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Recent Trends in Toll Transmission in the United States *

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YOUR country is advancing industrially and commercially with tremendous strides. Adequate telephone communication is of such great importance under these conditions that I felt a general statement as to methods in process of being applied to the plant of the Bell System would be interesting and possibly helpful. I am fully aware that, in some or even many respects, your problems will differ from ours. Much of what I have presented may, therefore, serve only to suggest research and development to meet your own requirements. Perhaps also, in some small way, this statement of progress in communication may stimulate research and development in other industries and services.

In the year 1885, only nine years after the telephone was invented, a Telephone Company was chartered in the United States for the following purpose: "to connect one or more points in each and every city, town, or place in the State of New York with one or more points in each and every other city, town or place in said State and in each and every other of the United States and in Canada and Mexico; and each and every of said cities, towns, and places is to be connected with each and every other city, town, and place in said states and countries, and also by cable and other appropriate means with the rest of the known world."

This was an ambitious program, and thirty years passed before the results of research and development could be embodied in apparatus and equipment to make it possible to talk between cities on the Atlantic and Pacific coasts of the United States, and about forty years passed before the establishment of telephone service between America and Europe. Telephone service was later extended to other parts of the world including your country, and it is now possible for a telephone subscriber in the United States to converse with a person at any one of thirty-four odd million subscriber stations in a large number of countries of the world. Further, it is possible to talk with persons on suitably equipped ships at sea. Expanding still further beyond the goal set in 1885, and departing from the idea of two-way conversation,

* One of three Iwadare Foundation lectures delivered during the past month in Japan by Dr. Colpitts.

this same company provides a portion of the facilities which make it possible for a person speaking at one place almost anywhere in the civilized world to have his voice heard at almost any other. I refer to broadcasting.

Figure 1 shows a wire map of a few of the principal toll lines in the United States. This toll plant affords facilities that, in connection with the local plant, enable any telephone subscriber at any point to communicate promptly with a subscriber at any other point in the United States, Canada, or Mexico.

With the growth of radio broadcasting, a service with which you are all familiar, it became necessary to provide circuits to interconnect radio broadcasting stations. Figure 2 shows a wire map of such interconnecting circuits commonly spoken of as "program circuits." Figure 3 shows schematically the radio-telephone circuits that connect the United States to foreign countries. Another extension of the service rendered by the Bell System is indicated by Fig. 4, which shows a wire map of circuits devoted to the telephotograph service.

It is not my purpose to take your time to discuss these past developments, since they have already been described quite fully in technical literature, which I know is available to you. I propose rather to discuss some of the more recent trends in toll circuit development in the United States, but the subject is so large that I can touch only upon the more salient factors, indicating to you the direction in which the art is moving.

This new art, or perhaps more accurately this extension of an older art, utilizes the results of continuing researches on vacuum tubes and their uses as amplifiers, modulators, and oscillators, on filters as a means of splitting up broad bands of frequencies into the relatively narrow bands required for telephony or the still narrower bands required for telegraphy, and on methods of electrically isolating a particular circuit so as to avoid crosstalk and noise. These are not all the factors requiring research, but are merely some of the more important ones.

In this connection, it should be emphasized that these new systems or methods are still under development, and that their development for commercial application will require continued effort over a considerable period. We have come to group these new systems or methods under the term "high-frequency broad-band wire transmission." Instead of confining ourselves to a frequency range extending to about 30,000 cycles, as used for our present carrier systems, we are setting for our objective the transmission and utilization of bands of frequencies a million or more cycles wide in the case of

