed in the output circuit and so that frequencies other than the wanted sideband frequencies are reduced to a minimum: the applied modulating frequencies may also be suppressed. Three forms of modulator are illustrated in Fig. **17**. The type shown in (i) is the simplest form of modulator it is possible to construct. Frequencies equal to those applied, to their sums and differences, to multiples of them and to their higher orders of sums and differences, are obtained across the load resistance.

A balanced type of modulator circuit is indicated in Fig. **17** (ii). If the halves of the circuit are electrically similar the carrier frequency, which is applied on a line of electrical symmetry, will be balanced out of the output circuit. Hence in the output circuit there will be present frequencies equal to the applied audio-frequency, multiples thereof, certain sum and difference frequencies, and multiples of the carrier frequency and higher orders of sums and differences. In general, the simple sum and difference frequencies are those of greatest magnitude, and it is one of these frequencies which is selected and transmitted to line.

In the double balanced (or bridge) type of modulator, a simple form of which is illustrated in Fig. **17** (iii), the output contains frequencies similar to those produced by the simple balanced modulator with the exception that the audio-frequency and certain other unwanted frequencies are not present. In general the unwanted products of modulation are smaller in this type of bridge than for any other and it is the one most commonly used in modern carrier systems. The subject of modulation is dealt with at greater length in Appendix No. 2.

Of the two side-band frequencies (carrier plus audio and carrier minus audio) produced in the modulator, one is selected by means of a band-pass filter for transmission to line. The functions of the band-pass filter may be summarised as follows:—(i) on the input side it suppresses unwanted frequencies and (ii) on the output side it prevents the output power from other channels being absorbed in the modulator. All of the channel band filters are connected on one side to the transmitting line amplifier.

For details of the design and construction of filter networks employing the normal coil types of inductors reference should be made to other papers[8, 9]. It is this type of filter which is used most commonly in carrier equipment in which the line frequencies do not

---

[8, 9] See Bibliography.

exceed, say, 60 kc. It is essential in certain developments and where high carrier frequencies are employed that band filters should have extremely sharp cut-offs; this requirement and the low ratio of band-width to mid-band frequency make necessary the use of filter components having very high " Q " values (" Q " being the ratio of reactance to resistance) and it has been found desirable to employ cut crystals of quartz as filter elements[15, 16, 17, 28]. When several filters are paralleled on one side, the design should be such that the equivalent inductance and capacitance across any one filter, due to the other filters in parallel, should resonate at its mid-band frequency. Hence networks are necessary at the common point of the filters to compensate for the lack of filters dealing with the frequencies outside those with which the system is concerned; these are often known as " compensating networks."

Line amplifiers, for both transmitting and receiving, must have a high degree of stability of amplification both with change of operating voltage and valve changes. In addition it is essential that a line amplifier should have a minimum of phase shift throughout the frequency range to be amplified, very little harmonic distortion, and a power handling capacity adequate to deal with the number of channels to be amplified simultaneously by it. The introduction of the negative feedback principle[10] enabled such amplifiers to be designed and rendered possible the rapid development of multi-circuit carrier telephony.

As the attenuation-frequency characteristic of a line is not constant with frequency it is necessary to compensate for attenuation distortion by an equaliser. Equalisation could be obtained by modifying the performance of the line amplifiers either by providing resonant circuits in the amplification path or by modifying the feed-back path to give the required overall characteristic. To use either of these alternatives would involve, due to unequal repeater section attenuations, the provision of amplifiers the characteristics of which would not be uniform one with another; in addition, obtaining equalisation by modification to the feedback circuit may, under certain conditions, involve instability. It is the practice in this country to use an attenuating network having an attenuation-frequency characteristic which is inverse to that of the line; it is placed at a point preceding the input to the receiving line amplifier. These networks are usually of the constant impedance (Zobel) type[11]; they possess the advantages that they do not complicate line terminating conditions and that sections may be added in series, the total equalisation being the sum of that of the individual sections. Equalisation by modification to the feed-back path is used in the United States of America, apparently with success.

The receiving band-pass filters (Fig. **14**) are similar to those used in the transmitting side. Demodulation is actually identical with modulation, the side-band being applied together with the carrier to the assembly of non-linear impedances. Audio frequencies from the output of the demodulator are usually of too low a level for direct application to the four-wire line, and hence a channel amplifier is used at this point. It is usual to insert a low-pass filter between the output of the demodulator and the channel amplifier. This filter prevents the application to the audio four-wire circuit of the demodulation products of leakage from adjacent bands and carrier leak from the demodulator.

The essential features of the carrier frequency generating equipment are (i) frequency stability, (ii) voltage output stability, (iii) purity of output waveform and (iv) low output impedance to ensure absence of crosstalk between frequency changers (modulators and demodulators) utilising the same carrier frequency supply. In some cases amplifiers or driven oscillators are provided between the actual carrier generators and the load.

In addition to the basic " four-wire " arrangements illustrated in Fig. **14**, carrier circuits may be worked with one pair only connecting the terminal stations. This may be effected by means of a two-wire arrangement as shown in Fig. **18** or by means of " group working," *i.e.*, the " go " and " return " channels of a circuit occupying different bands of the frequency spectrum (Fig. **19**). The arrangement shown in Fig. **18** is obviously the most economical in line plant, as the whole of the available frequency spectrum is used for transmission in both directions. In the arrangement shown in Fig. **19** approximately one half of the available spectrum is used for transmission in each direction; hence the line plant is used less than 50% as effectively as in the two-wire case. The grouped frequency method has the disadvantage that filtration is necessary at each point at which amplification is required, while the two-wire method requires the provision of differential transformers and balances at these points.

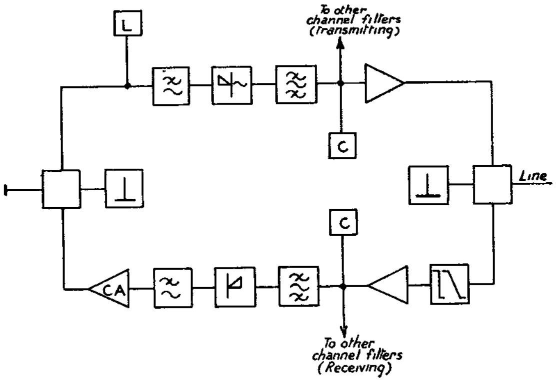


FIG. **18**.—SCHEMATIC OF TYPICAL CARRIER CIRCUIT END. TWO-WIRE ON LINE.

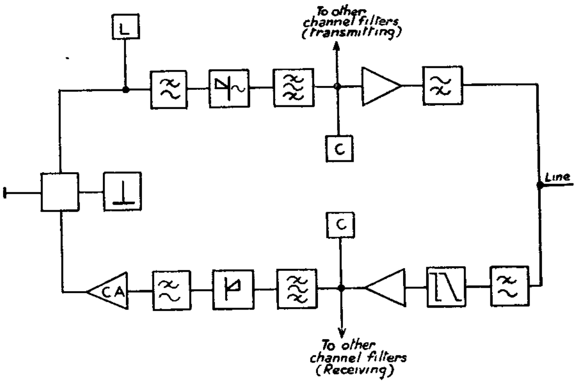


FIG. **19**.—SCHEMATIC OF TYPICAL CARRIER CIRCUIT END. GROUP WORKING.

15, 16, 17, 28, 10, 11. See Bibliography.

In addition, the two-wire scheme becomes impracticable as the attenuation-length is increased, due to the impossibility of obtaining adequate balance return losses. Applications of these methods of multi-circuit carrier working are specific rather than general.

Types in use.

There are at present in use in this country the following types of multi-circuit carrier equipments:—

(i) *Carrier System No.* 3. This system provides one audio and three carrier circuits on one aerial pair.

(ii) *Carrier System No.* 4. This type of equipment provides one audio and four carrier circuits on suitable cable pairs.

(iii) *Coaxial Cable Equipment.* This equipment is designed to provide 320 or 400 circuits (according to the frequency spacing) on two coaxial cable pairs. (See Appendix No. 1.)

(iv) *Twelve-Circuit Carrier Equipment.* Twelve channels are provided on each pair in specially designed cables, one cable being used for each direction of transmission.

To date, equipment of the types detailed as (i), (ii), and (iii) has been the subject of more descriptive literature than type (iv), which will therefore receive more attention here. The original Bristol-Plymouth twelve-circuit carrier equipment has received ample description[6], but this ground is being covered again in the following pages in order that the description of the latest type of equipment may be facilitated. The broad outline of twelve-circuit carrier working has been described by G. J. S. Little in a paper read before this Institution in 1938[12]. The extent to which twelve-circuit carrier equipment is now being used justifies dwelling at some length on its features.

Carrier System No. 3.

This system[13] is designed for aerial line routes ; two groups (each differing slightly in the carrier frequencies employed) may be used on any one route without undue crosstalk. It is used in this country mainly for installation on aerial routes which will probably be recovered and replaced by underground cable in a short time.

Carrier System No. 4.

This equipment[14] was designed to provide circuits on existing underground cable pairs which had been completely de-loaded or re-loaded with coils of small inductance. Equipment was first installed on pairs in the London-Oxford twelve-circuit carrier cables. It has also been used between Liverpool and Glasgow on 25 lb. conductors, which were loaded with 6 *m*H coils at 1000 yards spacing. This type of apparatus has also been used on submarine cables, the most extensive application in this connection being the provision of eight circuits (two " 1 + 3 " groups) between Belfast and Stranraer[3].

All the equipment actually in use has been manufactured by one contractor (Messrs. Siemens Bros.), and differs only in detail from that described by Messrs. Halsey and Millar[14]. The principal points of difference are as follows:—

(i) The carrier frequency generators (P.O. Oscillators Nos. 17A, B, C and D), differ from the No. 16 type oscillators and each consists of an electron-coupled oscillator circuit with a pentode buffer-amplifier stage, negative feedback being employed to give the required high degree of stability. It has been found that the oscillator frequency stability is reasonably satisfactory, and so far the use of temperature-controlled ovens to contain the oscillatory circuit components has not been found necessary.

(ii) Minor circuit changes have been made to the carrier frequency amplifiers which follow the oscillators, and different valves have been used.

(iii) The frequency changer circuit is as indicated in simplified form in Fig. 20.

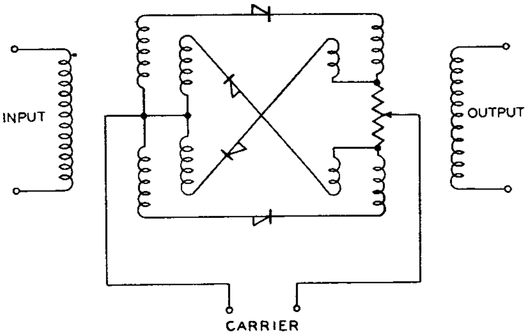


FIG. 20.—SCHEMATIC OF MODULATOR CIRCUIT. CARRIER SYSTEM NO. 4.

(iv) The filters have been made up of four-element instead of six-element networks ; the units are enclosed in screening cans, which are filled with wax.

(v) Valves Nos. 113 and 114 have been employed in the line repeater (Repeater No. 36A) in place of valves Nos. 106 and 107.

The performance of the equipment as provided is very similar to that designed by the Post Office. The details of the test equipment provided in conjunction with this type of apparatus are given elsewhere[3].

Coaxial cable equipment.

The type of equipment used to provide circuits on the London-Birmingham coaxial cable has been adequately dealt with[1] and no attempt will, therefore, be made to describe the system. The major features of importance, apart from the use of coaxial conductors, are the employment of group modulation and of crystal element filters[15, 16, 17, 28]. These features have affected the trend of design in other types of equipment.

Twelve-circuit carrier equipment.

Circuits are provided in the frequency range 12 – 60 kc., the carrier frequencies being the multiples of 4 kc. from 16 to 60 kc. inclusive. Lower sidebands are transmitted, the carriers being suppressed.

6, 12, 13, 14, 3. See Bibliography.

3, 1, 15, 16, 17, 28. See Bibliography.

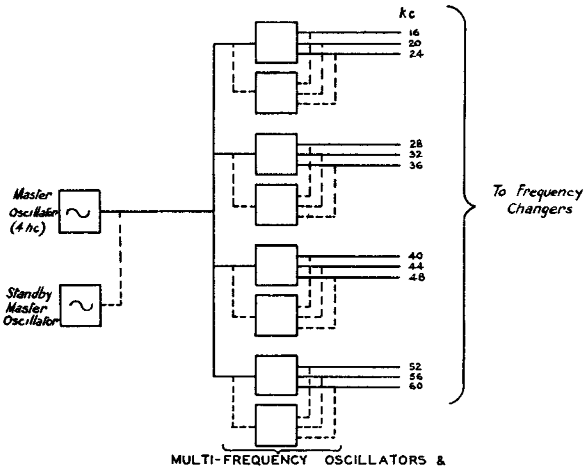
When the design of the equipment was commenced it was considered inadvisable to extend the range used to below 12 kc/s because (*a*) the small ratio of maximum to minimum frequency to be transmitted simplified the design of line amplifiers and (*b*) equalisation was simplified, as that portion of the attenuation-frequency characteristic of the line over which the variation of attenuation with frequency is large was not involved. Experience has since shown that a lower minimum frequency could have been used, but for the present a downward extension of the frequency range is not contemplated. Actually the 12 kc/s band available provides a useful frequency range for high quality (such as music) circuits; this matter is dealt with later.

The equipment operates on a four-wire basis, separate cables being provided for the " go " and " return " directions of transmission. Amplifiers are spaced at maximum intervals of 22 miles which gives an attenuation-length of approximately 60 db. at 60 kc/s. Amplification at intermediate stations is effected by line amplifiers similar to those used at the terminal stations.

A description follows of the equipment installed by Messrs. Standard Telephones and Cables Ltd. on the earlier projects (Bristol-Plymouth, and Edinburgh-Dundee-Aberdeen initial installations, etc.).

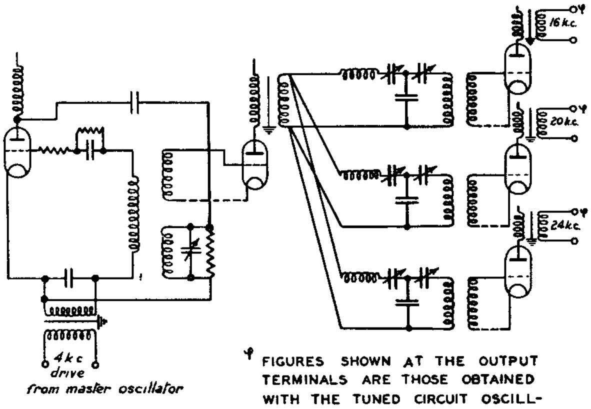
Messrs. S.T. & C. twelve-circuit carrier equipment.—Early installations.

