Systems for Wide-Band Transmission Over Coaxial Lines

By L. ESPENSCHIED and M. E. STRIEBY

In this paper systems are described whereby frequency band widths of the order of 1000 kc. or more may be transmitted for long distances over coaxial lines and utilized for purposes of multiplex telephony or television. A coaxial line is a metal tube surrounding a central conductor and separated from it by insulating supports.

IT appears from recent development work that under some conditions it will be economically advantageous to make use of considerably wider frequency ranges for telephone and telegraph transmission than are now in use [1, 2] or than are covered in the recent paper on carrier in cable.[3] Furthermore, the possibilities of television have come into active consideration and it is realized that a band of the order of one million cycles or more in width would be essential for television of reasonably high definition if that art were to come into practical use.[4, 5]

This paper describes certain apparatus and structures which have been developed to employ such wide frequency ranges. The future commercial application of these systems will depend upon a great many factors, including the demand for additional large groups of communication facilities or of facilities for television. Their practical introduction is, therefore, not immediately contemplated and, in any event, will necessarily be a very gradual process.

Types of High-Frequency Circuits

The existing types of wire circuits can be worked to frequencies of tens of thousands of cycles, as is evidenced by the widespread application of carrier systems to the open-wire telephone plant and by the development of carrier systems for telephone cable circuits.[2, 3] Further development may lead to the operation of still higher frequencies over the existing types of plant. However, for protection against external interference these circuits rely upon balance, and as the frequency band is widened, it becomes more and more difficult to maintain a sufficiently high degree of balance. The balance requirements may be made less severe by using an individual shield around

[1] For references, see end of paper.

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each circuit, and with sufficient shielding balance may be entirely dispensed with.

A form of circuit which differs from existing types in that it is unbalanced (one of the conductors being grounded), is the coaxial or concentric circuit. This consists essentially of an outer conducting tube which envelops a centrally-disposed conductor. The high-frequency transmission circuit is formed between the inner surface of the outer conductor and the outer surface of the inner conductor. Unduly large losses at the higher frequencies are prevented by the nature of the construction, the inner conductor being so supported within the tube that the intervening dielectric is largely gaseous, the separation between the conductors being substantial, and the outer conductor presenting a relatively large surface. By virtue of skin effect, the outer tube serves both as a conductor and a shield, the desired currents concentrating on its inner surface and the undesired interfering currents on the outer surface. Thus, the same skin effect which increases the losses within the conductors provides the shielding which protects the transmission path from outside influences, this protection being more effective the higher the frequency.

The system which this paper outlines has been based primarily upon the use of the coaxial line. The repeater and terminal apparatus described, however, are generally applicable to any type of line, either balanced or unbalanced, which is capable of transmitting the frequency range desired.

The Coaxial System

A general picture of the type of wide band transmission system which is to be discussed is briefly as follows: A coaxial line about 1/2 inch in outside diameter is used to transmit a frequency band of about 1,000,000 cycles, with repeaters capable of handling the entire band placed at intervals of about 10 miles. Terminal apparatus may be provided which will enable this band either to be subdivided into more than 200 telephone circuits or to be used *en bloc* for television.

Such a wide-band system is illustrated in Fig. 1. It is shown to comprise several portions, namely, the line sections, the repeaters, and the terminal apparatus, the latter being indicated in this case as for multiplex telephony. Two-way operation is secured by using two lines, one for either direction. It would be possible, however, to divide the frequency band and use different parts for transmission in opposite directions.

A form of flexible line which has been found convenient in the experimental work is illustrated in Fig. 2 and will be described more fully

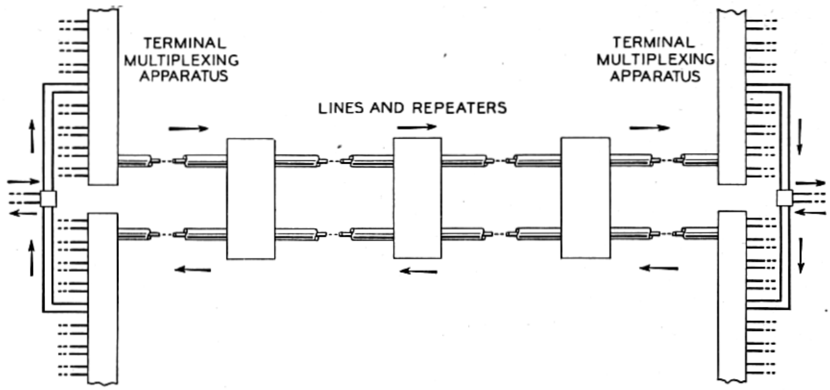


Fig. 1—Diagram of coaxial system.

subsequently. Such a coaxial line can be constructed to have the same degree of mechanical flexibility as the familiar telephone cable. While this line has a relatively high loss at high frequencies, the transmission path is particularly well adapted to the frequent application of repeaters, since the shielding permits the transmission currents to fall to low power levels at the high frequencies.

Of no little importance also is the fact that the attenuation-frequency characteristic is smooth throughout the entire band and obeys a simple law of change with temperature. (This is due to the fact that the dielectric is largely gaseous and that insulation material of good dielectric properties is employed.) This smooth relation is extremely

Fig. 2—Small flexible coaxial structure.

helpful in the provision of means in the repeaters for automatically compensating for the variations which occur in the line attenuation with changes of temperature. This type of system is featured by large transmission losses which are offset by large amplification, and it is necessary that the two effects match each other accurately at all times throughout the frequency range.

It will be evident that the repeater is of outstanding importance in this type of system, for it must not only transmit the wide band of frequencies with a transmission characteristic inverse to that of the line, with automatic regulation to care for temperature changes, but must also have sufficient freedom from inter-modulation effects to permit the use of large numbers of repeaters in tandem without objectionable interference. Fortunately, recent advances in repeater technique have made this result possible, as will be appreciated from the subsequent description.

An interesting characteristic of this type of system is the way in which the width of the transmitted band is controlled by the repeater spacing and line size, as follows:

1. *For a given size of conductor and given length of line, the band width increases nearly as the square of the number of the repeater points.* Thus, for a coaxial circuit with about .3-inch inner diameter of outer conductor, a 20-mile repeater spacing will enable a band up to about 250,000 cycles to be transmitted, a 10-mile spacing will increase the band to about 1,000,000 cycles, and a 5-mile spacing to about 4,000,000 cycles.
2. *For a given repeater spacing, the band width increases approximately as the square of the conductor diameter.* Thus, whereas a tube of .3-inch inner diameter will transmit a band of about 1,000,000 cycles, .6-inch diameter will transmit about 4,000,000 cycles, while a diameter corresponding to a full-sized telephone cable might transmit something of the order of 50,000,000 cycles, depending upon the dielectric employed and upon the ability to provide suitable repeaters.

Earlier Work

It may be of interest to note that as a structure, the coaxial form of line is old—in fact, classical. During the latter half of the last century it was the object of theoretical study, in respect to skin effect and other problems, by some of the most prominent mathematical physicists of the time. Reference to some of this work is made in a paper by Schelkunoff, dealing with the theory of the coaxial circuit.[6]

On the practical side, it is found on looking back over the art that the coaxial form of line structure has been used in two rather widely different applications: first, as a long line for the transmission of low frequencies, examples of which are usage for submarine cables,[7, 8] and for power distribution purposes, and second as a short-distance, high-frequency line serving as an antenna lead-in.[9, 10]

The coaxial conductor system herein described may be regarded as an extension of these earlier applications to the long-distance transmission of a very wide range of frequencies suitable for multiplex telephony or television.[11] Although dealing with radio frequencies, this system represents an extreme departure from radio systems in that a relatively broad band of waves is transmitted, this band being confined to a small physical channel which is shielded from outside disturbances. The system, in effect, comprehends a frequency spectrum of its own and shuts it off from its surroundings so that it may be used again and again in different systems without interference.