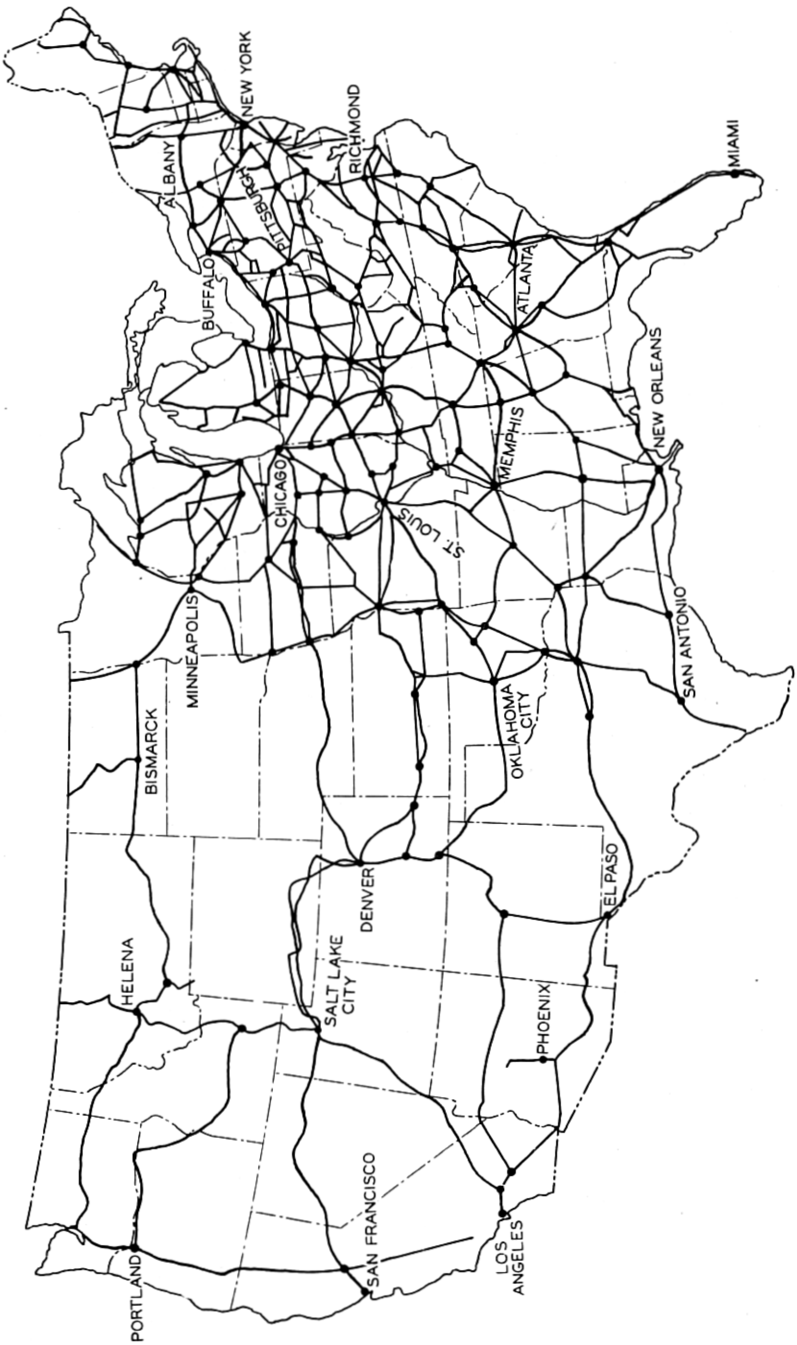

Fig. 1—Principal toll lines of the United States.