The carrier generating apparatus consists essentially of units connected as illustrated in Fig. **21**. At each station at which terminal equipment is provided there are two master oscillators, each generating at 4 kc/s. If the oscillator which is carrying the load fails the other may be switched into circuit immediately. (An alarm is given when any portion of the carrier generating equipment fails.) The output from the master oscillator is fed to multi-frequency oscillators which generate at fundamental frequencies of 20, 32, 44, and 56 kc. the frequencies being maintained stable by the induced 4 kc/s current. The output of the oscillating circuit of a multi-frequency generator (illustrated in schematic form in Fig. **22**) contains frequencies equal to that generated by the oscillating circuit together with frequencies 4 kc. above and below that frequency. Hence the four multi-frequency oscillators produce together the twelve carrier frequencies required. Before application to the frequency changers, the carrier frequency supplies generated by the multi-frequency oscillators are power - amplified (the amplifiers being incorporated in the multi-frequency generators themselves). An impure waveform of the carrier supply would cause harmonic frequencies to be applied to the frequency changers giving interference on harmonic channels. Purity of waveform is ensured by passing each of the carrier frequencies through a tuning unit designed to reject harmonic frequencies. The output of a tuning unit is applied to twelve loads, each of which may be a frequency changer or an artificial load taking the same amount of power as a frequency changer. This arrangement ensures a constant load on the output of the multi-frequency generators. Artificial loads are cut out or in by means of " U " links.



MULTI-FREQUENCY OSCILLATORS & STANDBY MULTI-FREQUENCY OSCILLATORS

FIG. **21**.—SCHEMATIC OF CARRIER GENERATING EQUIPMENT. MESSRS. S.T. & C.'s 12-CIRCUIT CARRIER SYSTEM.



† FIGURES SHOWN AT THE OUTPUT TERMINALS ARE THOSE OBTAINED WITH THE TUNED CIRCUIT OSCILLATING AT A FUNDAMENTAL FREQUENCY OF 20KC

FIG. 22.—MULTI-FREQUENCY GENERATOR. MESSRS. S.T. & C.'s 12-CIRCUIT CARRIER EQUIPMENT.

Duplicate multi-frequency generators are provided on a separate bay and may be brought into service by operating keys on the main carrier generating bay. For each twelve (or part of twelve) groups to be served, a bay of four multi-frequency generators is provided; one bay of stand-by multi-frequency generators is also provided.

Means are provided for indicating on a meter the beats produced by lack of synchronism between the master oscillators at a terminal station. Control stations can transmit 4 kc/s current to line while a distant station may, by means of the beat indicating meter, bring its own oscillators into synchronism with that at the control station. The accuracy of the frequency at the control station is ensured by comparison with the fourth harmonic of a 1 kc/s tone of high accuracy which may be transmitted from London.

The term " channel equipment " embraces frequency changers, band filters, channel amplifiers and auxiliary apparatus. Three standard bay-sides are required to accommodate the channel equipment for the twelve-circuits of a group. The bay lay-out adopted for one group end is illustrated in Fig. **23**; the rear of the bays is occupied by channel equipment. The limiters used are of the transformer and neon tube type and two are accommodated on one panel, care being taken to screen the units of different circuits from each other. The modulator and demodulator for one circuit are mounted on a common panel. The basic circuit of the modulator is shown in Fig. **24**. No low-pass filters are employed at the input to the modulator, the band filter characteristics being adequate to suppress sufficiently frequencies that might cause interference with adjacent bands. A modified form of bridge modulator is employed; the rectifiers are permanently biased by a voltage derived from the rectification of the carrier, and it is claimed that this arrangement produces less harmonic voltage than is obtained from the similar modulator with unbiased rectifiers. Equalisation of the audio-side-band and side-band-audio response is effected by variable impedance networks and by the impedance mismatch losses produced by pads inserted as shown in Fig. **24**. (The circuit arrangements at A and B are of the " early equipment " type.) Carrier leak from the modulator is made as small as possible by adjustment of the potentiometer.

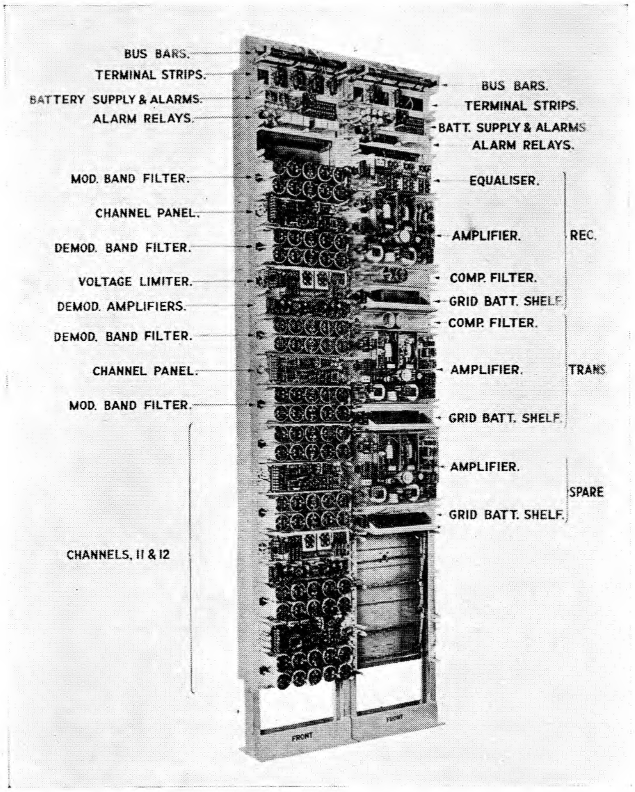


Fig. **23**.—Channel and Amplifier Bays, Cover off.

The transmitting and receiving band-pass filters for each channel are mounted on either side of the associated frequency changer. They have a design impedance of 600 ohms and are unbalanced. Each filter is composed of a number of series resonant circuits and each individual unit consists of a dust-core coil and a condenser mounted together in a copper can. With the filters used on the original Bristol-Plymouth installation, trouble was experienced due to the characteristics of the " canned " units varying with the humidity of the atmosphere. This difficulty has been overcome by exhausting the cans and then filling them with dry air and sealing. This form of construction results in a very stable filter characteristic, since no external impedances can affect the resonant frequency, and the component items are screened from external interference and the effects of humidity changes. The filter-compensating networks, which are made up in the same way as the filters, are mounted on individual panels.

The channel amplifiers are simple, single-stage triode amplifiers, two of which are provided on one $3\frac{1}{2}''$ panel. The gain of each amplifier is adjustable in 1 db. steps by means of a " U " link tapping on a transformer. Break jacks are provided so that filament and anode currents may be measured. A pair of amplifiers may be switched off by the insertion of a plug into a socket on the panel itself.

One panel accommodating a differential transformer and compromise balance is associated with the channel bays of each group, and may be patched in by means of cords if it is necessary to speak on a channel under test or to test under two-wire conditions.

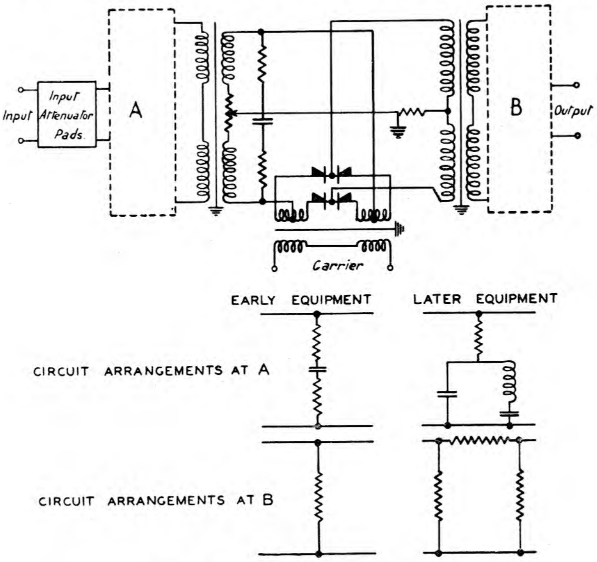


Fig. **24**.—Modulator Circuit.
Messrs. S.T. & C.'s 12-Circuit Carrier Equipment.

The line amplifiers, one for transmitting, one for receiving, and a spare are provided on one bay-side. All the amplifiers are similar in design, the only difference between the receiving and transmitting amplifiers being that the output impedance of the former is 600 ohms while that of the latter (which transmits directly into a line having an impedance at 60 kc/s of the order of 140 ohms) has an impedance similar to that of the line. Each amplifier has an input impedance of 600 ohms. In order that the spare amplifier can be used in place of the receiving

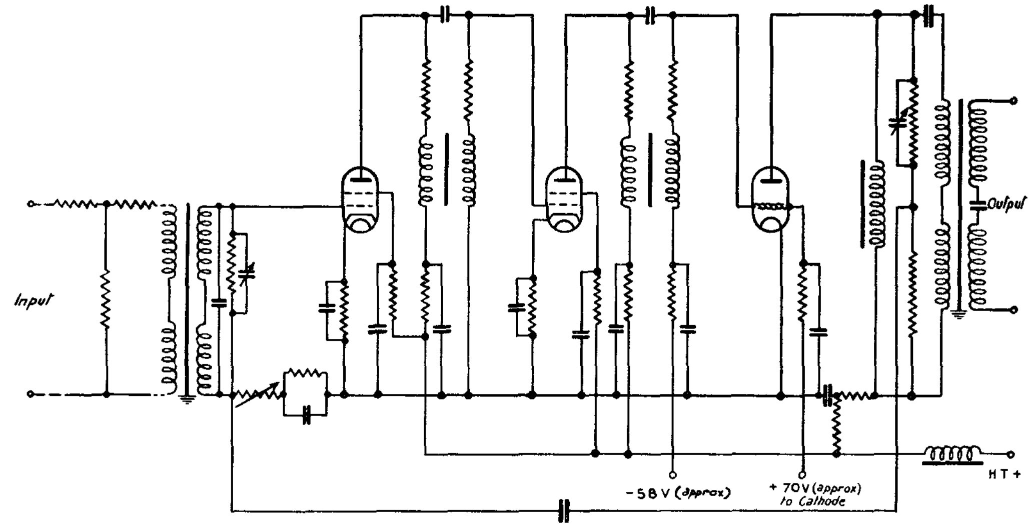


FIG. 25.—LINE AMPLIFIER. (SIMPLIFIED SCHEMATIC).
MESSRS. S.T. & C.'s 12-CIRCUIT CARRIER EQUIPMENT.

amplifier a transformer is provided to produce the necessary impedance transformation on the output side. The spare amplifier and transformer (if required) may be brought into use by means of patching cords applied to sockets on the face of the units.

(*Note.* The line impedance in the case of the Bristol-Plymouth cable approximates to 125 ohms and the impedance of the equipment differs accordingly.)

A simplified schematic diagram of the line amplifier is shown in Fig. **25**. It has a maximum gain of 65 db.; the first two stages using pentode valves and the last stage a co-planar grid valve. The inter-stage couplings are a combination of resistance-capacity and transformer coupling, this arrangement giving the necessary low phase shift and falling gains at high and low frequencies; the latter property ensures the stability of the amplifier at frequencies outside the range normally transmitted by the unit.

The co-planar grid valve[18] is essentially a triode with two control grids each symmetrically disposed with regard to the cathode and having equal effect upon it. One grid has a positive bias of about 70 volts and the other a negative bias of about 58 volts. The valve can handle comparatively large output powers with the relatively small H.T. voltage available, and produces low harmonic distortion. The negative bias is obtained from a dry cell battery mounted immediately below each amplifier.

Bridge feed-back is employed, and the total basic gain is such that both input and output impedances are unaffected by the adjustment of feed-back. The gain of the amplifier can be adjusted between 45 and 65 db. by means of resistance in the feed-back path. In the transmitting and intermediate station line-amplifiers the gain-adjusting resistor is tapped and the correct setting determined during the initial line-up; on receiving amplifiers a continuously adjustable control is provided. Gain control is also provided by means of attenuating pads at the input to the amplifier; these may be strapped into or out of circuit as required.

The equalisers used with the receiving amplifiers are of the constant resistance type, are unbalanced and have a design impedance of 600 ohms. They consist of a number of units providing various amounts of correction, the number of units strapped in series being determined by the attenuation-length of the repeater section concerned. A balanced and screened transformer is provided to match approximately the equaliser impedance with that of the line.

At intermediate stations the arrangement of the line amplifiers is similar to that at the terminal stations. All amplifiers are, however, identical, each having an input impedance of 600 ohms and an output impedance simulating that of the line. A transformer is provided on each equaliser panel to match approximately the line impedance (at 60 kc/s) with that of the equaliser.

Twelve-circuit carrier equipment—Performance requirements.

The equipment is designed to provide circuits of zero loss, with or without the connection of 3 db. two-wire extensions at each end. It has, however, been the practice to avoid stability difficulties by operating the circuits at 3 db. loss. The necessary loss has been produced in Messrs. S.T. & C.'s equipment by a 3 db. pad at the output of the demodulator.

Fig. **26** shows the gain-frequency characteristic (relative to that at 800 cycles) of typical channels. Curve " A " is for a channel on the original type of equipment, and " B " for a similar channel on equipment designed to have an improved response. A channel having a characteristic such as curve " A " is quite satisfactory if it alone provides a circuit, or if it is extended on circuits having small attenuation distortion, but a circuit involving the use of a number of links having " A " type characteristics would have considerable attenuation distortion.

The original equipment had audio-to-side-band and side-band-to-audio responses which were not level, but

---

[18] See Bibliography.

the two responses compensated for each other to produce an approximately level overall loss or gain. This arrangement is satisfactory if both ends of a group are of one Contractor's manufacture, but if group ends are not of the same make level audio-to-side-band and side-band-to-audio responses are necessary. Most of the early equipments have been modified to meet this requirement. Further details of the performance now required of twelve-circuit carrier equipment are indicated below:—

(i) The equipment must operate with standard repeater station battery supplies.

(ii) The channel equivalents, expressed as a loss relative to the overall equivalent at 800 c/s, must be within the limits indicated below.

Frequency (c/s).	300	400	600 to 2000	2400	2600
Loss in decibels relative to that at 800 c/s.	+4.3 to −1.3	+2.6 to −1.3	+1.3 to −1.3	+2.6 to −1.3	+4.3 to −1.3

(iii) The audio-to-side-band and side-band-to-audio equivalents, expressed as a loss relative to the equivalent at 800 c/s or the side-band frequency corresponding to 800 c/s, must be within the limits indicated in the following table:—

Frequency (c/s).	300	400	600 to 2000	2400	2600
Loss in decibels relative to that at 800 c/s.	+2.2 to − .7	+1.3 to − .7	+ .7 to − .7	+1.3 to − .7	+2.2 to − .7

(iv) The nominal transmission power per channel must be +5 db. relative to 1 *m*W.

(v) Line equalisation must be such that the overall line attenuation distortion does not exceed 2 db. (or 4 db. over any one repeater section).

(vi) Repeater impedances must match that of the line to a high degree. This is obtained by making the impedances presented to line such that a return loss of better than 14 db. is always obtained when feeding a load of $138\backslash\overline{6^\circ}$ ohms.

(vii) With two persons using Telephones No. 162 reading continuously and simultaneously so that the input of speech current to the two-wire ends of any two channels of a group is maintained as closely as possible at reference volume, the noise e.m.f. on any disengaged channel must not exceed 2 *m*V. when measured on a circuit noise meter having a frequency response weighted in accordance with the C.C.I.F. recommendations.

(viii) The crosstalk between channels derived from different groups but using the same carrier frequency must not be worse than 65 db,

(ix) Changes of equivalent due to the maximum permissible battery voltage variations must not exceed 0.3 db. at terminal stations and 0.1 db. at intermediate stations.