This new type of facility has not yet been commercially applied. It is, in fact, still in the development stage. Sufficient progress has already been made, however, to give reasonable assurance of a satisfactory solution of the technical problems involved. This progress is outlined below under three general headings: (1) the coaxial line and its transmission properties, (2) the wide band repeaters, and (3) the terminal apparatus.

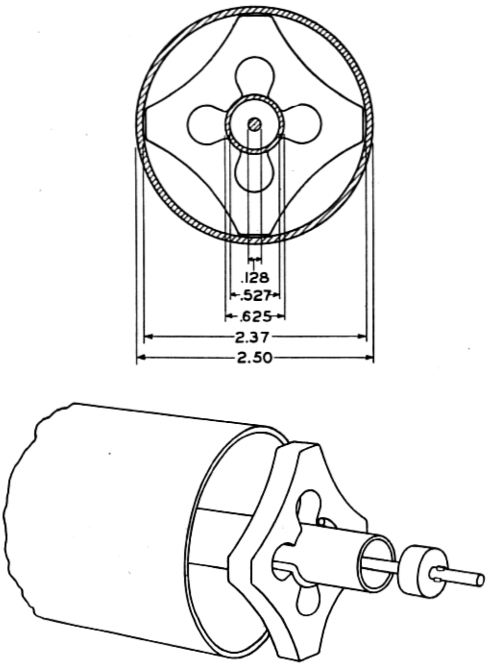
The Coaxial Line

An Experimental Verification

One of the first steps taken in the present development was in the nature of an experimental check of the coaxial conductor line, designed primarily to determine whether the desirable transmission properties which had been disclosed by a theoretical study could be fully realized under practical conditions. For this purpose a length of coaxial structure capable of accurate computation was installed near Phoenixville, Pa. Figure 3 shows a sketch of the structure used and gives its dimensions. It comprised a copper tube of 2.5 inches outside diameter, within which was mounted a smaller tube which, in turn, contained a small copper wire. Two coaxial circuits of different sizes were thus made available, one between the outer and the inner tubes, and the other between the inner tube and the central wire. The installation comprised two 2600-foot lengths of this structure.

The diameters of these coaxial conductors were so chosen as to obtain for each of the two transmission paths a diameter ratio which approximates the optimum value, as discussed later. The conductors were separated by small insulators of isolantite. The rigid construction and the substantial clearances between conductors made it possible to space the insulators at fairly wide intervals, so that the dielectric between conductors was almost entirely air. The outer conductor was made gas-tight, and the structure was dried out by circulating dry nitrogen gas through it. The two triple conductor lines were suspended on wooden fixtures and the ends brought into a test house, as shown in Fig. 4.

The attenuation was measured by different methods over the frequency range from about 100 kilocycles to 10,000 kilocycles. Investigation showed that the departures from ideal construction occasioned by the joints, the lack of perfect concentricity, etc., had remarkably little effect on the attenuation. In order to study the effect of eccentricity upon the attenuation, tests were made in which this effect was much exaggerated, and the results substantiated theoretical predictions. The impedance of the circuits was measured over the same range as the attenuation. A few measurements on a short length were made at frequencies as high as 20,000 kilocycles.



SPACING OF INSULATORS

LARGE SIZE : 4 FEET ON STRAIGHTAWAY
2 FEET ON CURVES
SMALL SIZE : 1 FOOT ON STRAIGHTAWAY
6 INCHES ON CURVES

Fig. 3—Structure used in Phoenixville installation.

Measurements were secured of the shielding effect of the outer conductor of the coaxial circuit up to frequencies in the order of 100 to 150 kilocycles, the results agreeing closely with the theoretical values. Above these frequencies, even with interfering sources much more powerful than would be encountered in practice, the induced currents dropped below the level of the noise due to thermal agitation of electricity in the conductors (resistance noise) and could not be measured.

The preliminary tests at Phoenixville, therefore, demonstrated that

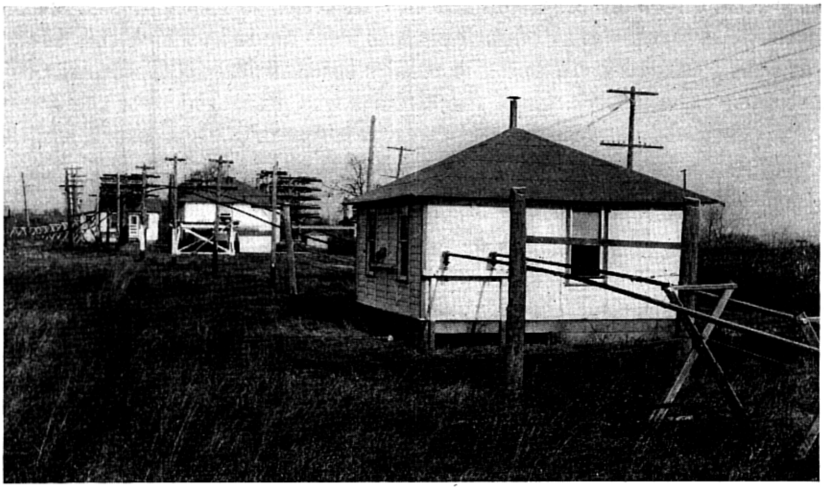


Fig. 4—Phoenixville installation showing conductors entering test house.

a practical coaxial circuit, with its inevitable mechanical departures from the ideal, showed transmission properties substantially in agreement with the theoretical predictions.

Small Flexible Structures

Development work on wide-band amplifiers, as discussed later, indicated the practicability of employing repeaters at fairly close intervals. This pointed toward the desirability of using sizes of coaxial circuit somewhat smaller than the smaller of those used in the preliminary experiments, and having correspondingly greater attenuation. Furthermore, it was desired to secure flexible structures which could be handled on reels after the fashion of ordinary cable. Accordingly, several types of flexible construction, ranging in outer diameter from about .3 inch to .6 inch, have been experimented with. Structures were desired which would be mechanically and electrically satisfactory, and which could be manufactured economically, preferably with a continuous process of fabrication.

One type of small flexible structure which has been developed is shown in Fig. 2. The outer conductor is formed of overlapping copper strips held in place with a binding of iron or brass tape. The insulation consists of a cotton string wound spirally around the inner conductor, which is a solid copper wire. This structure has been made in several sizes of the order of 1/2 inch diameter or less. When it is to be used as an individual cable, the outer conductor is surrounded by a lead sheath, as shown, to prevent the entrance of moisture. One or more of the copper tape structures without individual lead sheath may be placed with balanced pairs inside a common cable sheath.

Another flexible structure is shown in Fig. 5. The outer conductor in this case is a lead sheath which directly surrounds the inner conductor with its insulation. Since lead is a poorer conductor than copper, it is necessary to use a somewhat larger diameter with this construction in order to obtain the same transmission efficiency. Lead is also inferior to copper in its shielding properties and to obtain the same degree of shielding the lead tube of Fig. 5 must be made correspondingly thicker than is necessary for a copper tube.