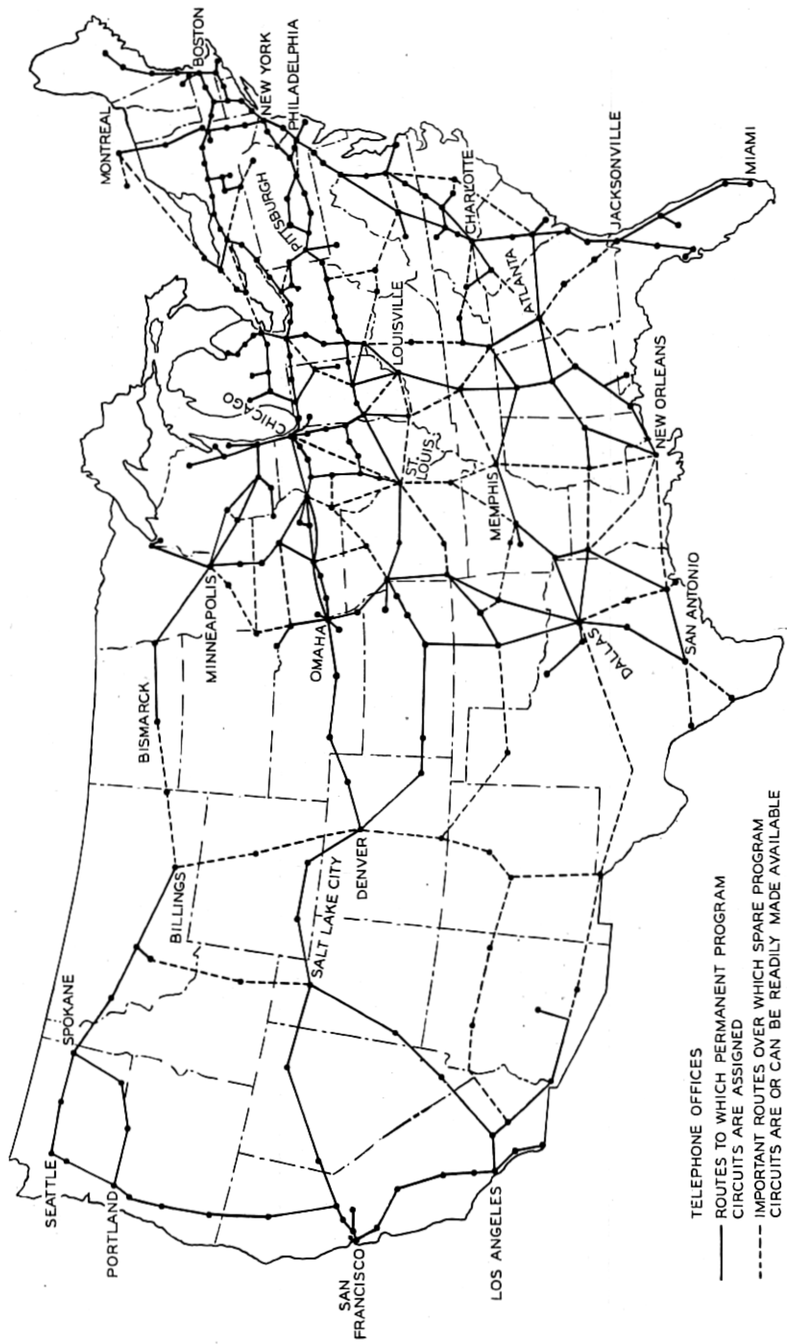

Fig. 2—Permanent and spare program circuits of the United States.

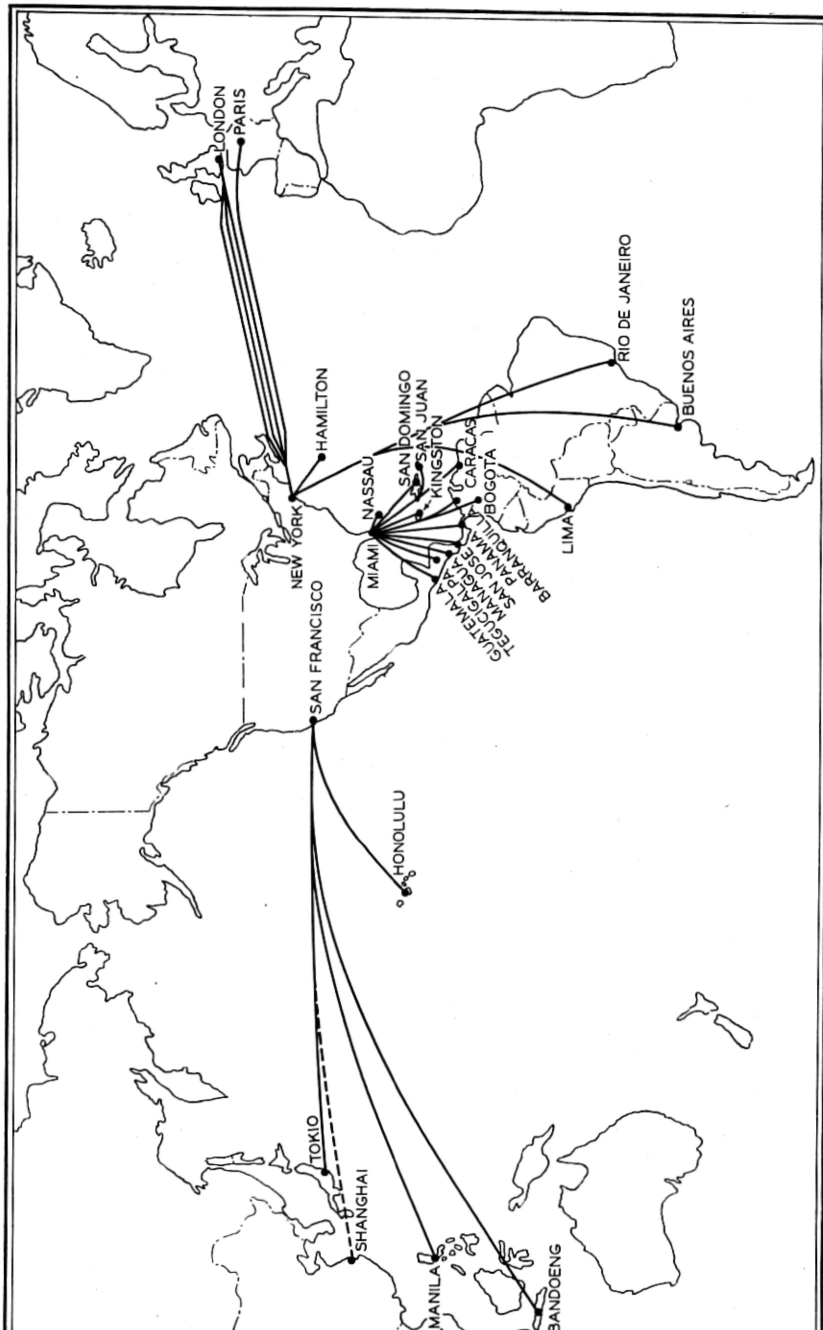

Fig. 3—Transoceanic radio telephone circuits operated by the Bell System.