Messrs. S.T. & C.'s latest equipment has a performance very much better than that demanded by the above requirements, while the earlier equipment also met the requirements except in regard to the audio-to-side-band and side-band-to-audio responses.

Fig. **26** indicates that the channel qualities meet the requirements with ample margin. The effective band-width transmitted is now from 200 to 2800 c/s. Repeater impedances presented to line are such that return losses in excess of 20 db. are obtained when measured under the above conditions.

Inter-channel interference is of the order of 0.2 *m*V., and inter-group crosstalk is usually better than 70 db. The measurement of crosstalk on twelve-circuit carrier equipment has been dealt with in a paper read before this Institution[4].

Developments following the early installations.

Early in the history of twelve-circuit carrier installations it became obvious that the following points would have to be considered:—

(*a*) It was undesirable to make permanent connections between channel equipment and particular cable pairs.

(*b*) The extension of the system might at any time involve the recovery or use on a different route of a group end, and the extension without demodulation of the circuits previously carried, *i.e.*, the provision of intermediate amplifier equipment in place of terminal equipment.

(*c*) As the two ends of any group might be of different manufacture their audio-to-side-band and side-band-to-audio characteristics must meet certain requirements.

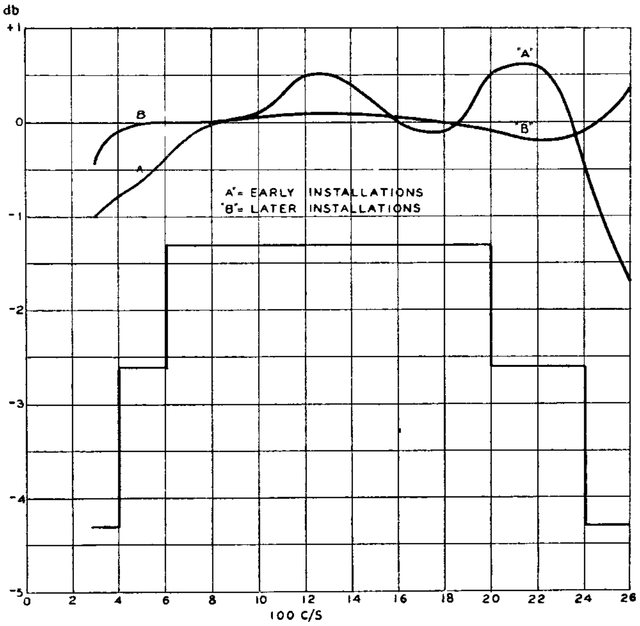
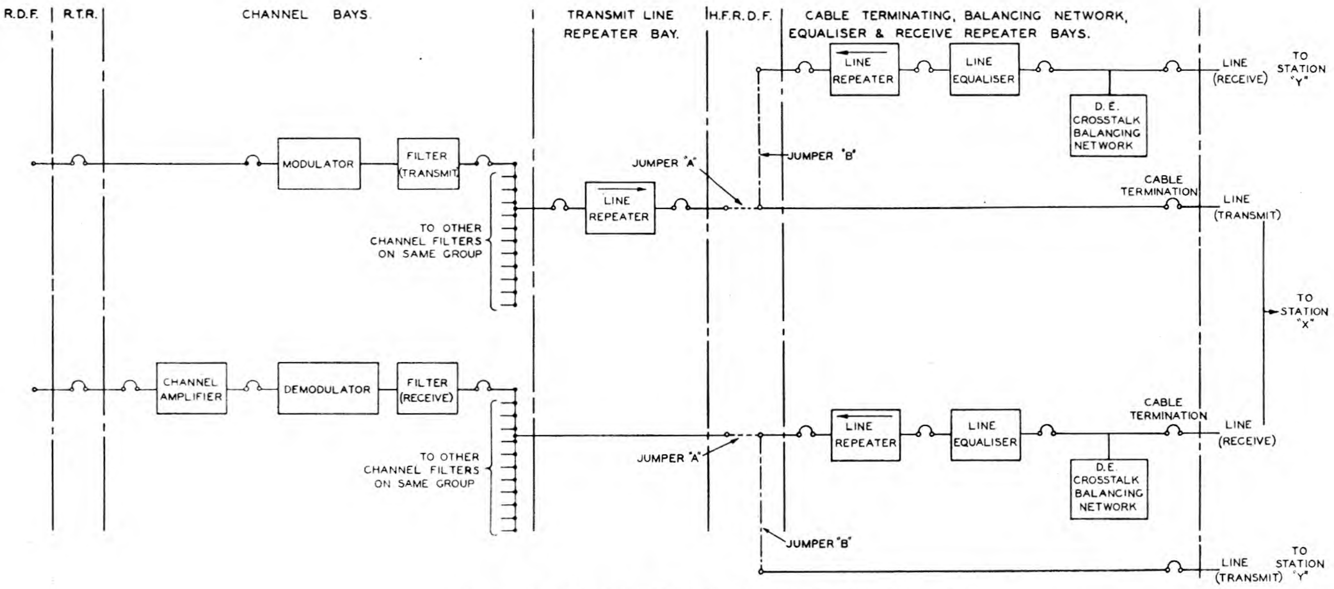


Fig. 26.—Typical Channel Characteristics. Messrs. S.T. & C.'s 12-Circuit Carrier Equipment.

---

[4] See Bibliography.



NOTE. JUMPERS "A" & TERMINAL EQUIPMENT ARE USED FOR 1 GROUP TERMINATED.
JUMPERS "B" & ASSOCIATED LINE EQUIPMENT ARE USED FOR 1 GROUP THROUGH.

FIG. 27.—12-CIRCUIT CARRIER EQUIPMENT. TERMINAL STATION. BLOCK SCHEMATIC DIAGRAM OF ONE GROUP.

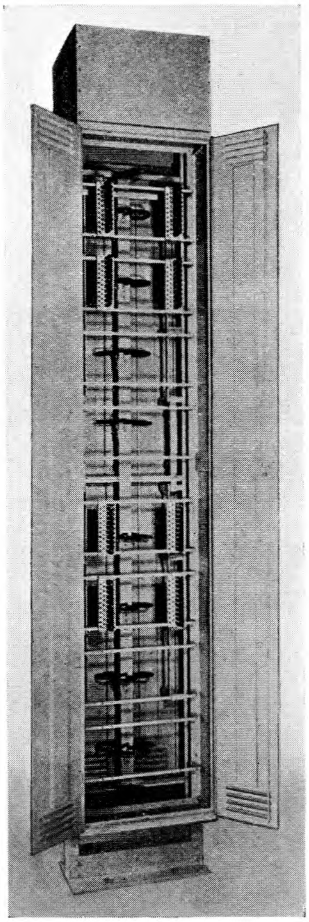


FIG. 28.—HIGH FREQUENCY REPEATER DISTRIBUTION FRAME. FRONT VIEW—DOORS OPEN.

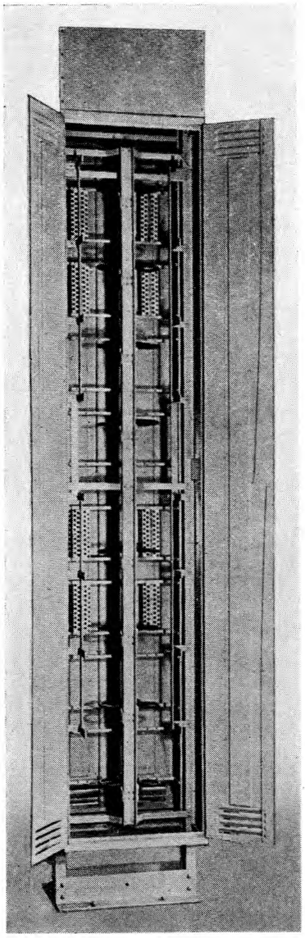


FIG. 29.—HIGH FREQUENCY REPEATER DISTRIBUTION FRAME. REAR VIEW—DOORS OPEN.

(*d*) As the use of the system extended it would be desirable to provide for carrier frequency synchronism.

The flexibility required by (*a*) and (*b*) has been obtained by the arrangement indicated in schematic form in Fig. **27**. The channel equipment and transmitting repeaters have been isolated from the line by a High Frequency Repeater Distribution Frame (H.F.R.D.F.), while the line equalisers and receiving repeaters have been associated with the receiving cable pairs. A single H.F.R.D.F. can accommodate four pairs of 24-pair cables and will, therefore, cater for the requirements of all but the largest repeater stations, in which case two or more frames may be employed. Figs. **28** and **29** are photographs of the frame produced by Messrs. G.E.Co. Jumpering on the H.F.R.D.F. is by means of single-pair screened cables.

The requirement of (*c*) has already been dealt with.

(*d*) To ensure frequency synchronism it is now required that the carrier generating equipment at terminal stations shall provide for the transmission to line of a pilot frequency or frequencies, and be capable of being controlled by a pilot frequency received from line. It is envisaged that when a complete network of carrier systems has been achieved throughout the country all carriers will, at any moment, be locked to one master supply only, control being taken by a master supply at any other station when necessary. It is required that master oscillators shall generate at a frequency of 1 kc. stable to within 1 part in 100,000 with all normal battery voltage and temperature variations. Carrier frequency synchronism will facilitate maintenance and permit the use of any carrier channels for V.F. telegraphs, music and, perhaps, slow-speed picture telegraphy.

The modified requirements and the decision to provide the far-end crosstalk networks at amplifier stations instead of at the mid-points of amplifier sections have resulted in the adoption of a modified bay lay-out as shown in Fig. **30** for terminal stations and Fig. **31** for intermediate stations. It will be observed from Fig. **30** that the cable terminations, receiving amplifiers, equalisers and distant-end crosstalk balancing frames for a number of pairs of cables are associated together, while the channel and transmitting amplifier equipment is also provided in groups. This lay-out simplifies circuit rearrangement and the addition of equipment.

Messrs. S.T. & C.'s twelve-circuit carrier equipment.—Later installations.

The later equipment incorporates most of those features shown desirable by experience with the earlier installations. Flexibility has been attained by providing a H.F.R.D.F., and the bay lay-out is as illustrated in Fig. **30**. (A photograph of the channel equipment of one group is shown as Fig. **32**.) The channel responses of the receiving and transmitting halves of the equipment have been modified, and a method of obtaining carrier frequency synchronism is being introduced.

The features, apart from the modified bay lay-out, which distinguish the later equipments from those installed earlier are as follows:—

(*a*) Both transmitting and receiving amplifiers have an input impedance of 600 ohms, while the output impedance approximates to 140 ohms. This makes possible the use of a common form of line amplifier for receiving and transmitting; the same amplifier is also

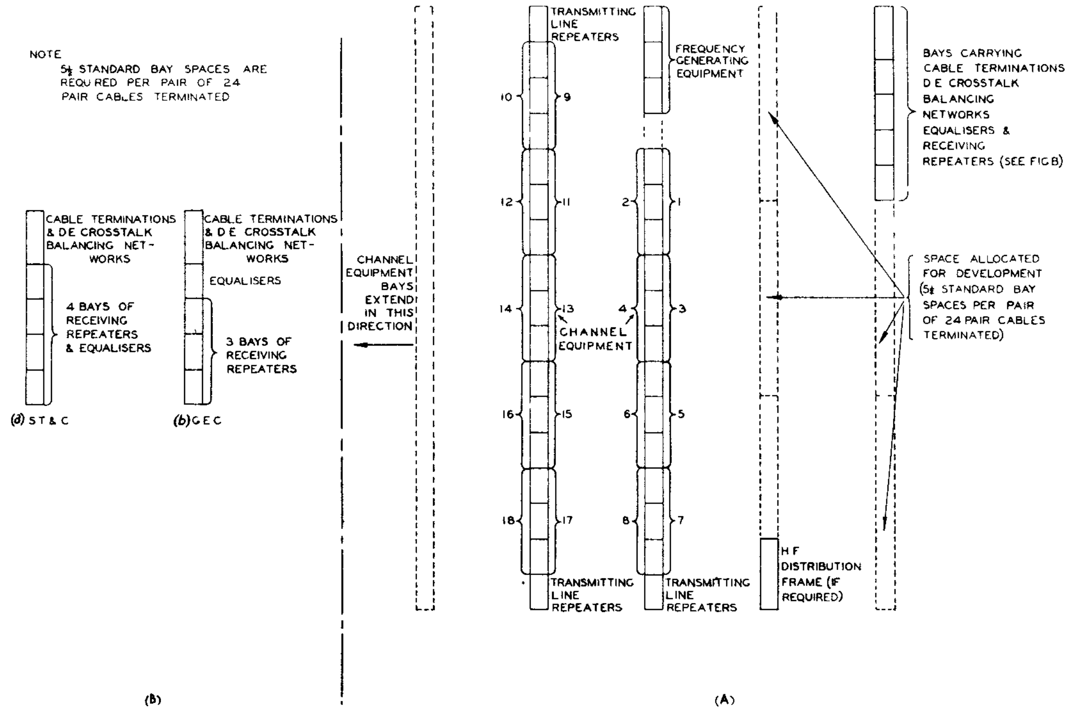


Fig. **30**.—12-Circuit Carrier Equipment. Typical Lay-out of Bays at a Terminal Station.

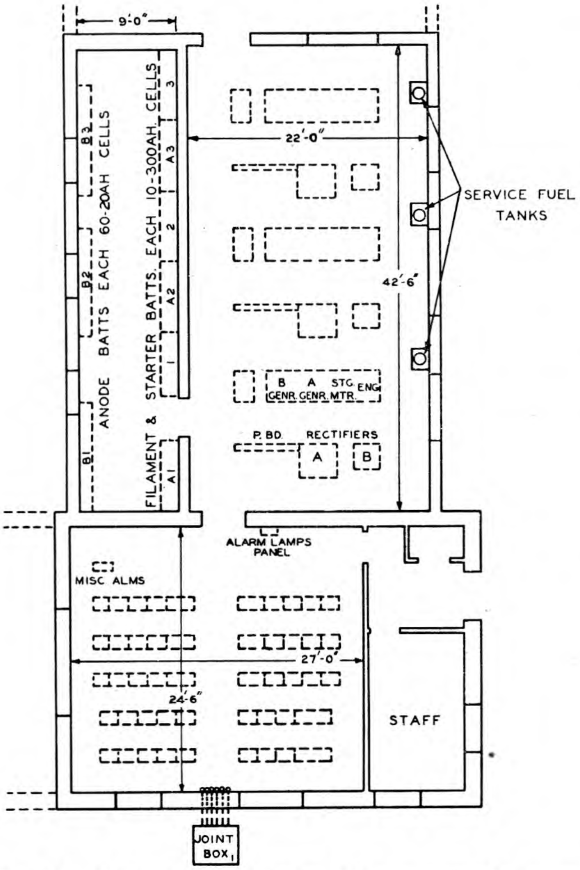


FIG. **31**.—UNATTENDED REPEATER STATIONS FOR 12-CIRCUIT CARRIER SYSTEMS. LAY-OUT FOR 3 SCHEMES.

used at the intermediate stations. It is necessary, in the case of receiving line amplifiers to match the 140 ohm output impedances with the 600 ohm receiving band filters; this is effected by means of transformers on the channel equipment bays.