The insulation used in the structure shown in Fig. 5 consists of hard

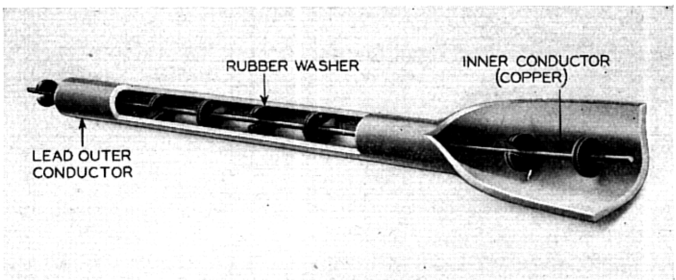


Fig. 5—Coaxial structure with rubber disc insulators.

rubber discs spaced at intervals along the inner wire. Cotton string or rubber disc insulation may be used with either form of outer tube. The hard rubber gives somewhat lower attenuation, particularly at the higher frequencies.

Another simple form of structure employs commercial copper tubing into which the inner wire with its insulation is pulled. Although this form does not lend itself readily to a continuous manufacturing process, it may be advantageous in some cases.

Transmission Characteristics

Attenuation

At high frequencies the attenuation of the coaxial circuit is given closely by the well-known formula:

$$\alpha = \frac{R}{2}\sqrt{\frac{C}{L}} + \frac{G}{2}\sqrt{\frac{L}{C}}, \tag{1}$$

where R, L, C and G are the four so-called "primary constants" of the line, namely, the resistance, inductance, capacitance and conductance per unit of length. The first term of (1) represents the losses in the conductors, while the second term represents those in the dielectric.

When the dielectric losses are small, the attenuation of a coaxial circuit increases, due to skin effect in the conductors, about in accordance with the square root of the frequency. With a fixed diameter ratio, the attenuation varies inversely with the diameter of the circuit. By combining these relations there are obtained the laws of variation of band width in accordance with the repeater spacing and the size of circuit, as stated previously.

The attenuation-frequency characteristic of the flexible structure illustrated in Fig. 2, with about .3 inch diameter, is given in Fig. 6.

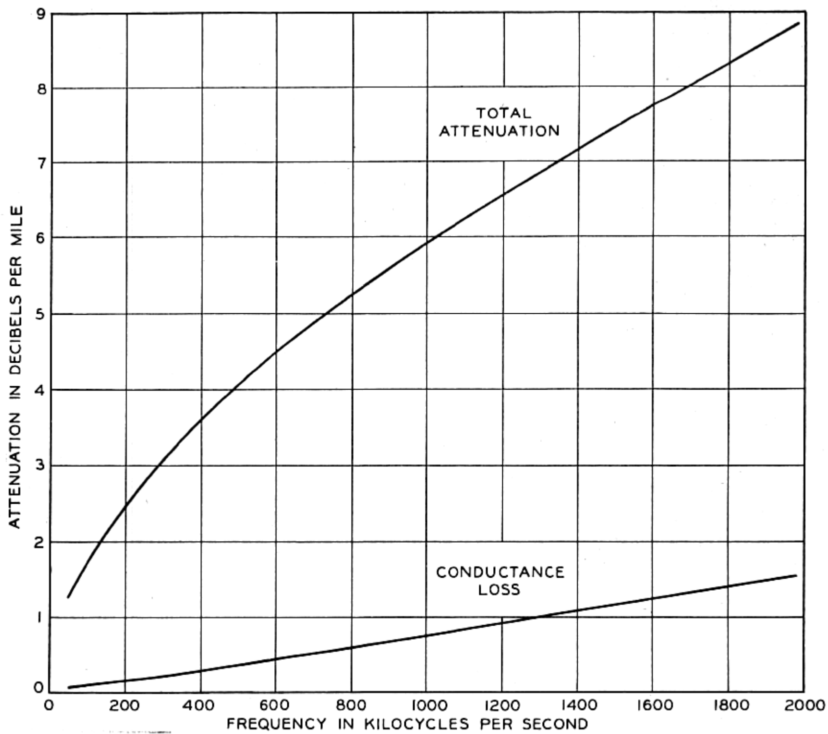


Fig. 6—Attenuation of small flexible coaxial structure (Fig. 2).

The figure shows also that the conductance loss due to the insulation is a small part of the total.

It is interesting to compare the curves of the transmission characteristics of the coaxial circuit with those of other types of circuits. Figure

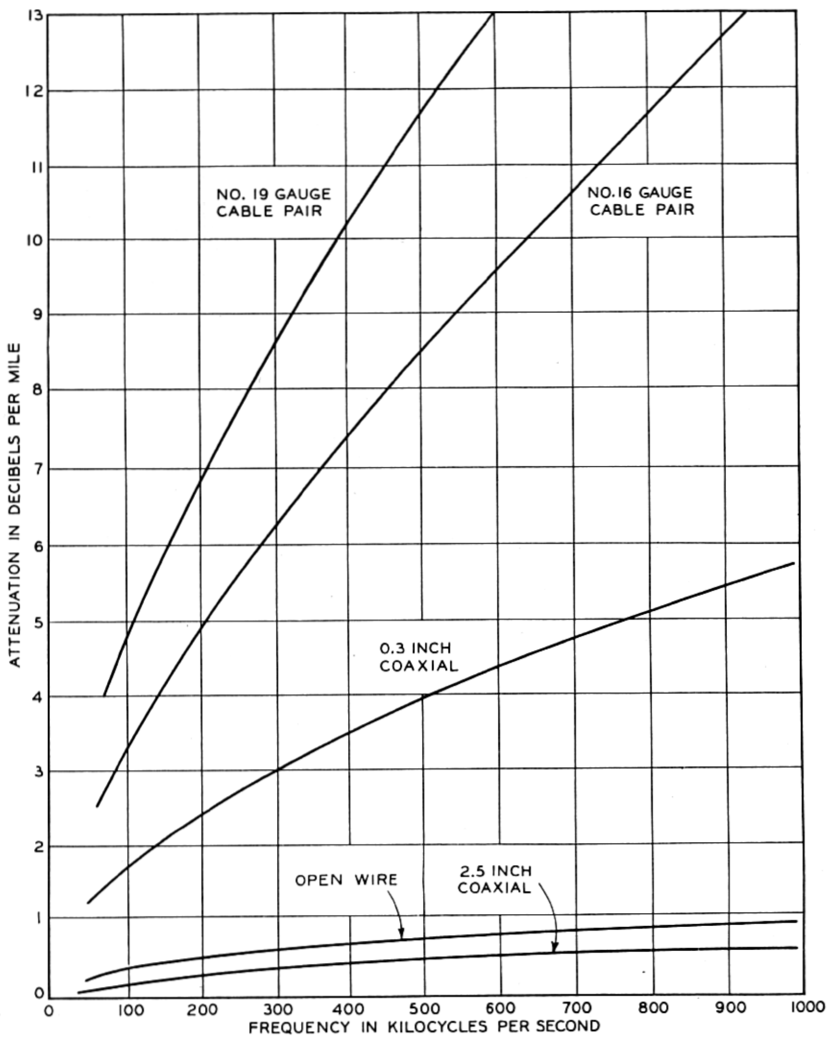


Fig. 7—Attenuation frequency characteristics of coaxial and other circuits.