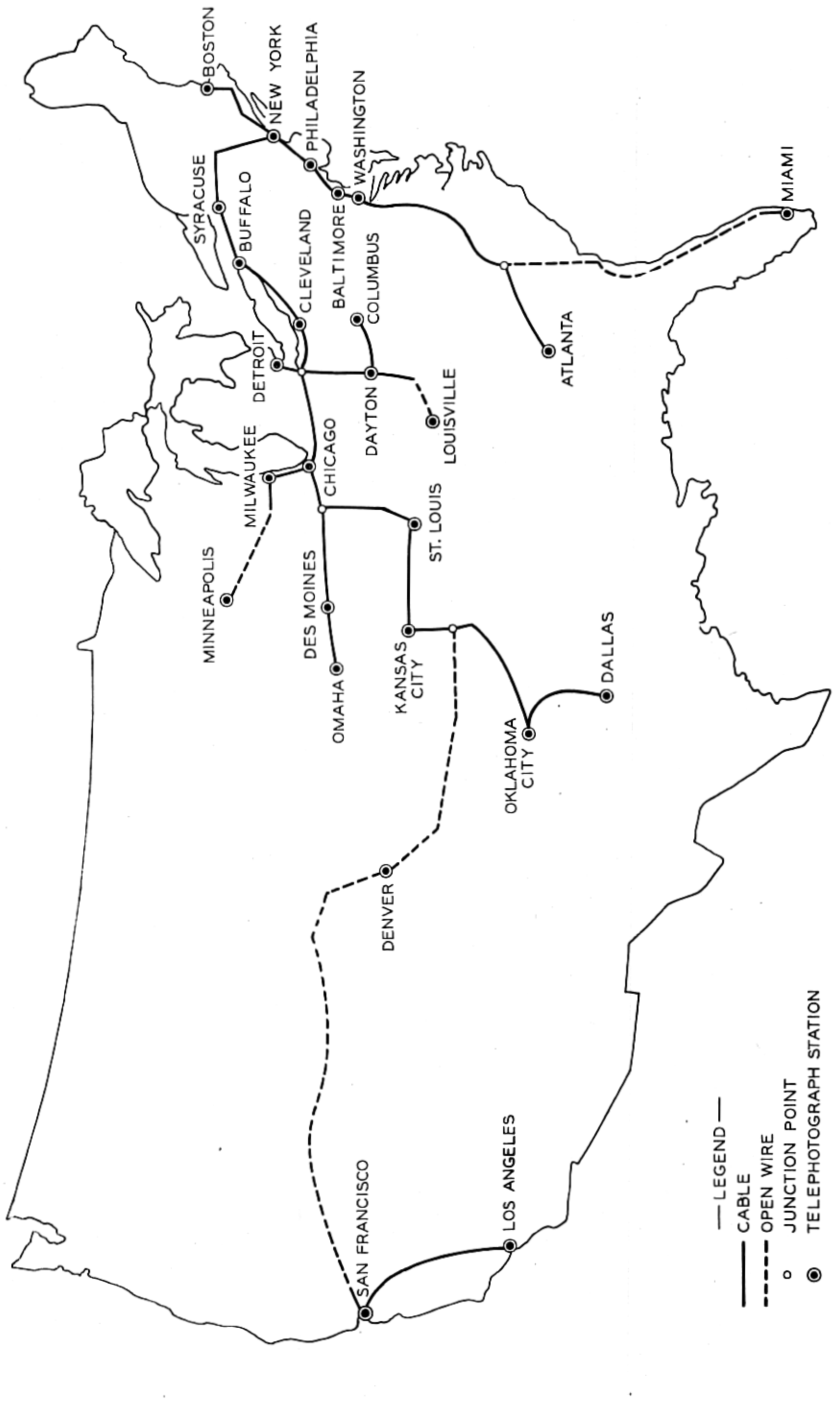

Fig. 4—Telephotograph circuits of the United States.

certain line structures. For other structures, the frequency range is narrower, but for all these systems the frequency range is transmitted as a single band, and split into communication channels for telephone or telegraph only at the terminals. If the transmission of television signals should become necessary, a very broad band—one or more million cycles—would, of course, be required. Although I have referred to television, our primary interest in broad-band wire transmission is for telephone transmission purposes, where the wide transmission band can be used to give a large number of talking channels.

You will recall that the idea of deriving more than one communication channel from a single pair of conductors, by what we now call carrier methods, is old—in fact, as old as the telephone itself. Until quite recently, however, physical devices and methods have not been available to make the carrier method utilizable in practice. Beginning about fifteen years ago, the Bell System began to install carrier systems, and since that time this method has had continued growth on open-wire lines, with the result that a substantial amount of toll traffic is now carried over carrier systems on open-wire lines. A relatively simple form of carrier equipment provides one two-way telephone circuit in addition to the usual voice frequency circuit, while more elaborate and refined equipment adds three two-way telephone circuits.