(*b*) Channel equalisation is effected by means of shunt equalisers as illustrated in Fig. **24** (later equipment).

(*c*) On the frequency changer panels pads of 1, 2, 4 and 8 db. are used at the modulator input (the actual input level to the modulator being about −14 db.), while the 3 db. pad at the output of the demodulator has been omitted, the gain of the channel amplifier being reduced accordingly. In order that a level of +7 db. can still be obtained from the channel amplifier its gain can be increased by means of an adjustable tap.

(*d*) Slight mechanical modifications have been made to the channel filter components.

(*e*) At the time of writing (September, 1938) the carrier generating equipment being installed is identical with that of the earlier installations. Messrs. S.T. & C. are, however, carrying out experimental work concerning the provision of synchronising facilities.

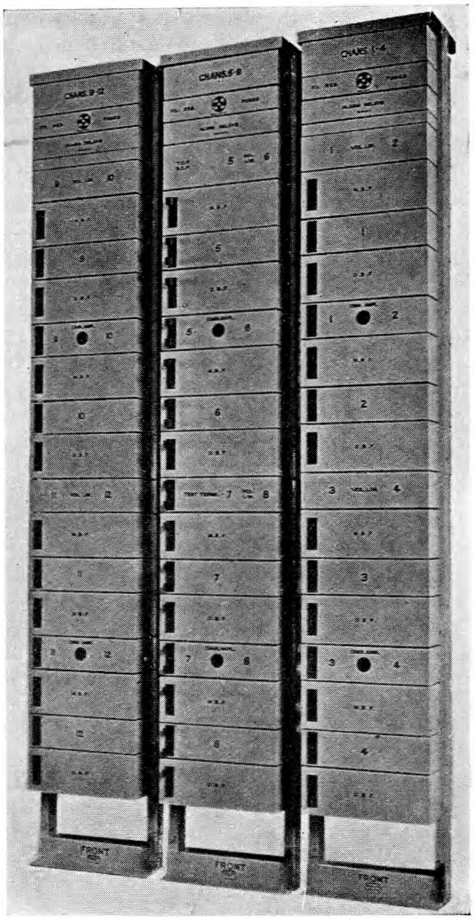


FIG. **32**.

Messrs. G.E.C.'s twelve-circuit carrier equipment.

The features of this equipment are illustrated in block schematic form in Fig. **33**. In design it differs greatly from the equipment previously described, the feature of outstanding importance being the use of double modulation, *i.e.*, the use of two stages of frequency changing per channel. It has been shown that this requires much simpler channel band filters, that greater manufacturing tolerances are permissible, the channel characteristics are less dependent upon variations in the band filters and a large proportion of similar equipment may be used in each channel (*i.e.*, manufacture and maintenance are facilitated)[19].

In this system the audio input of each channel first modulates a 6 kc. carrier frequency and the upper side-band obtained is filtered and applied to a second modulator in which a carrier frequency 6 kc. in excess of the virtual carrier of the channel is employed. The lower side-band so produced corresponds to the lower side-band which would be given by the audio-frequency modulating directly the virtual carrier. In the receiving equipment double demodulation takes place in the inverse manner to the modulation process.

---

[19] See Bibliography.

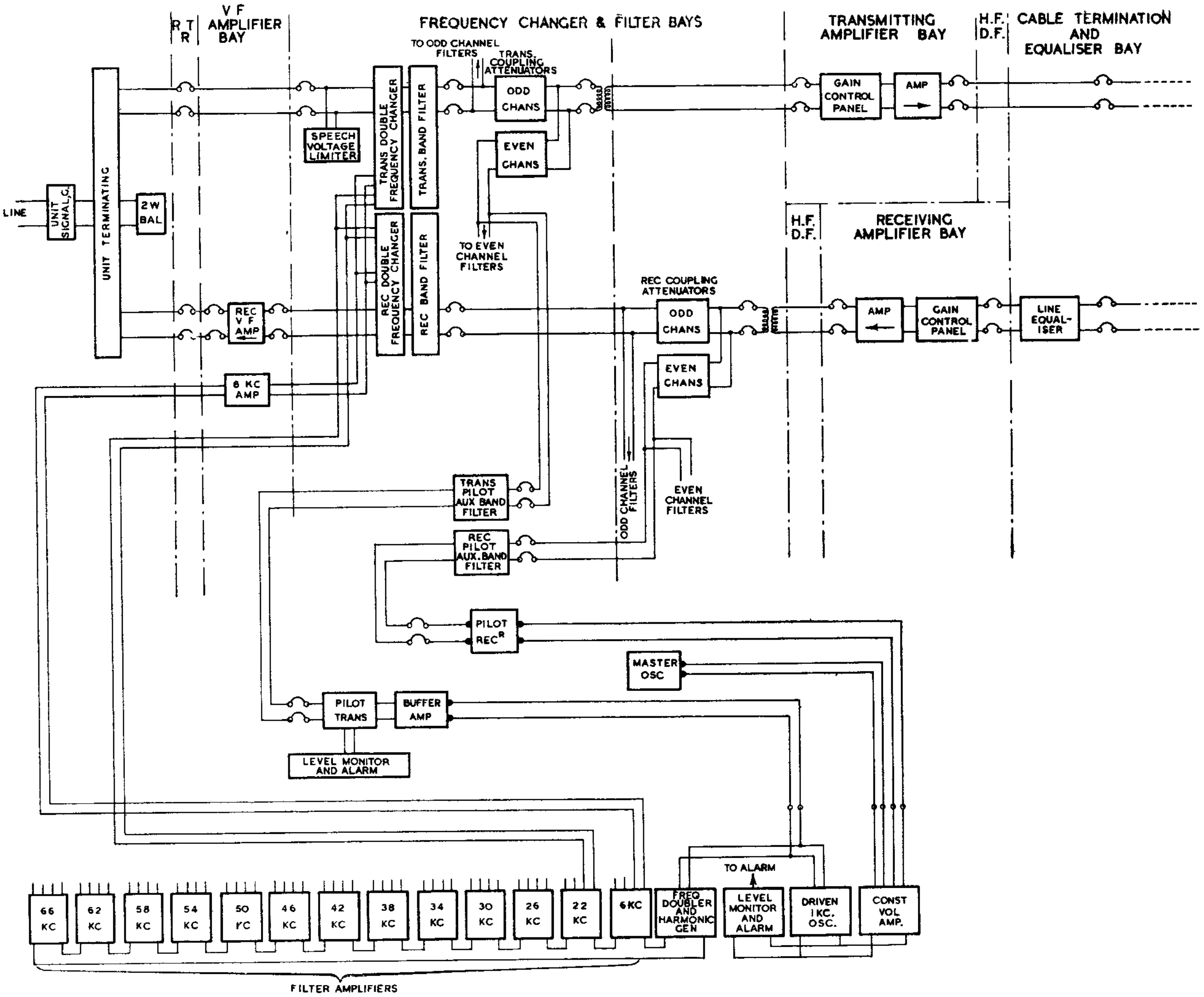


FIG. 33.—BLOCK SCHEMATIC DIAGRAM. MESSRS. G.E.C.'S 12-CIRCUIT CARRIER EQUIPMENT.

The limiters are of the dry plate rectifier type, and to avoid the possibility of a common potentiometer introducing inter-channel crosstalk, each limiter has its own bias potential supply circuit. A meter is provided on each limiter panel, and by operating a key the continuity of each potentiometer circuit can be checked.

Pads are provided at the input of the transmitting double frequency changer to enable adjustment of input levels to be made. The output of a low-pass filter is applied to a double balanced modulator of conventional type. The band filter following the first modulator passes the upper side-band to a single balanced modulator. Throughout the modulator unit the components employed are of the usual repeater type, no special form of construction being employed other than the use of dust core transformers.

The channel filters on both the receiving and transmitting equipments are composed of fewer sections than are usually used in the band filters of carrier systems; the use of double modulation and the resulting relaxation in attenuation requirements outside the pass-band make this possible. The filters of the odd and even channels are commoned in two separate groups on the line side, the odd and even sets of filters being connected together through pads; this feature relaxes the requirements of the band filters, although higher amplifier gains are required to overcome the extra attenuation of the pads. Three channel filters are on a single panel of standard width and 7 ins. deep. The elements of the receiving channel equipment are similar to those on the transmitting side. Owing to the use of these coupling attenuators on the filters and of two stages of demodulation, the output from the demodulator is at a level of approximately −33 db. Considerable gain (40 db.), therefore, is required of the channel amplifier, which is a three-stage resistance-capacity coupled unit, using bridge negative feed-back between the output and input portions of the circuit. The gain is adjustable in steps of 8 and 1 db. by means of tappings on the input pad and the secondary of the input transformer respectively. Triode valves are employed throughout. The nominal output level of the unit is 7 db. above 1 *m*W in 600 ohms when used with a 3 db. two-wire extension.

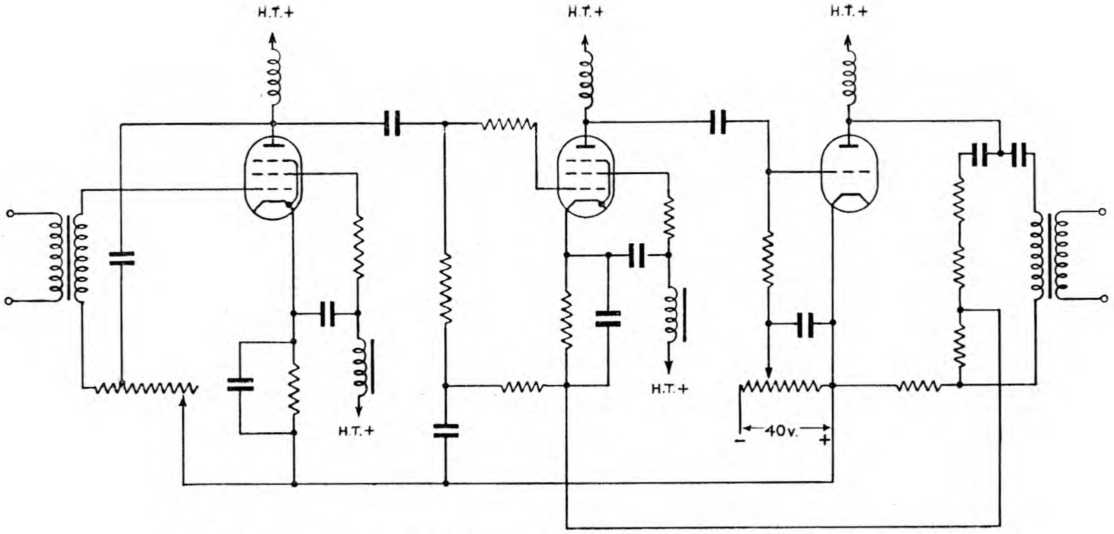


Fig. **34**.—Line Amplifier. Messrs. G.E.C.'s 12-Circuit Carrier Equipment.

The transmitting and receiving line amplifiers are identical and provide a gain of 65 db. ; one is illustrated in simplified form in Fig. **34**. It consists of two pentode and one triode stages, choke-capacity coupled. Negative feed-back is used on the first stage and also in bridge form between the output of the third and the input of the second stage. The triode output stage is used to provide the necessary high power handling capacity ; the special valve used employs a bias approaching 40 volts. In later units a tetrode will take the place of the triode valve and the necessity for a separate bias supply will be avoided. For the present, the bias is obtained for all units in a station from a special accumulator battery. As the valves concerned would be ruined should the bias supply fail, special precautions are taken to avoid a break in the supply.

No gain control is provided on the amplifier proper, but at the input of each unit is connected a gain control panel consisting of a series of balanced attenuators. Attenuator pads varying in value from 32 to 0.2 db. are provided and may be brought into or out of circuit by means of " U " links ; they are used to adjust the nominal repeater output (per channel) to +5 db. Line amplifiers and attenuators have a nominal impedance of 138 ohms. By means of adjustable tappings on the output transformer, the output impedance of the amplifier may also be made equal to 53 ohms, which is the approximate impedance at carrier frequencies of a type of coaxial submarine cable now in use. The spare amplifiers on the transmitting and receiving line amplifier bays may be brought into circuit when required (without breaking down the working circuit) by means of a system of " U " links together with a rapid change-over switch.

By the operation of switches, any anode or heater currents may be read on meters provided as an integral part of the bay equipment. Another feature which facilitates maintenance is the provision of links by means of which most of the units of equipment can be isolated for test. The main testing points are in the form of four sockets, the two inner sockets providing an earth connection. Screened testing leads and plugs are used throughout.

The carrier generating equipment provides for control either by a master oscillator or a controlling

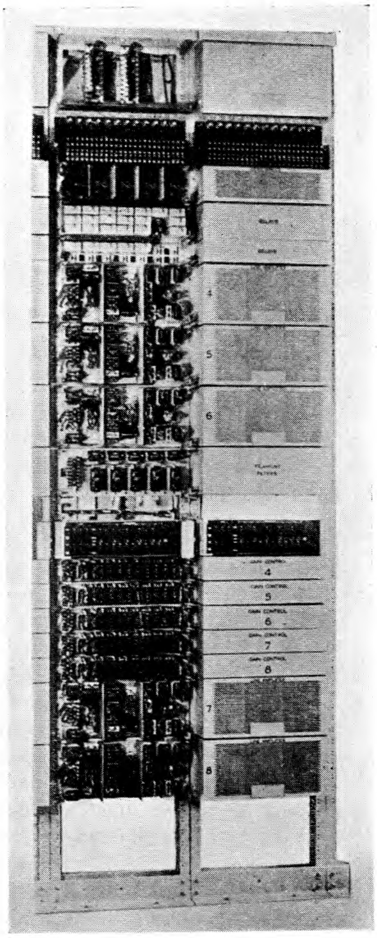


Fig. **35**.—Line Amplifier Bays. Rear view.

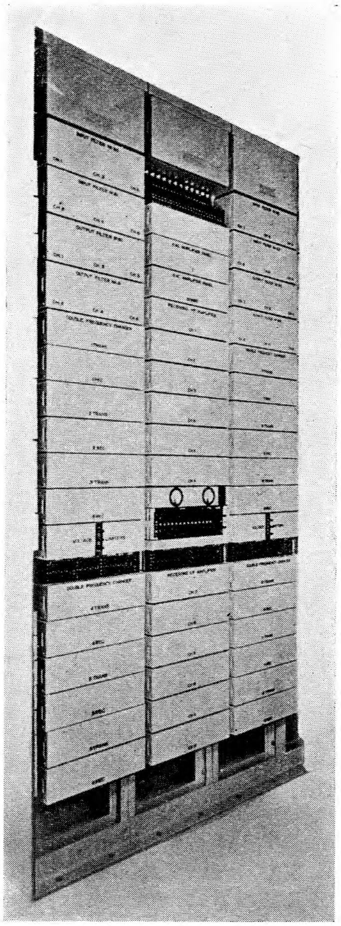


Fig. **36**.—One 12-Channel Group Equipment (Covers on).