7 shows the high-frequency attenuation of two sizes of coaxial circuit using copper tube outer conductors, of .3 inch and 2.5 inch inner diameter, and that of cable and open-wire pairs in the same frequency range.

Effect of Eccentricity

The small effect of lack of perfect coaxiality upon the attenuation of a coaxial circuit is illustrated by the curve of Fig. 8, which shows

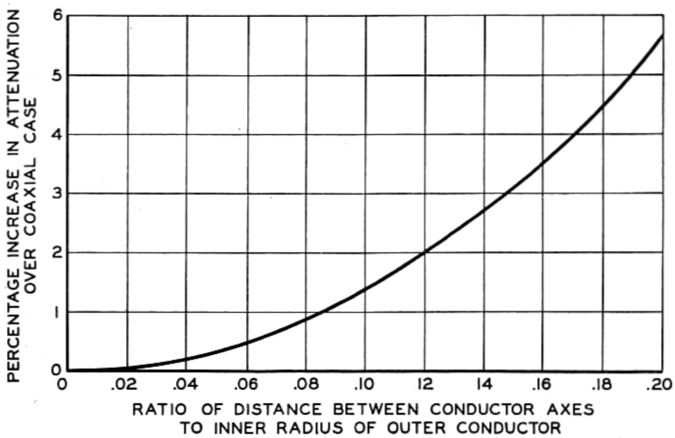


Fig. 8—Increase in attenuation of coaxial circuit due to eccentricity.

attenuation ratios plotted as a function of eccentricity, assuming a fixed ratio of conductor diameters and substantially air insulation.

Temperature Coefficient

With a coaxial circuit, as with other types of circuits, the temperature coefficient of resistance decreases as the frequency is increased, due to the action of skin effect, and approaches a value of one-half the d.-c. temperature coefficient.[12] Thus, for conductors of copper the a.-c. coefficient at high frequencies is approximately .002 per degree Centigrade. When the dielectric losses are small, the temperature coefficient of attenuation at high frequencies is the same as the temperature coefficient of resistance.

Diameter Ratio

An interesting condition exists with regard to the relative sizes of the two conductors. For a given size of outer conductor there is a unique ratio of inner diameter of outer conductor to outer diameter of inner conductor which gives a minimum attenuation. At high frequencies, this optimum ratio of diameters (or radii) is practically independent of frequency. When the conductivity is the same for both conductors, and either the dielectric losses are small or the insulation is distributed so that the dielectric flux follows radial lines, the value of the optimum diameter ratio is approximately 3.6. When the outer and inner conductors do not have the same conductivity, the optimum diameter ratio differs from this value. For a lead outer conductor and copper inner conductor, for example, the ratio should be about 5.3.

Stranding

Inasmuch as the resistance of the inner conductor contributes a large part of the high frequency attenuation of a coaxial circuit, it is natural to consider the possibility of reducing this resistance by employing a conductor composed of insulated strands suitably twisted or interwoven.[13] Experiments along this line showed that this method is impractical at frequencies above about 500 kilocycles, owing to the fineness of stranding required.

Characteristic Impedance

The high-frequency characteristic impedance of a coaxial circuit varies inversely with the square root of the effective dielectric constant, i.e., the ratio of the actual capacitance to the capacitance that would be obtained with air insulation. The impedance of a circuit having a given dielectric constant depends merely upon the ratio of conductor diameters and not upon the absolute dimensions. For a diameter ratio of 3.6, the impedance of a coaxial circuit with gaseous insulation is about 75 ohms.

Velocity of Propagation

For a coaxial circuit with substantially gaseous insulation, the velocity of propagation at high frequencies approaches the speed of light. Hence the circuit is capable of providing high velocity telephone channels with their well-recognized advantages. The fact that the velocity at high frequencies is substantially constant minimizes the correction required to bring the delay distortion within the limits required for a high quality television band.

Shielding and Crosstalk

The shielding effect of the outer conductor of a coaxial circuit is illustrated in Fig. 9, where the transfer impedance between the outer and inner surfaces of the outer conductor is plotted as a function of frequency. There will be observed the sharp decrease in inductive susceptibility as the frequency rises. On this account, the crosstalk between adjacent coaxial circuits falls off very rapidly with increasing frequency. The trend is, therefore, markedly different from that for ordinary non-shielded circuits which rely upon balance to limit the inductive coupling. As a practical matter, less shielding is ordinarily required to avoid crosstalk than to avoid external interference.

With suitable design the shielding effect of the outer conductor renders the coaxial circuit substantially immune to external interference at frequencies above the lower end of the spectrum. Hence the signals transmitted over the circuit may be permitted to drop

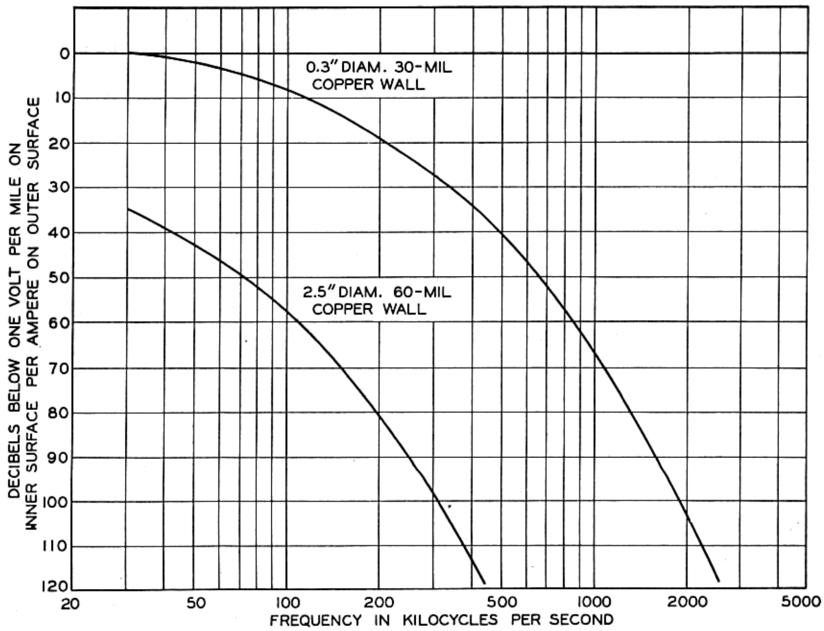


Fig. 9—Transfer impedance of coaxial circuit.

down to a level determined largely by the noise due to thermal agitation of electricity in the conductors and tube noise in the associated amplifiers. It appears uneconomical to make the outer conductor sufficiently thick to provide adequate shielding for the very low frequencies. Also it seems impractical to design the repeaters to transmit very low frequencies. Hence the best system design appears to be one in which the lowest five or ten per cent of the frequency range is not used for signal transmission. The coaxial circuit is, however, well suited to the transmission of 60-cycle current for operating repeaters, a matter which will be referred to later.

Broad-Band Amplifiers

In order to realize the full advantage of broad-band transmission, the repeater for this type of system should be capable of amplifying the entire frequency band *en bloc*. Furthermore, it should be so stable and free from distortion that a large number of repeaters may be operated in tandem. Although high-gain radio frequency amplifiers are in everyday use, these are generally arranged to amplify at any one time only a relatively narrow band of frequencies, a variable tuning device being provided so that the amplification may be obtained at any point in a fairly wide frequency range. The high gain is usually obtained by presenting a high impedance to the input circuits of the various tubes through tuning the input and interstage coupling circuits to approximate anti-resonance.