In addition to the economic urge to obtain the largest possible number of telephone channels over a given pair of wires, there is an additional factor that has influenced the development of broad-band systems, and that is, the speed of transmission. Even in the lowest-speed telephone circuits, the speed of transmission of voice waves, as judged by ordinary standards, is high, being from ten to twenty thousand miles per second (32,000 km. per sec.) in the loaded cable circuits that are now used for many of the long toll lines. For ordinary distances, moreover, the speed of transmission is not of any particular moment, but when the voice must be transmitted over distances of thousands of miles, it becomes important. Echo effects become exaggerated, and in a long connection, the actual time for speech to reach from the first subscriber to the second subscriber, added to the time required for the second subscriber to answer the first subscriber, may become an annoying factor. The broad-band transmission method furnishes circuits, however, in which the speed of transmission is raised from about 20,000 miles per second, as on loaded cable circuits, to a speed approaching that of light.

In developing a new toll system, there are many other factors, of course, that must be considered. In our case, just as in yours, there is first, an existing toll telephone plant, which must be utilized to the maximum advantage. Also, distances between toll offices or toll centers vary, and particularly the number of circuits required between given toll centers varies over a wide range. It follows, therefore, that there is no one type of construction or method which can be economically utilized in all situations. Figure 5, for example, showing a pole line carrying open-wire circuits and circuits in cable, illustrates some of our present methods.

The high-frequency broad-band transmission development is being proposed for three uses: (1) for application on telephone toll cables already in existence, or on future toll cables of very similar type of

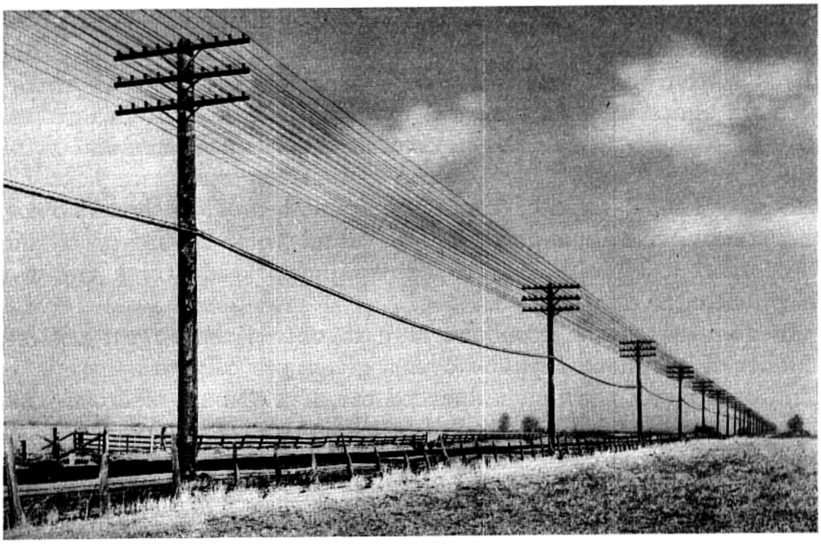

Fig. 5—A typical pole line carrying both open wire and cable.

construction; (2) for an extension to higher frequencies on open-wire telephone circuits, so as to secure more telephone channels on a given pair; (3) for application to new types of conductors capable of transmitting a very wide frequency band, such as the "coaxial" conductor, now being tried experimentally.

I need hardly point out to you that as the frequency of transmission is raised, the attenuation or line loss is greatly increased. This is due more particularly to two factors: an increase in series resistance due to skin effect, and an increase in shunt conductance due to increased dielectric losses. As the frequency increases, the currents transmitted tend more and more to avoid the inner parts of the conductor and to concentrate on the surface, so increasing the effective series resistance. Dielectric losses in the insulation between the conductors also increase with the frequency, and so increase the effective shunt conductance. Figure 6 shows graphically the increase in attenuation with frequency,