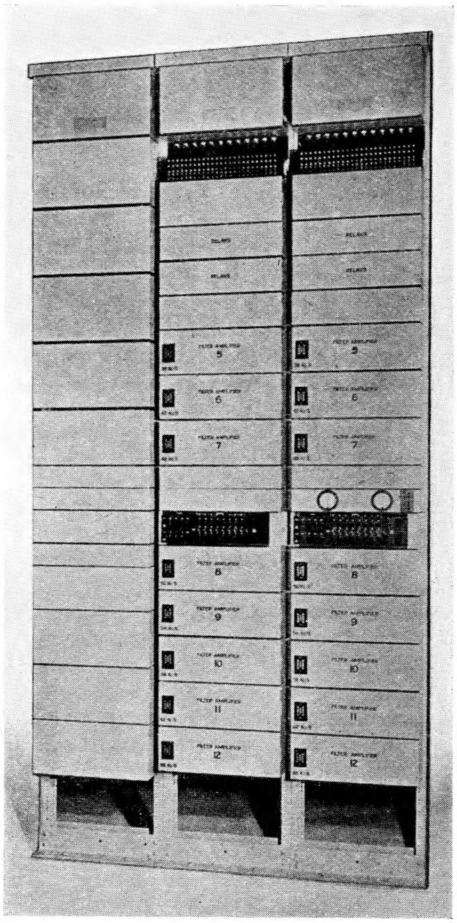


Fig. **37**.—Pilot and Oscillator Bays. Rear view. (Covers on).

1 kc. voltage received from a distant station. This voltage controls (*via* a constant volume amplifier) a driven 1 kc. oscillator which in turn feeds a frequency doubler and harmonic generator. A level monitoring panel is used to provide an alarm in the event of a failure of the 1 kc. supply from either source. At the output of the harmonic generating unit, filter amplifiers accepting and amplifying the required carrier frequencies are connected in series.

The " second stage " carrier frequencies are applied directly to the frequency changers and 24 groups can be supplied from one set of generating equipment; but the 6 kc. supply is amplified on each group of channel equipment as all frequency changers have to be given a supply at this frequency. To provide carrier frequency synchronism between stations, 1 kc. current from the driven 1 kc. oscillator is applied to a buffer amplifier and pilot transmitter; in the latter the 9 and 10 kc. components in the output of a multivibrator unit are transmitted to line *via* an auxiliary band filter and the even-channel transmitting coupling-attenuator. At the distant station these frequencies are filtered out and when rectified reproduce accurately the 1 kc. master supply. This 1 kc. supply is used to drive the 1 kc. oscillator at that station.

The carrier generating equipment proper is accommodated on one double-sided bay, one such bay being capable of driving 24 groups. In all cases a duplicate bay is provided. Between the generator bays is a master switch which, in the event of failure of any unit on the bay carrying the load, may be operated and the whole of the load thus transferred to the other bay. The switch contacts are arranged in horizontal formation at the top of the bays concerned and the mechanical arrangement is such that a clean and rapid change-over is effected. One double-sided bay, which is usually placed adjacent to the carrier-frequency generator bays, accommodates the master oscillator (if required), a pilot transmitting unit and spare, and equipment for four pilot receivers and spare together with the associated equipment and distribution apparatus. Photographs of line amplifier bays, a group of channel bays, and carrier generating bays are shown in Figs. **35**, **36** and **37**.

The master oscillator which generates a 1 kc. supply of high stability and accuracy consists of two panels, one being the master oscillator proper and the other carrying the temperature control unit. The oscillatory circuit is contained in a temperature controlled oven.

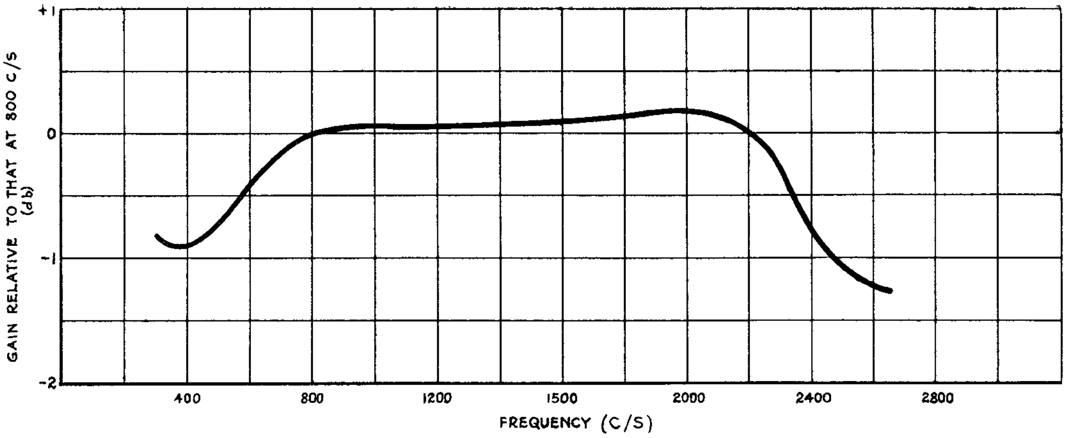


Fig. **38**.—Typical Channel Gain-Frequency Response. Messrs. G.E.C.'s 12-Circuit Carrier Equipment.

It is the function of the constant volume amplifier which follows the master oscillator to provide at the input terminals of the driven 1 kc. oscillator, a 1 kc. current the level of which is largely independent of that supplied to the amplifier. It consists of a two-stage transformer-coupled amplifier with a variable attenuator and low-pass filter in the output circuit. The limiting feature is effected by means of a relatively high resistance in series with the grid lead to the second valve. Across the output of the constant volume amplifier a level monitoring circuit is provided. This consists of a full wave rectifier (copper oxide) the input of which can be adjusted and which feeds a Weston " Sensitrol " relay. By means of the adjustment available it can be arranged that, for normal input levels, the relay " tongue " is in a neutral position ; any considerable increase or decrease in level results in the " tongue " touching adjustable stops and ringing an alarm bell.

The driven 1 kc. oscillator consists of an oscillating stage, into the grid circuit of which is injected the controlling 1 kc. current. A buffer stage is also employed. At the input of the frequency doubler and harmonic generator there is a dry plate rectifier frequency-doubling circuit which is followed by a filter. The necessary distortion is produced in the following valve stages. It is a function of the unit to generate a preponderance of odd harmonics ; even harmonics must as far as possible be suppressed, and this condition makes it essential that the unit is correctly set up and adjusted. The presence of even harmonics is likely to cause noise on each channel.

Each filter-amplifier unit is composed of a filter of simple design (which accepts a carrier of the required frequency) followed by two gain stages. Actually the first stage feeds two paralleled transformer loads, each of which feeds an amplifier stage. There are, therefore, two outputs, each of which carries half the load.

Performance.

At the time of writing a complete series of tests has not been carried out on this type of equipment. Some measurements have, however, been made of the audio-to-side-band and side-band-to-audio responses, inter-channel and inter-group crosstalk and noise. The measurements indicate that the equipment meets (in these respects) the requirements detailed earlier.

Fig. **38** shows a typical channel (audio-to-audio) characteristic ; it will be seen that the characteristic is that of a circuit of excellent quality.

CIRCUIT QUALITY.

For a circuit to be of good quality it must transmit a wide band of frequencies with a minimum of distortion (attenuation, harmonic and amplitude) ; it should have, as far as is practicable, a constant phase delay for all frequencies transmitted, a high velocity of transmission, and a minimum of echo, noise and crosstalk interference. On the score of intelligibility there is little advantage in transmitting a frequency range beyond, say, 300 to 2600 cycles (except at low received levels), but the voice appears much more natural and is more easily recognisable if frequencies in the range 300 to 3400 cycles are transmitted effectively. (A frequency is considered to be transmitted effectively if the loss at that frequency is not more than 8.7 db. in excess of that for 800 cycles.) The desirability of transmitting the wider range has been recognised by the C.C.I.F. which has standardised it for international circuits.

In general, attenuation distortion in carrier channels is relatively small, as, owing to the range of the frequencies transmitted, line equalisation is a simple matter, whilst such distortion in the channel equipment can, if necessary, be corrected by individual channel equalisers. The limits of attenuation distortion recommended by the C.C.I.F. for an international four-wire circuit are indicated in Fig. **26**.

If harmonic distortion is considered as the production of multiple frequencies due to transmission through a path of non-linear characteristics, this form of distortion affects carrier circuits mainly as noise interference rather than as the production of additional and harmonic frequencies in the channel proper. This is due to the fact that the frequencies transmitted to line are usually such that multiple frequencies lie outside the band producing them. Harmonic distortion introduced prior to frequency changing will appear in the same way as in an audio circuit. As inter-channel interference due to harmonic distortion in a common transmission path is more serious than harmonic distortion in an audio channel, care is taken in design to avoid harmonic production, and interference on this score is negligible. It must, however, be ensured that, with deterioration of valves due to age, excessive harmonics are not introduced in carrier transmission paths; special harmonic testing equipment is to be provided in connection with some forms of carrier apparatus.

Amplitude distortion, *i.e.*, change of gain or loss of the circuit with change of input power, is kept at a negligible figure by means of careful design.

As multi-circuit carrier systems usually operate on non-loaded cables the envelope velocity $\left(\text{approx. } \frac{d\alpha}{d\omega}\right)$ is high and phase distortion small.

The maximum transmission time from end to end of a circuit however long should not exceed 250 milliseconds (for mid-audio band frequencies) if a conversation is to continue without misunderstanding due to subscribers becoming conscious of transmission delay. On an audio circuit working on pairs loaded with 44 *m*H coils at 2000 yard intervals the transmission velocity is of the order of 20,000 miles per second; i.e., a circuit of only 5000 miles would have the maximum desirable transmission time. On a non-loaded carrier cable, however, the transmission velocity is of the order of 100,000 miles per second at carrier frequencies; hence the transmission time of 250 milliseconds would not be exceeded by a circuit 25,000 miles in length.

Owing to the impracticability of ensuring that the impedance match between a two-wire line and balance is perfect some echo on any four-wire circuit is unavoidable unless an echo suppressor is used. It is, however, apparent that the amount of echo which can be tolerated will depend upon the echo time (the sum of the transmission times for each direction of transmission), a lower echo attenuation being tolerable for short transmission times than for long. For example, on a circuit (without echo suppressor) having an echo time of 200 milliseconds, an echo attenuation of at least 38 db. is necessary, whereas on a circuit of 40 milliseconds echo time as little as 13 db. of echo attenuation is tolerable. Owing to the high transmission speed (approaching 186,000 miles/second in certain cases) the echo time of all but the very longest of inter-continental links is very small indeed and in consequence a small value of echo attenuation can be tolerated. This means a considerable saving in that echo suppressors are not usually required on carrier circuits.

Another effect of echo currents known as " near-singing " distortion, has to be considered; since the phase change of the circuit varies with frequency the echo currents phase in and out with the signal currents and so produce undulations in the gain-frequency response of the circuit. This effect has been examined by judgment tests on circuits having various degrees of stability, and it appears that the degradation of intelligibility is negligible, and hence echo suppressors are not required. The subject is receiving further study.

Externally induced noise in carrier circuits is usually negligible, most of those sources of disturbance which produce noise on audio channels tending to produce frequencies below the range transmitted. Most of the noise actually experienced on carrier channels is due to the production of unwanted frequencies in the course of modulation (see Appendix No. 2), and also to battery supply fluctuations. Inherent thermal agitation in conductors and valve current fluctuations also produce circuit noise, but both of these may usually be neglected unless the received level is low. A further source of interference is due to direct pick-up from radio transmitters; this can occur if an unscreened length of circuit is unbalanced at any point and, except on overhead lines, the cure is usually a simple matter.

Crosstalk may be intelligible or unintelligible. Intelligible crosstalk between carrier channels may be due to crosstalk taking place in the audio portions of the channels, to inter-group crosstalk at carrier frequencies (*i.e.*, pair-to-pair crosstalk) when each channel occupies the same position in the frequency spectrum and both upper or both lower side-bands are transmitted, or due to coupling in common equipment (carrier generators, etc.). Care is taken in the lay-out of equipment to keep audio-frequency crosstalk to a minimum, while care in the design of cables, adequate transposition in the case of aerial pairs, and the use of crosstalk balancing networks when necessary keeps pair-to-pair crosstalk small. In the case of coaxial cables the inherent self-shielding effect at the frequencies used keeps tube-to-tube crosstalk small. Decoupling arrangements are employed to keep at a small value crosstalk due to the use of common equipment. Intelligible crosstalk between carrier circuits in cables is usually better than 70 db.

Unintelligible crosstalk is, strictly, that produced by inverted speech and may be caused by the demodulation of adjacent channel frequencies which have been inadequately filtered. Satisfactory filtration is the cure for most forms of unintelligible crosstalk. Sounds having the rhythm of speech and produced by unwanted products of modulation are often considered as unintelligible crosstalk but are, more strictly, noise. Unintelligible crosstalk and noise on cable carrier circuits are usually such that a signal-to-noise ratio of at least 60 db. is obtained.

It will be appreciated from the foregoing that the quality of carrier circuits is inherently better than that of audio circuits, the smaller transmission time and relative immunity from interference being very important features.

MULTI-CHANNEL CARRIER CIRCUITS ON SUBMARINE CABLES.

The provision of multi-channel carrier circuits on submarine cables has taken place in two stages—

(1) Using existing submarine cables which had been designed to carry audio circuits and

(2) Using submarine cables designed specifically for carrier working. The early history of carrier working on the older types of submarine cable has been dealt with elsewhere[20]. The problems involved in working multi-channel carrier circuits on submarine cables are similar to those on land cables, but may be intensified. They are as follows:—

---

[20] See Bibliography.

(*a*) Near-end and far-end crosstalk.
(*b*) Permissible attenuation, having regard to the maintenance of an adequate signal-to-noise ratio.
(*c*) Maximum number of circuits to be obtained.
(*d*) Cost.
(*e*) The size and number of cables to be used.

The concentric type paragutta cable (described earlier) was designed specifically for multi-circuit carrier systems, and a number of such cables has been laid. Crosstalk between channels transmitting in the same direction does not arise in this type of cable, as only one " pair " is concerned and each channel occupies an individual frequency band. Far-end crosstalk between cables is not of great importance unless the return loss between the submarine cable impedance and that of the terminal apparatus is low; this would give rise to reflected near-end crosstalk. Actually a low value of return loss is often obtained at low frequencies due to the rate at which the impedance of the cable increases as the frequency is reduced; in addition, the crosstalk becomes worse with decrease of frequency, due to the unbalanced nature of the " pairs." This lack of screening and excessive unbalance at low frequencies would cause the near-end crosstalk at low frequencies to be high unless special attention were paid to screening. The required screening is effected by keeping the shore ends of the two cables several feet apart; in the sea the cables are laid at some distance apart (a mile or more) for convenience in repairs.

Provided that the crosstalk is sufficiently good, the remaining factors affecting the permissible attenuation-length are thermal agitation noise and first stage valve noise in the receiving amplifier. If the signal-to-noise ratio is not to be less than 58 db. (2 *m*V at a zero level point), the minimum received power must be 81 db. below 1 *m*W. With a normal output level of +5 db. this limits the permissible attenuation-length to about 86 db. Hence under normal conditions the number of channels which can be obtained is limited roughly to the number of 4 kc. bands lying between zero and the frequency for which the attenuation-length is 86 db.; *i.e.*, the shorter the cable, the larger is the number of circuits which may be obtained from it. There are three ways of extending the number of circuits as determined by consideration of the attenuation-length when using normal output levels:—

(*a*) Increase of sending power.
(*b*) Use of duplex working.
(*c*) Use of Compandors[21 and 29].