In amplifying a broad band of frequencies, it is difficult to maintain a very high impedance facing the grid circuits. The inherent capacitances between the tube elements and in the mounting result in a rather low impedance shunt which can not be resonated over the desired frequency band. It is, therefore, necessary to use relatively low impedance coupling circuits and to obtain as high gain as possible from the tubes themselves. The amount of gain which can be obtained without regeneration depends, of course, upon the type of tube, the number of amplification stages, the band width, and also upon the ratio of highest to lowest frequency transmitted.

Repeater Gain

The total net gain desired in a line amplifier is such as to raise the level of an incoming signal from its minimum permissible value, which is limited by interference, up to the maximum value which the amplifier can handle.

As pointed out above, the noise in a well shielded system is that due to resistance noise in the line conductors and tube noise in the amplifiers. In some of the repeaters which have been built, the amplifier noise has been kept down to about 2 db above resistance noise, corresponding to about 7×10^{-17} watt per voice channel. In a long line with many repeaters the noise voltages add at random, or in other words, the noise powers add directly. Assuming, for example, a line with 200 repeaters, the noise power at the far end would be 200 times that for a single repeater section. In general, the line and amplifier noise will not be objectionable in a long telephone channel if the speech sideband level at any amplifier input is not permitted to drop more than about 55 db below the level of the voice frequency band at the transmitting toll switchboard.

The determination of the volume which a tube can handle in transmitting a wide band of frequencies involves a knowledge of the distribution in time and frequency of the signaling energy and of the requirements as to distortion of the various components of the signal. The distribution of the energy in telephone signals has been the subject of much study. This distribution is known to vary over very wide limits, depending upon the voice of the talker and many other factors. It is, therefore, obvious that the problem of summing up the energy of some hundreds of simultaneous telephone conversations is a difficult one.

Enough work has been done, however, to indicate fairly well what the result of such addition will be.

As to distortion in telephone transmission, the most serious problem has been to limit the intermodulation between various signals which are transmitted simultaneously through the repeater and appear as noise in the telephone channel. The requirement for such noise is similar to that for line and tube noise, and similarly it will add up in successive repeater sections for a long line. With present types of tubes operating with a moderate plate potential, the modulation requirement can be met only at relatively low output levels. To improve this situation and also to obtain advantages in amplifier stability, the reversed feedback principle employed for cable carrier amplifiers, as described in a paper by H. S. Black,[14] has been extended to higher frequency ranges. It has been found that amplifiers of this type having 30 db feedback reduce the distortion to such an extent that each amplifier of a long system carrying several hundred telephone channels will handle satisfactorily a channel output signal level about 5 db above that at the input of the toll line.

The maximum gain which can be used in the repeater, therefore, is, in the illustrative case given above of a long system carrying several hundred telephone channels, the difference between the minimum and maximum levels of 55 db below and 5 db above the point of reference, respectively, or a total gain of 60 db. (With a .3-inch coaxial line of the type shown in Fig. 2, this corresponds to a repeater spacing of about 10 miles.) If a repeater is to have 60 db net gain and at the

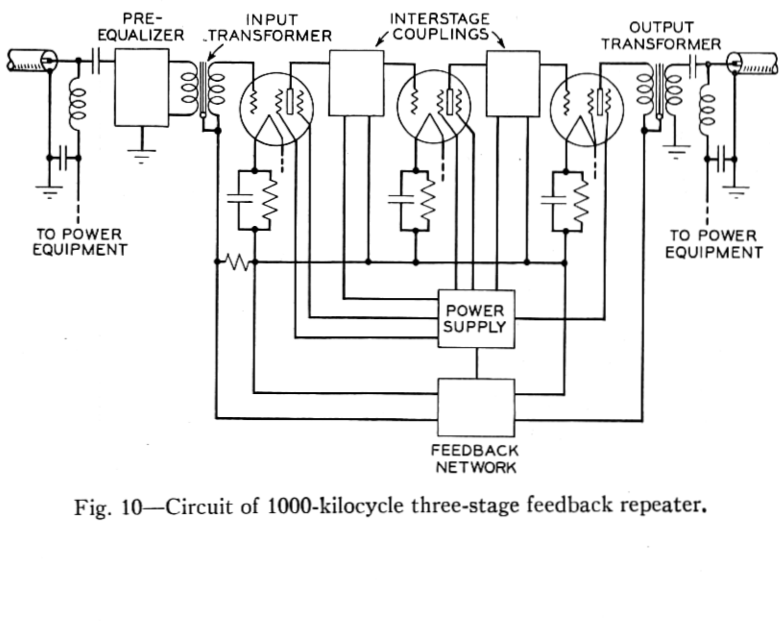


Fig. 10—Circuit of 1000-kilocycle three-stage feedback repeater.

same time about 30 db feedback, it is obvious that the total forward gain through the amplifying stages must be about 90 db. The circuit of an experimental amplifier meeting the gain requirements for a frequency band from 50 to 1000 kilocycles is shown schematically in Fig. 10.

Gain-Frequency Characteristic

As pointed out above, the line attenuation is not uniform with frequency. For a repeater section which has a loss of, say, 60 db at 1000 kilocycles, the loss at 50 kilocycles would be only about 15 db. Such a sloping characteristic can be taken care of either by designing the repeater to have an equivalent slope in its gain-frequency characteristic or by designing it for constant gain and supplementing it with an equalizer which gives the desired overall characteristic. Both methods have been tried out, as well as intermediate ones. Figure 11

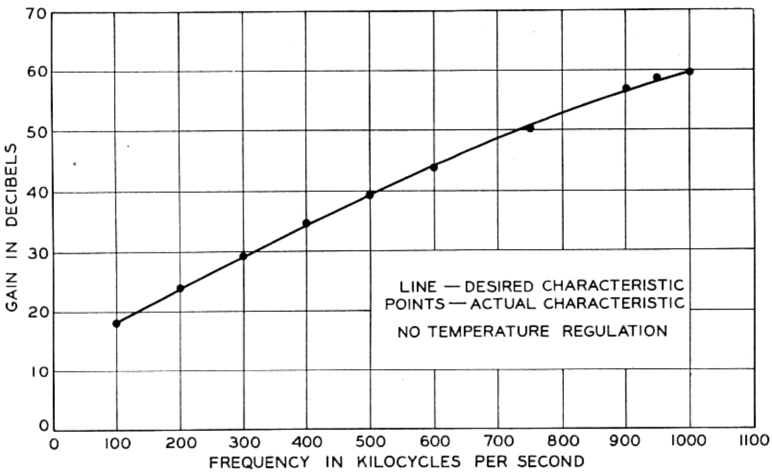


Fig. 11—Gain of 1000-kilocycle repeater compared with line characteristic.

illustrates such a sloping characteristic obtained by adjusting the coupling impedances in a three-tube repeater, designed in this case for 60 db gain at 1000 kilocycles. The accompanying photograph, Fig. 12, gives an idea of the apparatus required in such a repeater, apart from the power supply equipment.

Regulation for Temperature Changes

It is necessary that the repeater provide compensation for variations in the line attenuation due to changes of temperature. In the case of aerial construction such variations might amount to as much as 8 per cent in a day or 16 per cent in a year. If the line is underground the annual variation is only about one-third of the above value and the changes occur much more slowly. On a transcontinental line the annual variation might total about 1500 db. Inasmuch as it is desirable to hold the transmission on a long circuit constant within about ± 2 db, it is obvious that the regulation problem is a serious one.