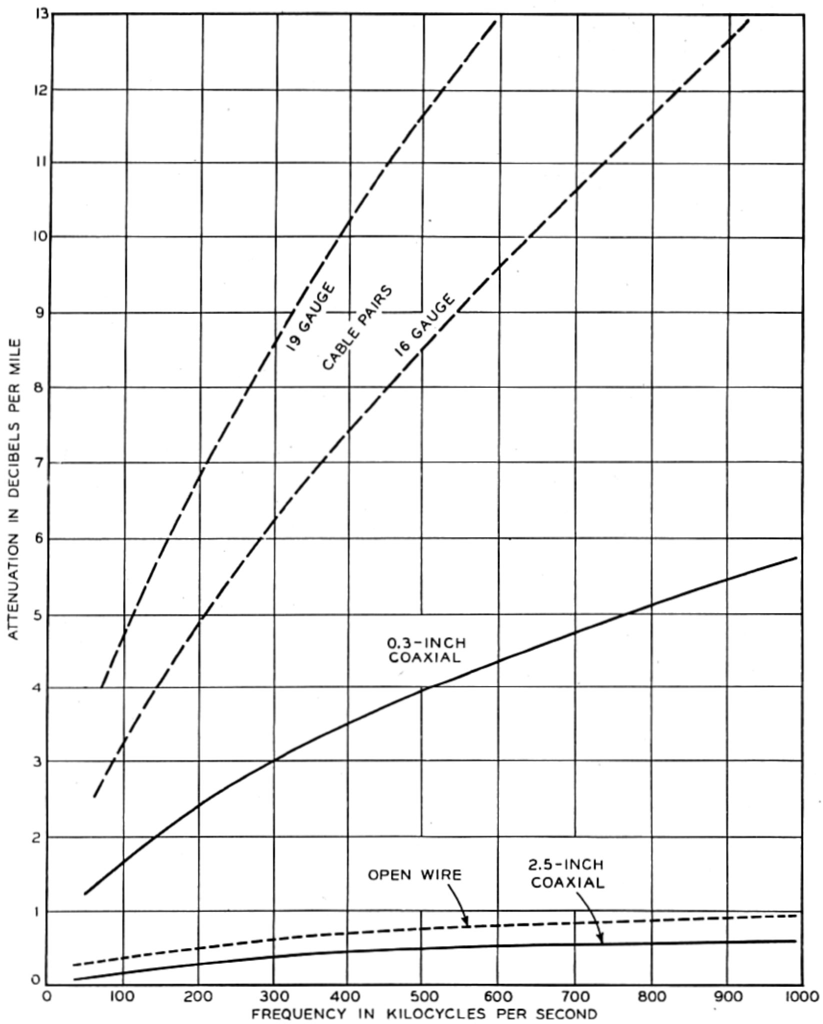

Fig. 6—Attenuation-frequency characteristics of various types of telephone circuits.

and also shows the relative attenuations of various types of construction.

Until the vacuum tube amplifier became available, the only practical method of overcoming high attenuation in a given type of line construction was to provide larger conductors. With the development of the vacuum tube, high amplification became available as an alternative method. Since increasing the size of the conductor in order to decrease attentuation involves large expense, we are naturally led to consider the use of as much amplification as possible.

Before referring further to the utilization of high amplification, I wish to point out that at the present time for distances greater than about 150 miles (240 km.) in cable, we utilize the so-called 4-wire method to obtain two-way telephone transmission; that is, transmission in one direction is carried by one pair of wires, and transmission in the other direction is carried by a second pair of wires. What is in effect the same method is employed in our present carrier systems, transmission in one direction being superposed on one frequency, and transmission in the other direction being superposed on a different frequency.

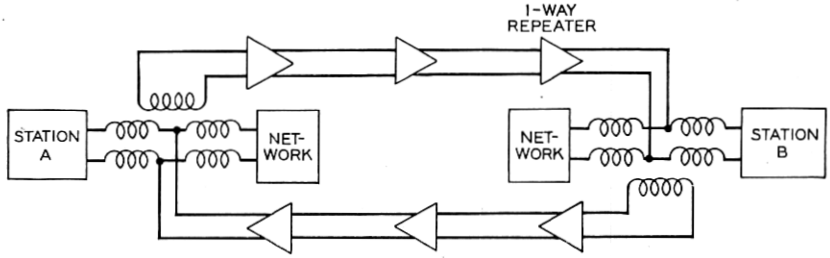

Fig. 7—Block schematic of a four-wire circuit showing two two-wire circuits with one-way repeaters.

Figure 7 shows diagrammatically a 4-wire telephone circuit in cable. You will note that one-way amplifiers are introduced in each pair of wires at points which in present practice are about fifty miles (80 km.) apart. The question naturally arises: Why not increase the distance between amplifiers and at the same time increase their amplification, and so reduce the cost? The answer is that two sources of noise disturbance have to be considered: first, induction from neighboring circuits; second, the noise of thermal agitation.

The line circuit, depending in degree upon the type of construction, receives unwanted interference from the outside, such as induced currents from power lines, lightning, and crosstalk from adjacent circuits, and it is not possible, as a result, to allow the transmitted speech signals to be attenuated below a certain level with respect to such noise interference. As a consequence, the amount which we can allow a speech signal to be attenuated before it reaches an amplifier, depends on how completely the transmission system is free from external interference.

Two methods are commonly employed to minimize external interference: shielding, and a geometrical arrangement of the conductors of the circuit so as to balance out certain forms of interference. The open-wire line, which has no shielding, depends wholly on the symmetry of its conductors and the transpositions to balance out interference. Conductors surrounded by metal sheath, such as cable pairs, are less subject to interference than open-wire lines. The conductors of a pair are close together, are well transposed by twisting, and are shielded to a certain extent by the outside lead covering. As a result of this, the noise due to outside sources has a low level, and the telephone speech currents can be permitted to become attenuated to a relatively low value before reaching an amplifier where they are stepped up to their original value. It is evident, of course, that such cable pairs, being made up of small conductors close together and having paper dielectric, have correspondingly high attenuations.