It is apparent that (*a*) is limited by consideration of the power handling capacity of the cable and the cost of the high power amplifying equipment involved. It is not possible to work more than a limited number of circuits on a duplex basis owing to the difficulty of constructing line balances to be adequate at the higher frequencies. The use of compandors makes possible the use of receiving levels lower than −81 db., but it is unlikely that levels below −100 db. will be employed.

In the case of relatively short cables, such as those working between Port Kail (Scotland) and Donaghadee (Ireland) the number of channels obtainable is high and as a result group modulation has been employed[3].

In certain cases it is not economical to lay more than one cable and as the number of duplex circuits obtainable is limited, it becomes necessary to employ group working, *i.e.*, to divide the usable frequency range lying above the possible duplexing range into two approximately equal parts and to use the higher frequencies for transmission in one direction and the lower frequencies for the reverse direction. It is also necessary to resort to group working on one cable of a pair in the event of the breakdown of the other; in this case "directional filters" are switched into circuit to divide the available frequency band into two parts.

The coaxial submarine cable is very satisfactory from the point of view of circuit-carrying capacity when the length is relatively short, and also for maintenance. However, the limited number of circuits obtainable when the length of the cable is great is a serious disadvantage. Attention has therefore been focussed on the development of pair cables constructed in a manner similar to that of the standard 24-pair land cables, but having, in addition, the necessary armouring. The design of such cables is now under consideration. Attention is also being paid to the possibility of producing a coaxial cable having a continuously loaded inner conductor and a dielectric having even better characteristics than paragutta.

ACCEPTANCE TESTS AND MAINTENANCE.

The standard of knowledge and ability required for satisfactory control and efficient maintenance of carrier equipment is clearly higher than that for many other types of equipment, partly because of its relative complexity and partly because there is considerably more difficulty in locating a fault in a supersonic circuit than in a D.C. circuit or audio-frequency A.C. circuit.

Apparatus to provide two complete twelve-circuit carrier terminals, an intermediate amplifier station and carrier-frequency generating equipment, has been installed at the Central Training School at Dollis Hill and instruction is given both in acceptance testing and in maintenance of the equipment. The limited experience so far obtained indicates that the fault liability is low. The failure of equipment common to twelve or more circuits, such as the master oscillator and line amplifier, has been guarded against by a fairly liberal provision of spare panels which can rapidly be put into service by U links or cords, thereby leaving the faulty panel free for tests.

The No. 4 type carrier equipment is at present accepted and lined up by co-operation with officers from the Engineer-in-Chief's Office, as only a few installations have so far been ordered.

STANDARDISATION.

Specifications CW 61 (formerly 598) and LW 31 (formerly E.-in-C. 498) lay down the constructional details (together with electrical requirements at the

---

[21, 29] See Bibliography.

[3] See Bibliography.

factory stage) and overall repeater section requirements, respectively, for twelve-circuit carrier cables, and the five firms manufacturing this type of cable all work to these specifications, *i.e.*, twelve-circuit carrier cable design is standardised. Some measure of standardisation of buildings, more particularly for the intermediate stations, has been achieved. The distant-end crosstalk balancing networks and the method of mounting and connecting them in circuit are in process of being standardised. There remains the important and more complex question of the equipment.

The two manufacturers who have so far supplied twelve-circuit carrier equipment to the British Post Office each developed a design independently; they followed a number of fundamental principles laid down by the Post Office, such as the 4 kc/s spacing between circuits, and the use of normal repeater station power supplies, but there are a number of differences in principle between the two systems, apart from the inevitable differences in electrical and mechanical detail. Any attempt to obtain the benefits of initial standardisation, and to avoid these differences in principle and detail and the duplication of effort, would have resulted in considerable delay in the installation of the first few twelve-circuit carrier systems and the loss of the resultant economies. The principal advantage of the development and installation of more than one type of equipment is that practical experience of each can be obtained and the results incorporated in standardised equipment later.

Since the production of the first designs, the lay-out of the equipment of both firms has been brought into line with the requirements of circuit flexibility, so that lay-out is standardised so far as the inherent differences between the two systems permit.

For such reasons as simplification of the training of maintenance staff, maintenance procedure, replacement of faulty panels and valves, and extensions to installations, detailed standardisation is desirable, and would become more so if any other firms were to supply equipment. The need for standardisation is accentuated by a decision in principle recently made by the P.O. Engineering Department that groups of twelve-carrier circuits should form the basic unit for building up, by group modulation, "super-groups" of circuits for transmission over coaxial cables; the latter now use equipment designed by the Department and differing in many respects from twelve-circuit carrier equipment. This decision was later the subject of a specific recommendation of the C.C.I.F. (at the 1938 Oslo Conference). Other relevant recommendations of the conference which should be mentioned here are as follows:—

1. Coaxial cable and twelve-circuit carrier cables should use a spacing of 4 kc/s between carrier frequencies.
2. The audio band to be effectively transmitted should be increased from 300-2,600 to 300-3,400 c/s for both twelve-circuit carrier and coaxial cables.
3. Erect side-bands should be transmitted on twelve-circuit carrier systems.

With regard to the second recommendation, measurements carried out by a number of administrations and by the S.F.E.R.T. laboratory at Paris showing the relation between transmission quality and the frequency band effectively transmitted have proved that the band 300 to 3,400 c/s is distinctly superior to any narrower band; this is true both with existing commercial telephone instruments and with those incorporating the recent improvements made in transmitters and receivers.

While the recommendations of the C.C.I.F. apply essentially to international circuits, these will very probably be adopted for inland circuits and their introduction can conveniently be considered with the general question of standardisation.

For the No. 4 type carrier equipment and the initial equipment for the coaxial cable detailed Departmental specifications are available.

FUTURE DEVELOPMENTS IN GREAT BRITAIN.

The effect of Recent Recommendations regarding the Performance of International Telephone Circuits.

None of the carrier systems in use in this country is in accordance with all of the recommendations of the 1938 C.C.I.F. conference (see under "Standardisation"). The twelve-circuit and coaxial equipments all transmit lower side-bands; none of them transmits effectively up to 3,400 c/s and the No. 4 type and coaxial cable equipments use carrier frequencies not spaced at 4 kc. intervals.

If it be decided to make future systems in the national network meet the new requirements four channels only will be obtained in the band now occupied by the No. 4 system, and the design of the twelve-circuit and coaxial cable equipment will need modification. The early coaxial cable installations used a carrier spacing of 5 kc/s, but re-design on a basis of 4 kc/s spacing was envisaged. To transmit erect side-bands it will be necessary to re-design the group modulating equipment. The system already transmits effectively up to 3,100 c/s and the re-design of filters will make possible the transmission of the wider band.

To obtain the wider transmission band on twelve-circuit carrier equipment it will, in all probability, be necessary to abandon the use of direct modulation and single filtration as in Messrs. S.T. & C.'s system, and to adopt either double modulation with improved filters of normal construction or employ crystal element filters. To avoid the use of the very large crystals which would be required in filters for frequencies as low as 12 kc. a system similar to the American "K" type could be adopted[22]. In this system crystal element filters are used and the channel modulation places the twelve bands into the range 60 to 108 kc/s; this band is then group modulated with a carrier frequency of 120 kc., the lower side-band (12 to 60 kc/s) being transmitted[12].

The old and new equipment would not be suitable for working together, the transmission of different virtual side-bands being the principal difficulty in-

---

[22, 12] See Bibliography.

volved. To maintain the desired flexibility of equipment it will be necessary to use, in connection with each of the existing types of group equipments, a frequency inverter, the function of which will be to produce erect virtual side-bands. The design of such a device is now under consideration.

Standardisation of the Twelve-Channel Group.

To limit the number of types of carrier equipment to be produced and maintained, and also to facilitate the leading out of groups at intermediate points on long routes it is desirable to standardise a basic group. This will probably be of twelve circuits, covering the frequency range 12-60 kc/s and having the characteristics required by the latest C.C.I.F. recommendations. It is possible that this will be the basic unit for twelve-circuit and coaxial cable equipment and it may also be possible to use it on radio links. The use of nine- and ten-channel groups for radio working has already received attention[23].

Group Working on Twelve-Circuit Carrier Cables.

The possibility of working more than 12 channels on each pair in twelve-circuit carrier cables is at present receiving attention. Measurements have shown that far-end crosstalk can be made satisfactory on all pairs in some cables at frequencies up to 160 kc. by the use of condensers only. On other cables this will not be feasible, but it will be possible to work 24 channels on all the pairs, and 36 channels on a large number of pairs. Poling (*i.e.*, interchange of " howl " and " listen " pairs which may change the value of the crosstalk) causes little or no trouble up to 60 kc/s, but will need closer attention at the higher frequencies. Crosstalk balancing frames will be necessary at the additional intermediate repeater stations unless it is found possible to balance two repeater sections by networks at one point.

A field trial is now in progress on the London-Cambridge cables; two pairs are being balanced for crosstalk at frequencies up to 160 kc.

Twelve-Circuit Carrier working on Existing Cables.

A field trial of twelve-circuit carrier working is being arranged, using de-loaded pairs in two existing cables between Derby and Leeds, one for each direction of transmission. Distant-end crosstalk balancing by networks will be carried out in the normal way. If the trial proves satisfactory it may be possible on some routes to lay one additional cable to work with an existing cable which will be de-loaded for the purpose.

Twelve-Circuit Equipment for International Circuits.

Twelve-circuit carrier equipment has already been used to provide international circuits on submarine cables. In all cases to date, however, the carrier equipment has been placed at the submarine cable terminals. The 1939 Anglo-French cable which has been designed specifically for twelve-circuit carrier working will, however, have amplifier equipment only at its ends, and ultimately the carrier terminals will be at London and Paris.

Automatic Compensation for Variations in Line Attenuation.

Whilst the lengths of circuits and temperature changes on underground cables in this country are such as to make automatic regulation of transmission levels less necessary than in some other countries, some attention is being given to the problem, since it is a desirable objective for our longer circuits and for continental circuits. Compensation is complicated by the fact that the slope as well as the magnitude of the attenuation-frequency characteristic of a pair is affected. This means that complete compensation cannot be effected by switching attenuation pads into and out of the circuit as required; it is also necessary to introduce networks compensating for the change of slope of the attenuation-frequency curve (sometimes known as twist regulation).

It may be necessary to change the gain of repeaters at fairly close intervals along a line and the slope of the equalisation characteristic at somewhat wider intervals. Several methods of accomplishing this have been patented (as an example see British Patent Specification 482382), and experimental installations have been set up in America[24]. In the case of the London-Birmingham coaxial system arrangements have been made for repeater gain changes necessitated by line temperature changes to be made manually. Automatic regulation may be introduced if necessary at a later date.

It is probable that automatic regulation will be accomplished by the transmission of one or more pilot frequencies, the gain and equalisation changes being effected in an electro-mechanical or purely electrical manner. In America it is the practice to use a looped cable pair as one arm of a bridge circuit, the out of balance current produced by changes in conductor resistance occasioned by temperature variations being used to control a motor which switches resistance into or out of the regulating networks inserted in the line.

Transmission by means of Hyper-frequency Wave Guides.

Hyper-frequencies (say of the order of 1000 Mc/s and above) can be transmitted effectively by means of such a " line " as a simple metal tube or a rod of insulating material. The frequency band which is transmitted most effectively depends upon the configuration of the transmitting structure, the permittivities of the structure and its surroundings and the shape of the electrodes applying the oscillations to the transmitting medium.

The use of such wave guides may, with the development of hyper-frequency oscillators and amplifiers, become a commercial proposition. Experimental work and theoretical studies have been in progress in several countries for a number of years[25, 26] and many

---

[23] See Bibliography.

[24, 25, 26] See Bibliography.

patents have been granted. Whilst it is too soon yet to foresee any immediate application, it seems not unreasonable to suppose that from the deeper understanding of the laws of nature and the ability to use them which must result from this work, there will emerge practical developments during the next few years.

ACKNOWLEDGEMENTS.

The authors gratefully acknowledge their indebtedness to Messrs. G.E. Co. Ltd. and S.T. & C. Ltd for the provision of photographs and to Messrs. Siemens Bros. & Co. Ltd. for the provision of slides. They are also grateful to these firms for the supply of panels for demonstration purposes.

Thanks are also due to Messrs. S. M. E. Rousell and G. H. M. Gleadle who read the proof copy of this paper.

AUTHORS' NOTE.

Since the preparation of this paper in September, 1938, the development of multi-channel carrier equipment has proceeded rapidly; a few notes on the present position of certain features of the development will be of interest.

The quantity of coaxial and twelve-channel type equipment in use has been greatly increased.

Tests on Messrs. G.E.C.'s twelve-channel carrier equipment have been completed, small modifications shown necessary have been carried out and satisfactory circuits are provided upon a number of routes.

The detail of a new twelve-channel type equipment (Carrier System No. 7) has been decided upon; this type of equipment will be made by both Messrs. S.T. & C. and Messrs. G.E.C., and results in a preliminary stage of standardisation being attained. The initial stage of frequency changing places twelve channels into the frequency range 60-108 kc.; crystal element channel filters are used. A subsequent stage of frequency changing will be employed to translate the 60-108 kc/s group into the range 12-60 kc/s. Circuit characteristics considerably superior to those recommended by the C.C.I.F. for international circuits will be obtained. The equipment is so designed that either 12 or 24 channels can be operated upon a pair in twelve-channel type cables. It is suitable for use as providing the basic group of coaxial cable super-groups, the initial frequency changing stage producing the group recommended by the C.C.I.F. as the basic group.

Arrangements have been made for the provision of equipment to operate at the junction of coaxial and twelve-channel cables; this makes it unnecessary to restore to audio-frequency at such junctions.

Specifications and sample models of group inverter equipment have been prepared; considerable use will be made of inverters as the new type (erect side-band) twelve-channel equipment is brought into use.

The experiments on twelve-channel type equipment installed to work on audio cables between Derby and Leeds is approaching completion. From the evidence available to date it appears that the experiment will be successful.

With the advent of 2 V.F. signalling, it has become necessary to ensure that all carrier channels shall operate with the terminal station oscillators in synchronism. Synchronising arrangements have been provided whenever necessary, and a standard "twelve-channel" synchronising system is being introduced; this standardised system involves the transmission to line of a 60 kc. pilot signal.

APPENDIX No. I.

NOMENCLATURE.

The significance of a number of terms used in this paper is given below.

Channel: A unidirectional transmission path.

Circuit: A means of both-way communication, *i.e.*, one "go" channel and one "return" channel.

Group: A group of circuits is formed when, after frequency changing, all of the "go" and "return" channels are commoned to single "go" and "return" transmission paths. A number of such groups may be subjected to further frequency changing and commoned to form a "super-group," *e.g.*, twelve channels in the frequency range 12-60 kc. might be commoned to form a group and three such groups might be subjected to frequency changing and commoned to form a "super-group" 144 kc/s in width.

Coaxial pair: Two conductors, one symmetrically surrounded by, but electrically separated from the other.

Frequency changer: This term is used to refer to both modulators and demodulators.