In a single repeater section of aerial line the variation might amount to ± 2.5 db per day or ± 5 db per year. Such variations, if allowed

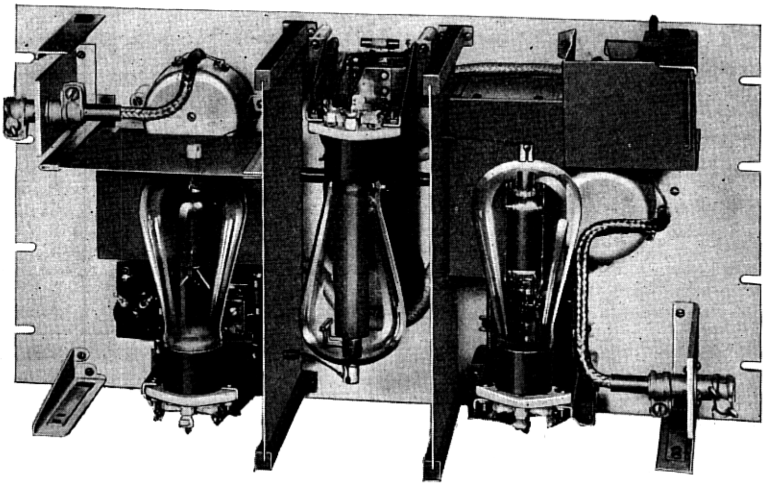


Fig. 12—Photograph of 1000-kilocycle repeater.

to accumulate over several repeater sections, will drop the signal down into the noise or raise it so as to overload the tubes. It is, therefore, advisable to provide some regulation at every repeater in an aerial line so as to maintain the transmission levels at approximately their correct position. For underground installations the regulating mechanism may be omitted on two out of every three repeaters.

In choosing a type of regulator system the necessity for avoiding cumulative errors in the large number of repeater sections has been borne in mind. In view of the wide band available, a pilot channel regulator system was naturally suggested. Such a scheme employing two pilot frequencies has been used experimentally to adjust the gain characteristic in such a way as to maintain the desired levels throughout the band. The accuracy with which this has been accomplished for a single repeater section is illustrated in Fig. 13. Over the entire band of frequencies and the extreme ranges in temperature which may be encountered, the desired regulation is obtained within a few tenths of a db.

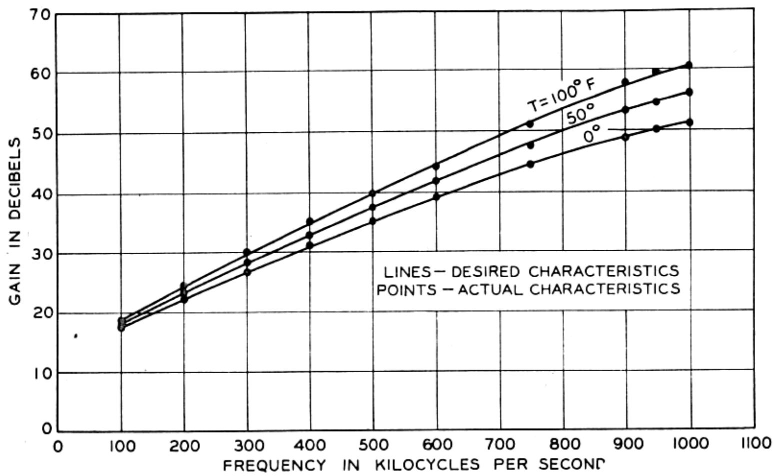


Fig. 13—Temperature regulation—line and repeater characteristics.

Repeater Operation, Power Supply, Housing, Etc.

In view of the large number of repeaters required in a broad-band transmission system it is essential that the repeater stations be simple and involve a minimum of maintenance. With the repeater design as described it is expected that most of the repeaters may be operated on an unattended basis, requiring maintenance visits at infrequent intervals.

An important factor in this connection is the possibility of supplying current to unattended repeaters over the transmission line itself. The coaxial line is well adapted to transmit 60-cycle current to repeaters without extreme losses and without hazard. The repeaters with regulating arrangements as built experimentally for a million-cycle system are designed to use 60-cycle current, which in this case appears to have the usual advantages over d.-c. supply. One repeater requires a supply of about 150 watts. The number of repeaters which can be supplied with current transmitted over the line from any one point depends upon the voltage limitation which may be imposed on the circuit from considerations of safety.

For a repeater of the type described with current supplied over the line, only a very modest housing arrangement will be required. For the great majority of stations, it appears possible to accommodate the repeaters in weatherproof containers mounted on poles, in small huts, or in manholes.

Higher Frequency Repeaters

Most of what has been said above applies particularly to repeaters transmitting frequencies up to about 1000 kilocycles. However, study has been given also to repeaters, both of the feedback and the non-feedback type, for transmitting higher frequencies. Experimental repeaters covering the range from 500 to 5000 kilocycles have been built and tested. These were capable of handling simultaneously the full complement of over 1000 channels which such a broad band will permit. The frequency characteristic of one of these repeaters, and the measured attenuation of a section of line of the type tested at Phoenixville are shown in Fig. 14.

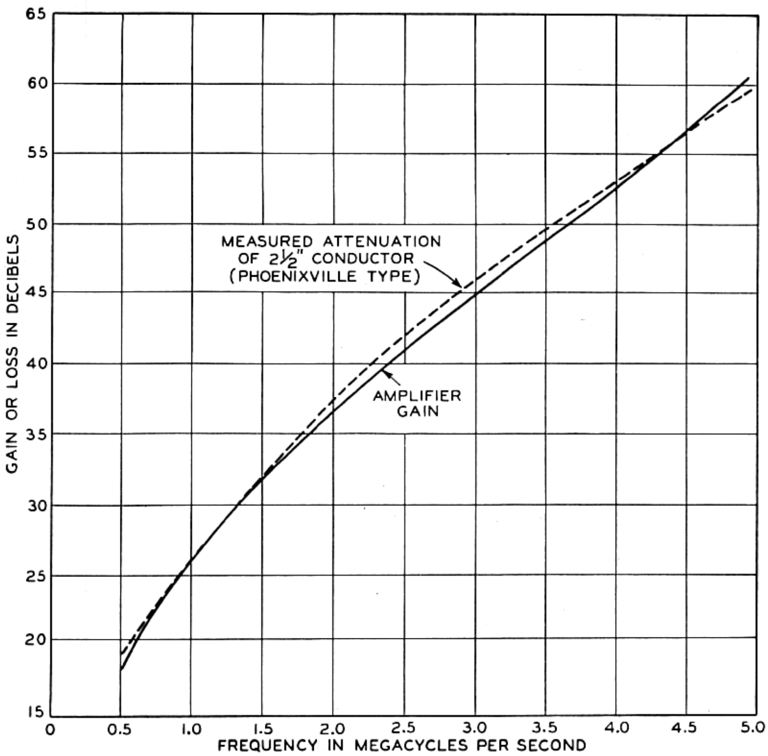


Fig. 14—Frequency characteristic of coaxial line and 5000-kilocycle repeater.

Terminal Arrangements

In order to utilize a broad band effectively for telephone purposes, the speech channels must be placed as close together in frequency as practicable. The factors which limit this spacing are: (1) The width of speech band to be transmitted and (2), the sharpness of available selecting networks.