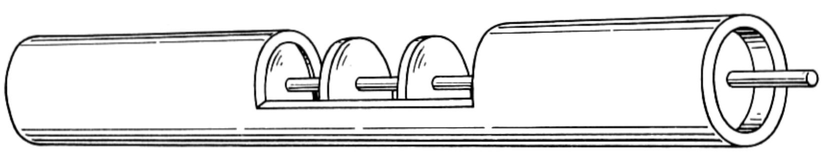

Fig. 8—Diagrammatic representation of the coaxial structure.

The ideal conductor would be one for which the attenuation over the whole operative frequency range was not too great, and at the same time one completely shielded from the influence of external electric or magnetic fields. The so-called coaxial conductor approximates to these requirements. This conductor transmits efficiently over a wide frequency band, and at the same time is well shielded from external influences, the degree of shielding being higher at the higher frequencies where greater amplification is needed to overcome the greater attenuation.

The coaxial conductor upon which we are experimenting consists of an inner wire and outer tube separated by spacing insulators. It is desirable to separate the two conductors by a minimum amount of solid insulation to the end that the dielectric will be largely air, and the losses at high frequencies be at a minimum. Figure 8 shows diagrammatically a coaxial structure. At high frequencies the current travels chiefly on the outside of the inner conductor, and on the inside of the outer conductor. It will be obvious to you that there is a wide latitude of choice in the dimensions of coaxial structures.

Although we are experimenting with a structure capable of transmitting a band of one or two million cycles in width, a coaxial structure capable of transmitting a band twenty million cycles in width is apparently not wholly unfeasible.

The question naturally arises whether, with interference from outside sources almost wholly or entirely eliminated, it is possible to allow speech currents to be attenuated to an unlimited degree before the introduction of amplification to bring them back to their original value. With all outside interference eliminated, however, noise arising within the conductor itself sets the limit. This interference is termed resistance noise or sometimes thermal-agitation noise because it is a function of the temperature of the conductor. It is apparently due to the continual moving around of the free electrons which exist in all conductors. Our Laboratories have investigated this phenomenon and determined its characteristics. This resistance noise varies in amount with the resistance of the conductor and with the temperature. It is uniformly distributed over the whole frequency range from lower voice frequencies up to the highest frequency which we have considered using. One ready means of observing this phenomenon is to provide an amplifier covering the voice range, with its input connected across the resistance, and to listen on the output of the amplifier with a telephone receiver. If the amplifier has an amplification of about 140 db, the noise heard in the telephone receiver is about as loud as would be heard in the receiver were it connected directly across the output from a telephone substation.

To prevent this thermal or resistance noise from being noticeable in a telephone conversation, we must limit the amount of amplification used at any one point in a long system, even though it were perfectly shielded, to an amount considerably less than 140 db. These considerations have led us to conclude that for a long circuit with many amplifiers distributed along the route, the amount of amplification at any one point should not exceed about 70 db.

The amount of amplification involved in present-day telephone circuits is illustrated by the 4-wire cable circuit, in which amplifiers are located in each pair at intervals of about 50 miles (80 kilometers) and each amplifier is set to give an amplification of about 25 db, or a power amplification of 300 times. For such a circuit between, say, New York and Chicago, a distance of about 900 miles (1450 km.), the total amplification is about 500 db, or a power amplification of 10^{50}. It is obviously necessary that these amplifiers must be made very *stable* so that the cumulative variations in the many amplifiers may not make it impossible to obtain the required degree of overall stability of transmission. The total amplification is affected by the requirement that the New York-Chicago circuit is expected to have a net attenuation of not over 9 db, and to be stable within about $\pm$ 2 db.

These figures may seem large and the requirements difficult to meet, but with the systems under development, the magnitude of the high-amplification problem is even greater. In the carrier on cable development, the circuits will consist of non-loaded pairs, and it will be necessary to so space the amplifiers and adjust their amplification that the total amplification on, for example, a New York-Chicago circuit will be about 3000 db at the center of the frequency band, or a power ratio of 10^{300}. Obviously, the stability requirement has been made much more rigid. With a typical coaxial circuit, the overall amplification at a million cycles for a thousand-mile circuit (1600 km.) may well be 6500 db or a power ratio of 10^{650}.

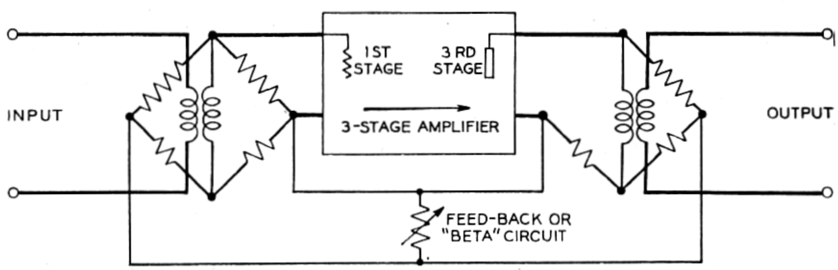

Fig. 9—Simplified schematic diagram of a feedback amplifier.