Attenuation distortion: Change in gain or attenuation of a line or piece of apparatus with change of frequency, the input power being maintained constant at all frequencies.

Amplitude distortion: Change in gain or attenuation of a line or piece of apparatus with change in amplitude of the applied voltage, the frequency being maintained constant.

Harmonic distortion: The production in a line or piece of apparatus of frequencies other than those applied at the input terminals.

Virtual Carrier Frequency: The carrier frequency which, if used, would effect by one stage of modulation (or demodulation) the same transposition of frequencies as actually obtained by two or more stages of modulation (or demodulation).

Erect side-band: The side-band obtained by adding the audio-frequencies to the virtual carrier-frequency.

Inverted side-band: The side-band obtained by subtracting the audio-frequencies from the virtual carrier-frequency.

APPENDIX No. II.

NOTES ON FREQUENCY CHANGING
(as applied to carrier telephony on lines)

In any carrier telephone system it is desired to transmit the intelligence contained in an audio-frequency band extending from f_1 to f_2 cycles by means of a band of frequencies, not exceeding $(f_2 - f_1)$ cycles in width, and lying at some position in the frequency spectrum which is normally outside the audio-frequency range. A modulating device is used to perform the required conversion ; if the frequencies in the range f_1 to f_2 and a carrier-frequency f_c are applied to such a device the output current will contain frequencies covering bands $(f_c - f_2)$ to $(f_c - f_1)$ and $(f_c + f_1)$ to $(f_c + f_2)$. Either of these bands, which are known as the lower and upper (or inverted and erect) side-bands respectively, is capable of transmitting the intelligence contained in the band f_1 to f_2. Hence to conserve space in the frequency spectrum available one side-band only is transmitted. A further advantage obtained by the transmission of a single side-band only is that phasing out due to different transmission times of corresponding frequencies $(f_c \pm f)$ in the side-bands is avoided. The frequency f_c may be present at the output of the modulator, but it, too, is usually suppressed in order to avoid cross-modulation as well as to avoid the transmission of unnecessary frequencies and the consequent loading of amplifiers. If the frequency f_c is suppressed at the transmitting end it must be re-applied at the receiving end in order that it and the transmitted side-band may be applied to a frequency-changing device (termed, of course, a demodulator in this case) and so reproduce the frequencies f_1 to f_2. The reintroduced carrier at the distant terminal need not be in phase with that at the transmitting end, but it is desirable that synchronism of the carrier-frequency should be approached. For speech, lack of synchronism should not exceed about 10 c/s, for music 5 c/s, and for V.F. telegraphs 2 c/s, while on circuits employing 2 V.F. signalling no asynchronism is permissible.

The basic principle involved in producing the required side-frequencies may be stated as follows. If voltages $E_1 \sin ct$ and $E_2 \sin at$ are applied to a network, then for the network to be a satisfactory modulator the output current must contain a relatively large component equal to $KE_1E_2 \sin ct, \sin at$. By simple trigonometry this will be seen to involve the production of frequencies $(c \pm a)$. Suitable networks are (*a*) an arrangement of non-linear impedances and (*b*) any circuit in which one function of the circuit varies at one frequency and a second function with another frequency. As an example (fortunately, not a practical application) of (*b*) consider a conductor oscillating with a frequency " *c* " in a magnetic field the intensity of which varies with a frequency " *a* " ; it would be found that the e.m.f. induced in the conductor would contain components of frequencies $(c \pm a)$. The frequency-changing devices used in practice invariably employ non-linear impedances in circuit arrangements which come under the headings of both (*a*) and (*b*). The non-linear impedance elements used take the form of diodes, multi-electrode valves back biased to the point of anode current cut-off, and metal rectifiers.

To obtain the side-bands mentioned in the first paragraph of this appendix it is usual to employ amplitude modulation, *i.e.*, assuming the carrier supply is of the form $E_1 \sin ct$, and the modulating frequency (angular) is " *a*," then the output current from the modulator should be—

$$i = kE_1 \sin at, \sin ct \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(i)}$$

i.e., E_1 is made dependent upon " *a*."

In practical modulators multiple and higher order sum and difference frequencies are produced but it is arranged that, as far as possible, those unwanted products which cannot be eliminated by adopting symmetrical circuits have a minimum amplitude or are suppressed by filters.

As an alternative to the type of modulation represented by equation (i), the amplitude of a carrier supply $E_1 \sin ct$ could be maintained constant, and the angular frequency or the phase varied in accordance with " *a*," *i.e.*, alternating voltages of the form

$$E_1 \sin [c(1 + m \sin at)t] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(ii)}$$

and $$E_1 \sin [ct + m \sin at] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(iii)}$$

could be produced. The expressions (ii) and (iii) are the products of frequency and phase modulation respectively ; they have little application in practice as they can be shown to involve the production of an infinite series of side frequencies for each modulating frequency concerned.

In carrier telephony it is the practice to aim at achieving amplitude modulation. Networks employing copper oxide rectifiers are used when frequencies up to about 200 kc. are involved (at frequencies much in excess of this the effective capacity of the rectifier element affects seriously the back impedance of the element—some authorities are, however, of the opinion that copper oxide rectifiers may be used up to 1 Mc), while biased multi-electrode or diode valves are used for frequencies above that for which metal rectifiers are suitable. Typical applied voltage/current characteristics for the non-linear impedances concerned are illustrated in Fig. **39**. As none of the

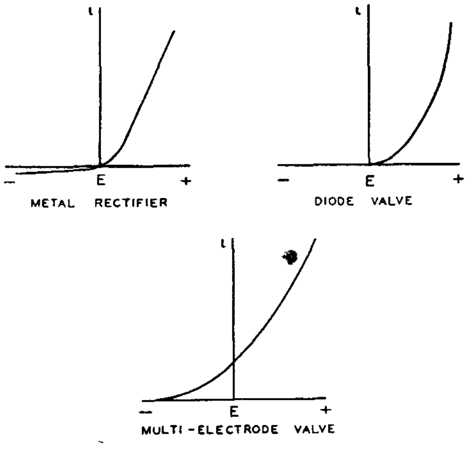


FIG. **39**.—CHARACTERISTIC OF CERTAIN NON-LINEAR IMPEDANCES.

curves is discontinuous a characteristic may be expressed to any degree of accuracy by means of a Taylor's series.

i.e., $i = C_0 + C_1e + C_2e^2 + C_3e^3 + \ldots\ldots\ldots\ldots\ldots \text{(iv)}$

As the coefficients of equation (iv) decrease rapidly with increasing orders of " e " it may be used with convenience (if the amplitudes of the applied e.m.f.s are small) when examining the performance of the simpler networks employing non-linear impedances. As an example of the use of equation (iv) it is of interest to examine the form of the output current from a single balanced type of modulator; this is one of the three types of modulator most commonly employed in carrier telephony, and one of the three considered in this appendix.

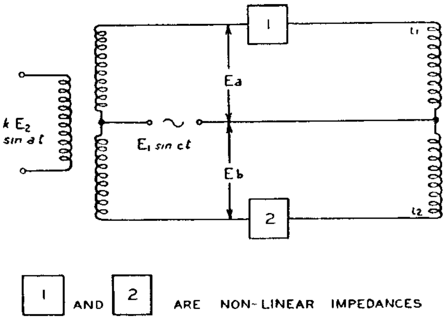


FIG. 40.—SCHEMATIC OF SINGLE BALANCED MODULATOR.

The windings of the input transformer (see Fig. **40**) are so arranged that—

$$E_a = E_1 \sin ct + E_2 \sin at$$
$$\text{and} \quad E_b = E_1 \sin ct - E_2 \sin at$$

Then, assuming the load to be a pure resistance (which is nearly true in practice) it will serve merely to modify the value of the coefficients in equation (iv).

$$i_1 = C_1E_a + C_2E_a^2 + C_3E_a^3 + \ldots\ldots\ldots\ldots$$

(*Note*: $C_0 = 0$ as the relevant curve passes through the origin.)

If the non-linear impedances 1 and 2 have identical characteristics

$$i_2 = C_1E_b + C_2E_b^2 + C_3E_b^3 + \ldots\ldots\ldots\ldots$$

The windings of the output transformer are so arranged that, assuming the transformer to be perfect, $E = K(i_1 - i_2)$ and hence the frequencies in the output may be examined by considering the value of $(i_1 - i_2)$.

$$(i_1 - i_2) = C_1(E_a - E_b) + C_2(E_a^2 - E_b^2) + C_3(E_a^3 - E_b^3) + \ldots\ldots\ldots\ldots \text{(v)}.$$

Evaluating each of the terms of equation (v) separately

$$\begin{aligned} C_1(E_a - E_b) &= C_1(2E_2 \sin at) \\ C_2(E_a^2 - E_b^2) &= C_2(2E_1 \sin ct)\,(2E_2 \sin at) \\ &= 4C_2E_1E_2 \sin ct.\ \sin at \\ &= 2C_2E_1E_2 \left[\cos(c-a)\,t - \cos(c+a)\,t\right] \\ C_3(E_a^3 - E_b^3) &= C_3(E_a - E_b)\,(E_a^2 + E_b^2 + E_aE_b) \end{aligned}$$

which may be shown

$$= C_3(2E_2 \sin at)\,[3E_1^2 \sin^2 ct + E_2^2 \sin^2 at]$$

It may be shown by simple trigonometry that the product of sin at and $\sin^2 ct$ introduces frequencies of " a " and $(2c \pm a)$, while the product of sin at and $\sin^2 at$ produces frequencies " a " and " $3a$." The examination of equation (v) shows that, if terms higher than the third are ignored, the output from a single balanced type modulator will contain the frequencies " a," " $3a$," $(c \pm a)$, and $(2c \pm a)$. It will be noted that the carrier-frequency is not present.

In general, it may be stated that any modulator supplied with a carrier e.m.f. of angular frequency " c " and a modulating e.m.f. of angular frequency " a " will have in its output circuit frequencies among the series indicated below.

$$\underbrace{\left.\begin{array}{lllll} a, & 2a, & 3a, & 4a, & ---- \\ c, & 2c, & 3c, & 4c, & ---- \\ (c\pm a), & (c\pm 2a), & (c\pm 3a), & (c\pm 4a), & ---- \\ (2c\pm a), & (2c\pm 2a), & (2c\pm 3a), & (2c\pm 4a), & ---- \end{array}\right\}\text{etc.}}_{\text{etc.}}$$

In practice, balanced modulators are used and this, by reason of the symmetry of the network, reduces the number of unwanted frequencies in the output circuit. It is one of the functions of the filter which follows the modulator to pass only the frequencies corresponding to the required side-band, but certain of the unwanted components will also lie in the band; the effect of such components is usually negligible and corresponds to less than 3% harmonic production.

It is common practice to operate a modulator with such a value of carrier voltage that the rectifiers may be considered as working on the linear portions of the characteristic. It will be assumed that the rectifiers have such characteristics (see Fig. **41**) when examining the operation of the ring or double balanced type modulator which is illustrated in Fig. **42**.

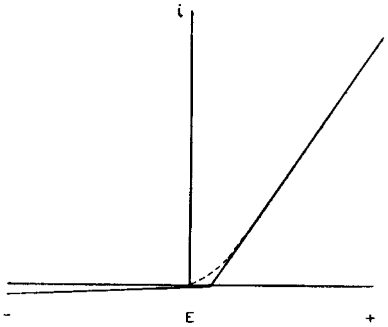


FIG. 41.—APPROXIMATE E − i CHARACTERISTIC OF A METAL RECTIFIER.

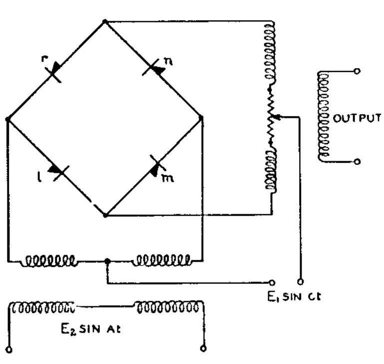


FIG. 42.—DOUBLE BALANCED MODULATOR.

If the amplitude of the carrier voltage is much greater than the amplitude of the audio voltage it follows that during one half cycle of the carrier voltage rectifiers *l* and *n* are conducting and during the next half cycle *m* and *r* are conducting; the rectifier ring may therefore be considered simply as a commutator and the network reduces to that indicated as Fig. **43.** Hence a cycle of modulating e.m.f. of the form shown as (*a*) in Fig. **44** would produce in the output circuit a current of the waveform illustrated as (*b*). It will be obvious from inspection that this is the resultant of a square topped wave of fundamental angular frequency " *c* " amplitude-modulated by a voltage of angular frequency " *a*."

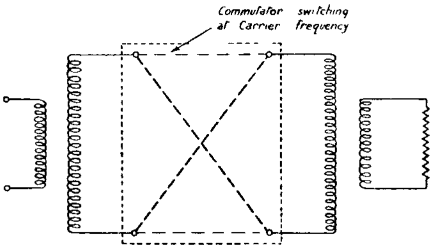


Fig. **43.**—Equivalent Circuit of Double Balanced Modulator.

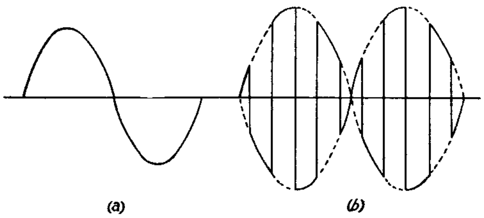


Fig. **44.**—Input and Output Waveforms of Circuit of Fig. 45.

If the applied low-frequency voltage is $E_2 \sin at$, (*b*) may be expressed as

$$i = KE_2 \sin at . \frac{4}{\pi} \left[\sin ct + \frac{1}{3} \sin 3\,ct + \frac{1}{5} \sin 5\,ct + \ldots . \right]$$

Examination of this expression indicates that frequencies $(c \pm a)$, $(3c \pm a)$, $(5c \pm a)$, etc., only are present, *i.e.*, frequencies equal to those applied and to their multiples are absent as well as sums and differences of odd order. The departure of the *e-i* characteristic from the ideal introduces products $(c \pm 3a)$, $(c \pm 5a)$, etc. The use of an unbalanced bridge introduces carrier leak and certain sums and differences such as $(c \pm 2a)$, $(c \pm 4a)$, etc. The amplitudes of the unwanted products are considerably less than those of the wanted products. Balance of the bridge is attained by the selection of rectifier elements and the application of the carrier supply to the line of electrical symmetry; a potentiometer between the half windings of the input or output transformer is employed in order that the second requirement can be met.

Modern carrier practice in this country employs modulators of the single balanced and double balanced types only, but in view of the use to which the modulator illustrated in Fig. **45** is being put, particularly in the United States of America, it is of interest to examine it. It will be observed that this modulator (often known as Cowan's modulator) effectively short circuits the output of the transformer during one half cycle of carrier supply, and offers a high impedance during the next half cycle. Hence the voltage produced across the input of the attenuator pad will be of the form illustrated in (*b*) of Fig. **46.**

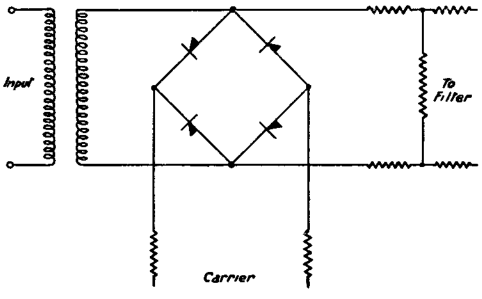


Fig. **45.**—The Cowan Modulator.