As to the width of speech band, the present requirement for commercial telephone circuits is an effective transmission band width of at least 2500 cycles, extending from 250 to 2750 cycles. It has been found that a band of this width or more may be obtained with channels spaced at 4000-cycle intervals. Band filters using ordinary electrical elements are available,[3] for selecting such channels in the range from zero to about 50 kilocycles. Channel selecting filters using quartz crystal elements [15, 16] have been developed in the range from about 30 to 500 kilocycles. The selectivity of a typical filter employing quartz crystal elements is shown on Fig. 15.

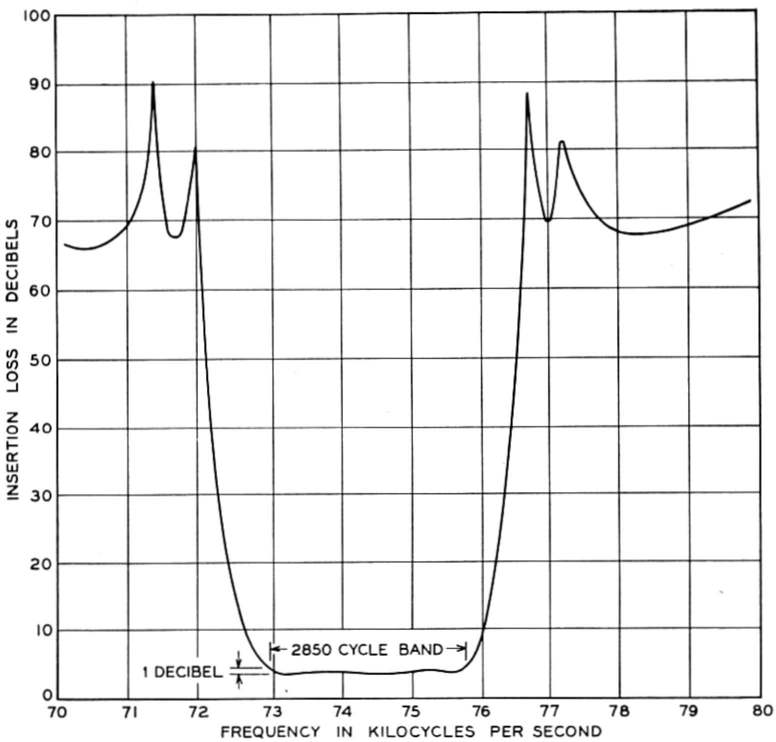


Fig. 15—Frequency characteristic of quartz crystal channel band filter.

Initial Step of Modulation

The initial modulation (from the voice range) may be carried out in an ordinary vacuum tube modulator or one of a number of other non-linear devices. The method chosen for the present experimental work employs a single sideband with suppressed carrier, using a copper-oxide modulator associated with a quartz crystal channel filter. The terminal apparatus required for two-way transmission over a two-path circuit is shown diagrammatically on the left-hand side of Fig. 16.

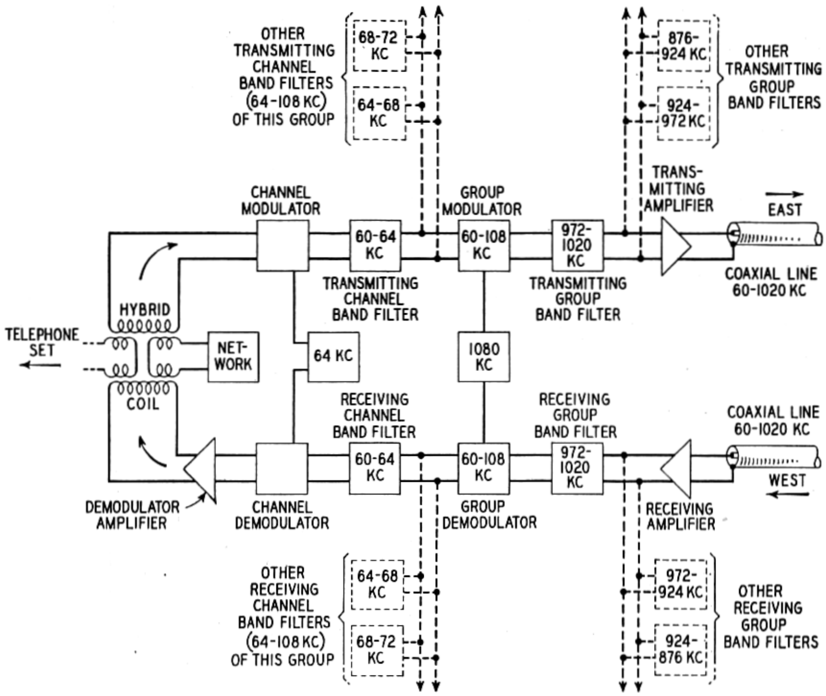


Fig. 16—Schematic of four-wire circuit employing two steps of modulation.

A frequency allocation which has been used for experimental purposes employs carriers from 64 to 108 kilocycles for the initial step of modulation. The lower sidebands are selected and placed side by side in the range from 60 to 108 kilocycles, as illustrated in Fig. 17, forming a group of 12 channels.

Double Modulation

In order to extend the frequency range of a system to accommodate a very large number of channels, it appears to be more economical to add a second step of modulation rather than carry the individual channel modulation up to higher frequencies. Such a second step of modulation has been used experimentally to translate the initial group of 12 channels en bloc from the range 60 to 108 kilocycles up to higher frequencies. It is possible to place such groups of channels one above another as illustrated in the upper part of the diagram of Fig. 18, up

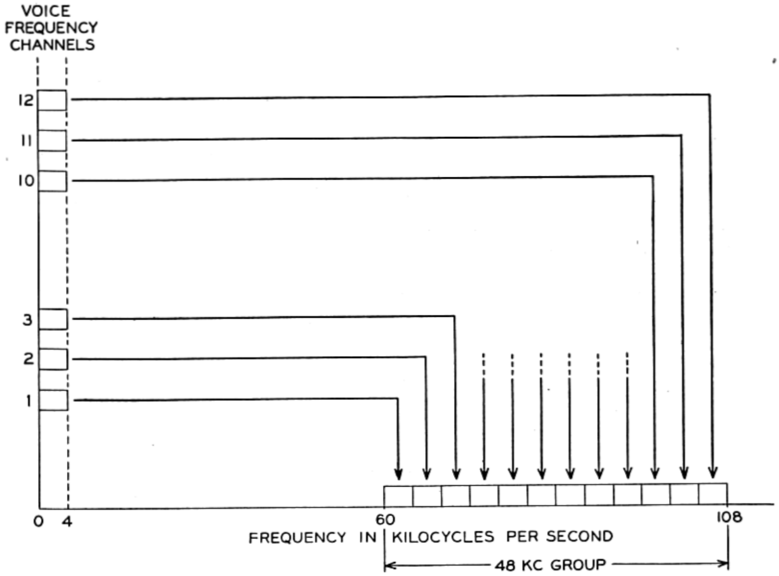


Fig. 17—Diagram illustrating frequency allocation for first step of modulation.

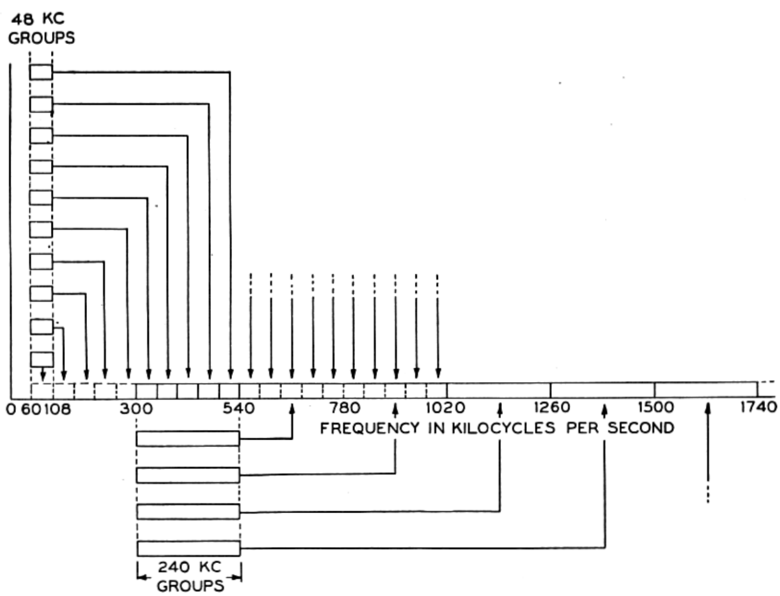


Fig. 18—Diagram illustrating frequency allocation for two or three steps of modulation.

to about 1000 kilocycles, wasting no frequency space between groups and thus keeping the channels spaced at intervals of 4 kilocycles throughout the entire range.

The apparatus required for this purpose is shown schematically in Fig. 16, which illustrates the complete terminal arrangements for a single channel employing double modulation. The figure indicates by dottled lines where the other channels and groups of channels are connected to the system.

A modulator for shifting the frequency position of a group of channels inherently yields many different modulation products as a result of the intermodulation of the signal frequencies with the carrier frequency and/or with one another. Out of these products only the "group sideband" is desired. The number of the modulation products resulting merely from the lower ordered terms of the modulator response characteristic is extremely large. All such products must be considered from the standpoint of interference either with the group which is wanted in the output or with other groups to be transmitted over the system. Various expedients may be used to avoid interference as follows: (1) A proper choice of frequency allocation will place the undesired modulation products in the least objectionable location with respect to the wanted signal bands; (2) a high ratio of carrier to signal will minimize all products involving only the signal frequencies; (3) the use of a balanced modulator will materially reduce all products involving the second order of the signal; (4) selectivity in the group filters will tend to eliminate all products removed some distance from the wanted signal group. Giving due regard to these factors, balanced vacuum tube group modulators have been developed which are satisfactory for the frequency allocations employed.

Triple Modulation

For systems involving frequencies higher than about 1000 kilocycles it may be desirable to introduce a third step of modulation. In some experiments along this line a "super-group" of 60 channels, or five 12-channel groups, has been chosen. The lower part of Fig. 18 illustrates, for a triple modulation system, the shifting of super-groups of 60 channels each to the line frequency position. This method has been employed experimentally up to about 5,000 kilocycles. It is of interest to note that even in extending these systems to such high frequencies, channels are placed side by side at intervals of 4000 cycles to form a practically continuous useful band for transmission over the line.

Demodulation

On the receiving side the modulation process is reversed. The apparatus units are similar to those used on the transmitting side, and are similarly arranged. Figure 16 illustrates this for the case of double modulation.

Carrier Frequency Supply

In systems operating at higher frequencies it is necessary that the carrier frequencies be maintained within a few cycles of their theoretical position in order to avoid beat tones or distortion of the speech band. Separate oscillators of high stability could, of course, be used for the carrier supply but it appears more economical to provide carriers by means of harmonic generation from a fundamental basic frequency. Such a base frequency may be transmitted from one end of the circuit to the other, or may be supplied separately at each end.

Television

The broad band made available by the line and repeaters may be used for the transmission of signals for high-quality television. Such signals may contain frequency components extending over the entire range from zero or a very low frequency up to a million or more cycles.[4] The amplifying and transmitting of these frequencies, particularly the lower ones, presents a serious problem. The difficulty can be overcome by translating the entire band upward in frequency to a range which can be satisfactorily transmitted. To effect such a shift, the television band may first be modulated up to a position considerably higher than its highest frequency and then with a second step of modulation be stepped down to the position desired for line transmission.

This method is illustrated in Fig. 19 for a 500-kc. television signal band. The original television signal is first modulated with a relatively high frequency, two million cycles in this case (C_1). The lower sideband, extending to 1500 kilocycles, is selected and is modulated again with a frequency of 2100 kilocycles (C_2). The lower sideband of 100 to 600 kilocycles is selected with a special filter so designed that the low frequency end is accurately reproduced. The television signal then occupies the frequency range of 100 to 600 kilocycles as shown on the diagram and may be transmitted over a coaxial or other high frequency line. At the receiving end a reverse process is employed. The same method using correspondingly higher frequencies may be used for wider bands of television signals.

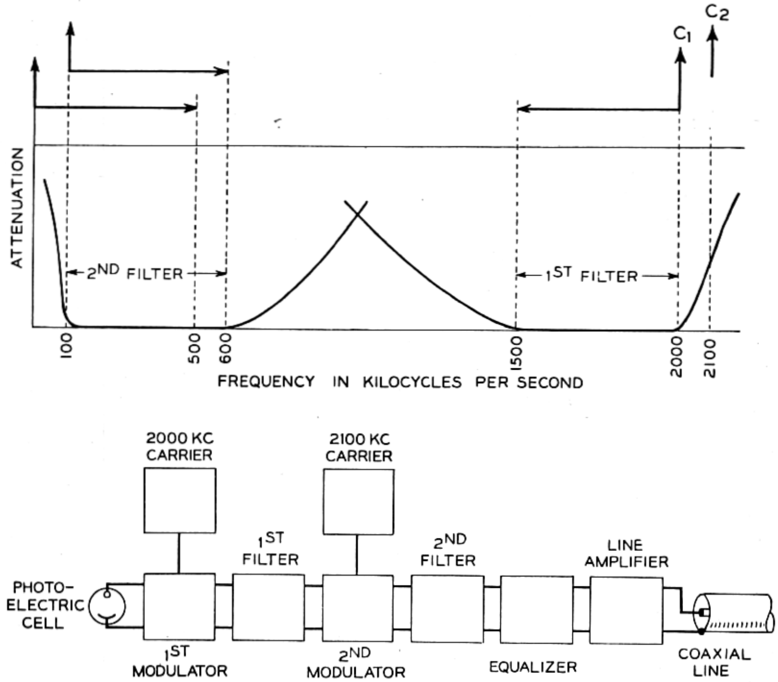


Fig. 19—Double modulation method for translating television signals for wire line transmission.

Other Communication Facilities

The telephone channels provided by the system may be used for other types of communication services, such as multi-channel telegraph, teletype, picture transmission, etc. For the transmission of a high-quality musical program, which requires a wider band than does commercial telephony, two or more adjacent telephone channels may be merged. The adaptability of the broad-band system to different types of transmission thus will be evident.

As already noted, the commercial application of these systems for wide-band transmission over coaxial lines must await a demand for large groups of communication facilities or for television. The results which have been outlined are based upon development work in the laboratory and the field, and it is probable that the systems when used commercially will differ considerably from the arrangements described.

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