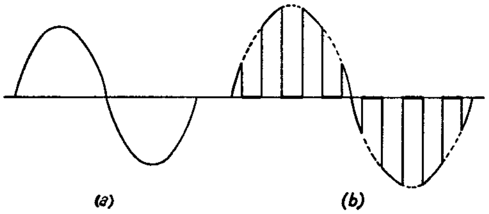


Fig. **46.**—Input and Output Waveforms of Cowan Modulator (using Ideal Rectifiers).

If the input voltage is expressed as $E_2 \sin at$, (*b*) may be expressed as

$$i = KE_2 \sin at . \frac{2}{\pi} \left[\frac{\pi}{4} + \sin ct + \frac{1}{3} \sin 3\,ct + \text{- - -} \right]$$

It will be observed that the frequencies present in the output are similar to those present in the output of the double balanced modulator, but that, for the same applied voltages, the amplitudes are halved, and that a frequency equal to that applied is present.

As has been mentioned, metal rectifiers are suitable for use in modulator networks when the frequencies concerned do not greatly exceed 200 kc.; at frequencies much in excess of this figure the capacity of an element so modifies its back characteristic as to make it unsuitable for the purpose concerned. At higher frequencies it is customary to use valves in a circuit of the single balanced type. The valves may be diodes or multi-grid valves, bias being used when necessary to bring the grid potential to the point of anode current cut-off. Fig. **47** illustrates such a modulator.

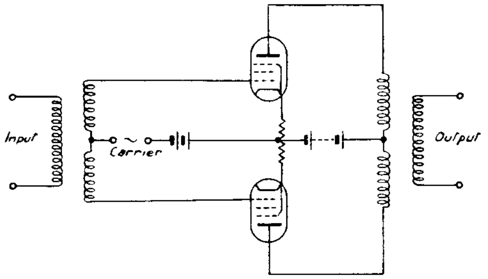


FIG. 47.—SINGLE BALANCED MODULATOR, USING PENTODE VALVES.

So far, the problem considered has been the production of side-bands by one audio-frequency band modulating a carrier frequency. It has been seen that most of the unwanted products of modulation lie outside the side-band range and are suppressed by the channel filter. Further, such unwanted products as do appear in the transmitted side-band are present only during the period of the speech producing them; they therefore appear as a distortion of the received speech and are readily tolerated if their level is lower than 30 db. below the level of the wanted frequencies.

However, when the modulation at one step of a series of side-bands, each the product of a previous stage of modulation, is considered (*i.e.*, group modulation) it is apparent that unwanted products of modulation due to one channel may lie in the bands occupied by other channels. Hence inter-channel interference is introduced, and such interference is tolerable only if at least 60 db. below the wanted signal. It will be appreciated that the requirements of a group modulator are considerably more severe than of a channel modulator.

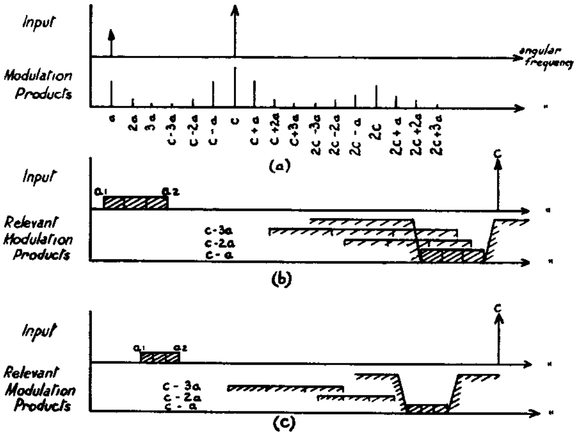


FIG. 48.—DIAGRAMS ILLUSTRATING THE PRODUCTION BY MODULATION OF WANTED AND UNWANTED FREQUENCIES.

Fig. **48** illustrates in graphical form the production of wanted and unwanted frequencies in modulators.

Fig. **48**(*a*) illustrates some of the products which are present in the output of a simple unbalanced modulator to which frequencies " *c* " and " *a* " are applied. The length of the vertical lines represents *very* roughly the relative magnitude of the e.m.f.s involved.

Fig. **48**(*b*) illustrates a frequency range a_1 to a_2, modulating a carrier *c*, the lower side-band frequencies being filtered out for transmission. The figure is drawn for the case when $a_2/a_1 > 2$ and it will be seen that, in addition to multiples of frequencies in the range a_1 to a_2, certain of the (c-$2a$) and (c-$3a$), etc., products will lie in the transmitted band.

Fig. **48**(*c*) is similar to (*b*) except that $a_2/a_1 < 2$, in which case the most important of the unwanted products of modulation fall outside the transmitted band and hence do not give rise to interference.

The band a_1 to a_2 may be considered as a single audio band to be modulated, or as a series of side-bands undergoing group modulation; in Fig. **48**(*b*) and (*c*) the band is divided into three parts in order to illustrate either the first or second condition.

When modulation of a carrier-frequency by a band of audio-frequencies is concerned it is not possible to restrict the ratio of the maximum to minimum modulating frequencies in order to reduce the magnitude of unwanted components falling in the transmitted range; nor, as has been indicated previously, is it necessary. When, however, group modulation is concerned it is often possible so to select the range of modulating frequencies employed that the conditions for minimum interference obtain. Such selection has been arranged in the case of the equipment for coaxial cables; in this case groups occupy the frequency range from 60 to 100 kc. and super-groups 300 to 500 kc.

It has proved necessary to modulate a group of channels covering more than one octave; examples are the Carrier System No. 4 type of equipment which employs the frequency range 0.2 to 16 kc., and the twelve-circuit type of equipment which works over the range 12 to 60 kc. It has therefore been necessary to produce group modulators in which the unwanted products are so low that a signal-to-noise ratio of at least 60 db. is obtained on each channel. The modulators used are of the single balanced or double balanced types (using valves or metal rectifiers according to the group frequency employed) particular care being taken to meet the following requirements:—

(*a*) High ratio of carrier to signal voltage.
(*b*) Choice of optimum rectifier and load impedances.
(*c*) Choice of group carrier frequency so that certain of the products are unimportant.
(*d*) In the case of valve modulators, straightening the valve characteristic by the application of negative feed-back.

No mention is made in the above to demodulation, since the mechanism is identical with that of modulation.

APPENDIX No. III.

BALANCING TWELVE-CIRCUIT CARRIER CABLES.

Procedure of Messrs. Pirelli General Cables Ltd. with Mid-Repeater-Section Networks.

Capacitance-unbalance measurements are made, after laying, on four lengths which are then jointed together to form a " section " of about 500 yards. The unbalances reduced are side-to-side, side-to-earth, and, to some extent, side-to-phantom. A test-selected joint between two such sections is made, the same unbalances receiving attention. On the 1000 yards lengths, all cases of capacitance unbalance, conductor resistance and unbalance and mutual capacitance are check-tested and straight joints made to give 2000 yard lengths on which air pressure tests are made. No mutual capacitance matching is carried out. Straight joints are made between all 2000 yards lengths except at the mid-point of each half repeater-section (where " poling " tests are made for distant-end crosstalk at 5 kc/s) and except at the joint nearest to the balancing hut (which is a straightening-out joint for each half repeater-section). The two half repeater-sections are then " straight " through the distant-end crosstalk balancing frame and the insertion and adjustment of condensers and resistors between pairs on the frame improves the distant-end crosstalk on the complete repeater-section.

The following table gives average values of distant-end crosstalk for three repeater-sections, side-to-side and pair-to-pair, in decibels at 60 kc/s both before and after " condenser balancing " at the network building:—

	BEFORE Condenser Balancing.		AFTER Condenser Balancing.	
	Pair-to-Pair	Side-to-Side	Pair-to-Pair	Side-to-Side
Max. Max.	109	91	112	104
Av. Max.	102	86	107	99
Av. Mean	76	76	87	86
Av. Min.	60	66	79	80
Min. Min.	58	60	78	76

The specified values for the frequency range 12 to 60 kc/s are minima of 70 db. for 90% of the combinations and 65 db. for all combinations.

Procedure of Messrs. Standard Telephones & Cables, Ltd.

Cable lengths 1 and 2 (176 yards each) are joined together mainly on the basis of mutual capacity, but they are also balanced for side-to-side, side-to-phantom, and side-to-earth. The same procedure is followed for lengths 3 + 4, 5 + 6 and 7 + 8. Then the four lengths 1 + 2, 3 + 4, 5 + 6 and 7 + 8 are joined together on the basis of unbalances. At the joint between the two sections 1 + 2 + 3 + 4 and 5 + 6 + 7 + 8, admittance unbalance is measured and the pairs are poled within quad, if necessary, to reduce side-to-side unbalance. The 0.8 mile sections are then joined together on the basis of mutual capacity (mutual capacity of the adjacent 0.1 mile sections being considered) to build up a repeater-section.

The limits worked to on eight lengths (0.8 mile) are as follows:—

Side-to-side—Av. Av.	10 μμF.
Max. Max.... ...	50 ,,
Side-to-phantom—Av. Av. ...	80 ,,
Max. Max.... ...	500 ,,
Side-to-earth—Av. Av.	50 ,,
Max. Max.... ...	250 ,,

APPENDIX No. IV.

A NOTE ON THE CALCULATION OF CROSSTALK.

This appendix is intended to show that, provided the practical conditions permit, it is possible to use the value of crosstalk on a length of cable to estimate the crosstalk on a number of similar lengths joined together.

If several *similar* lengths of cable (coaxial or pair type) or open wire are jointed together without balancing operations, the near-end or far-end crosstalk can be calculated from a knowledge of the coupling or crosstalk between the circuits in one length.

Thus, considering the case of direct near-end crosstalk, let x miles be the length of each section, e^{-k} the voltage ratio of the crosstalk attenuation between the circuits concerned in a section at some frequency and $\gamma = \beta + j\alpha$ the propagation constant of each circuit (k and β are in nêpers per mile and α is in radians per mile). Then the crosstalk due to the first section is e^{-k}; that due to the second section is changed in magnitude and phase relative to the crosstalk in the first section since it travels an extra distance of $2x$. The crosstalk in the second section is therefore $e^{-2\gamma x} \times e^{-k}$. Similarly, the crosstalk attenuation for the third section is $e^{-4\gamma x} \times e^{-k}$,

Summing up for " n " sections we obtain

$$\text{N.E. crosstalk} = e^{-K} = e^{-k}(1 + e^{-2\gamma x} + e^{-4\gamma x} + e^{-6\gamma x} + \ldots\ldots)$$

the term inside the bracket is a geometric series of common ratio $e^{-2\gamma x}$. Summing this to " n " terms we have

$$e^{-K} = \frac{e^{-k}(1 - e^{-2\gamma x n})}{(1 - e^{-2\gamma x})}$$

or $e^{-K} = \dfrac{e^{-k}(1 - e^{-2\gamma l})}{(1 - e^{-2\gamma x})}$ where $l = nx$ is the total length of a circuit.

$$\text{Now } e^{-2\gamma x} = 1 - 2\gamma x + \frac{(2\gamma x)^2}{1.2} - \text{etc.},$$

and if γx is so small that the third (and subsequent) terms may be neglected then $e^{-K} = \dfrac{e^{-k}(1 - e^{-2\gamma l})}{2\gamma x}$

This result has also been obtained by somewhat different methods[27].

---

[27] See Bibliography.

Considering extreme conditions,

(1) If $2\gamma l$ is so small that at any particular frequency we may neglect $(2\gamma l)^2$ by comparison with $2\gamma l$ then $e^{-K} = e^{-k}.n$ and the near-end crosstalk is proportional to " *n*," *i.e.*, to the total length of the circuit.

$$\text{Hence K (decibels)} = k \text{ (decibels)} - 2.303 \times 8.686 \log_{10} n$$

$$\therefore \quad \text{K (db.)} = k \text{ (db.)} - 20 \log_{10} n$$

This is a convenient form for calculation. Thus, if " *n* " is 2, *i.e.*, the length is doubled, the crosstalk becomes 6 db. worse. This is voltage addition.

(*Note*:—Where the cable manufacture or overhead construction is such that the crosstalk couplings in successive lengths are different in sign and magnitude, and no balancing operations are carried out, the crosstalk increases as $\sqrt{n}$ instead of as " *n*." This is the addition of powers.)

$$\text{We may write } e^{-K} = \frac{e^{-k}}{x} \,.\, nx = \frac{e^{-k}}{x} \,.\, l$$

It has also been shown[27] that

$$e^{-K} = \frac{Z_{1,2}}{2Z_0} \,.\, l$$

where $Z_{1,2}$ is the uniformly distributed mutual impedance between the circuits, Z_0 is the characteristic impedance of the circuits. The quantity $\frac{e^{-k}}{x} = \frac{Z_{1,2}}{Z_0}$ is sometimes referred to as the " coupling factor " of the circuits concerned and is a quantity which may be obtained by measurements. It will be observed that it is greater with a smaller value of Z_0 (as, for example, in lighly loaded cables or in non-loaded cables at higher frequencies).

(2) On the other hand, if " *n* " is large or the frequency is high so that $e^{-2\gamma l}$ is small compared with unity then $e^{-K} = \frac{e^{-k}}{2\gamma x}$

$$\therefore \quad \text{K (db.)} = k \text{ (db.)} + 20 \log_{10} 2\gamma x$$

and the crosstalk is independent of the total length of the circuit. It is well known that near-end crosstalk cannot be affected by couplings electrically remote from the end of the circuits at which the measurements are made.

For values of γl intermediate between the above two extreme cases it is convenient to take the modulus of the expression thus:—

$$e^{-K} = \frac{e^{-k}(1 - e^{-2\gamma l})}{2\gamma x}$$

$$= \frac{e^{-k}}{x} \,.\, \frac{(1 - e^{-2\beta l} \,.\, e^{-2j\alpha l})}{2(\beta + j\alpha)}$$

$$\therefore \quad e^{-K} = \frac{e^{-k}}{x} \, \frac{[1 - e^{-2\beta l} \,.\, (\cos 2\alpha l - j \sin 2\alpha l)]}{2(\beta + j\alpha)}$$

$$\therefore \quad (e^{-K})^2 = \frac{e^{-2k}}{x^2} \,.\, \frac{[(1 - e^{-2\beta l} \,.\, \cos 2\alpha l)^2 + e^{-1\beta l} \,.\, \sin^2 2\alpha l]}{4(\beta^2 + \alpha^2)}$$

$$\therefore \quad |e^{-K}| = \frac{e^{-k}}{x} \,.\, \frac{\sqrt{1 - 2e^{-2\beta l} \,.\, \cos 2\alpha l + e^{-1\beta l}}}{2\sqrt{\beta^2 + \alpha^2}}$$

Since one of the terms in this expression gives an exponential curve, and the other involves a cosine term which undulates with frequency, the curve of crosstalk against frequency will also undulate. This is a well known characteristic of near-end crosstalk, and is due to the currents from the various points travelling different distances along the line and so arriving at the sending end in various phase relations.

Similar methods may be used for far-end crosstalk.

---

[27] See Bibliography.