Furthermore, with the relatively simple circuit shown in Fig. 7, the amplifiers are called upon to handle merely the currents corresponding to one telephone conversation, while in the broad-band system an amplifier is required to handle simultaneously a large number of carrier telephone channels. To avoid the generation of extraneous frequencies or intermodulation products which would cause interference between the channels, an amplifier must be adopted which is more nearly perfect in this respect than any heretofore standard.

This problem of amplifier stability and perfection was solved some little time ago by an invention of one of our engineers. This engineer devised a new amplifier circuit which has been termed the "stabilized feedback amplifier." Some older types of amplifiers took some of their output and fed it back to the input for the purpose of *increasing* the amplification. This new feedback circuit controls the phases of the currents in the amplifier and feedback circuits so that the amplification is *decreased*. As a result, we have available an amplifier which is remarkably stable and closely *linear* in its performance. Figure 9 shows schematically the circuit of such an amplifier, but the actual detailed design is not simple and involves great technical skill.

Since the high amplifications just discussed are employed to offset the equally high attenuation of the line structures, careful consideration must be given to the stability or constancy of the attenuation caused by the line structure. The fact is that as the temperature changes, the attenuation of any line structure varies correspondingly. If the line structure is underground in cable, the temperature changes are slow in rate and the variations in line attenuation correspondingly slow, but if the structure is in aerial cable or consists of open wire, not only do we have variations in temperature with the season of the year, but large daily variations as well. With an aerial cable, for example, the change in loss of 19-gauge B & S non-loaded pairs throughout the year for a circuit 1,000 miles (1600 km.) in length amounts to approximately 500 db in the frequency band we propose to use. For our long cable circuits operated on voice frequencies, we have developed automatic regulating means, so that amplification is varied to compensate for changes in attenuation. With the much higher attenuations and equally higher amplifications involved in broad-band systems, more refined methods of compensating for temperature changes are under development. This is a very serious problem and sets one limit to the use of such systems.

I spoke of the new type of amplifier, employing negative feedback, which became available at a most fortunate time. It is almost equally fortunate that, due to continued research and development, new and simpler forms of electric wave filters became available. Time does not permit me to go into details, but in these newer types of electric filters suitably cut quartz crystals are utilized. Developments have also made it possible to use inductance coils with iron cores. As a result of these two changes the filter structure is simplified and its size reduced.

Fundamental to the whole broad-band transmission development, there are many other elements which have required much research and development effort such, for example, as modulators and demodulators, but I shall be able to discuss only the more striking problems underlying all broad-band systems as they pertain to certain specific applications.

Cable Carrier Systems

We plan as a first step to apply the cable carrier system to pairs in existing cables. These cables were designed and manufactured with the expectation that they would be required to transmit frequencies only up to a few thousand cycles, that is, these cables were not designed to meet crosstalk requirements at high frequencies. Crosstalk between pairs in a cable arises from a lack of geometrical symmetry between each pair and every other. As a result of very careful research, we have developed a method of connecting small mutual inductance coils, or condensers, or both, between all the pairs concerned, and in this way reducing crosstalk to a satisfactory degree. At present coils alone are being used. Figure 10 shows schematically the balancing method.

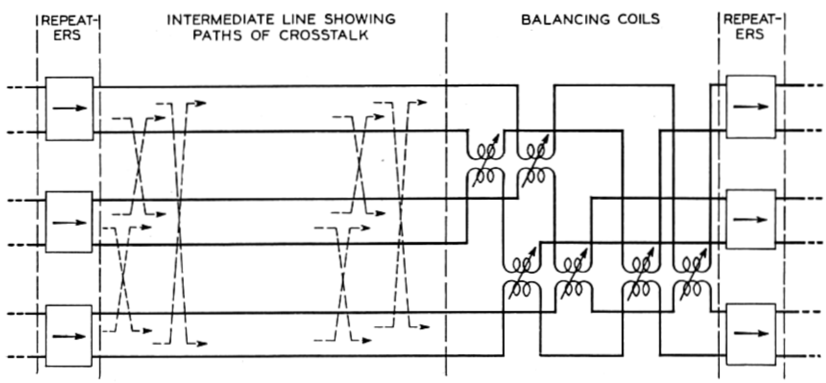

Fig. 10—Diagrammatic representation of method of balancing out cross-talk.

It is obvious that in this process of balancing out the crosstalk, the value given to the adjusting coil or condenser must be determined for each particular unit involved. When the balancing units have been installed and once adjusted, however, we feel that they will remain permanent. Present indications are that by adopting this procedure, we can employ frequency ranges up to 60,000 cycles upon our toll cables, and this will permit us to secure 12 one-way channels on each pair of conductors. With at least our present type of cables, we anticipate that it will be necessary to use separate cables in opposite directions to avoid the additional crosstalk that arises when adjacent pairs are used to transmit in opposite directions. Referring to our present cables, if the pairs which it is desired to utilize are loaded, it is necessary first to remove the loading coils. Repeaters will be spaced about 17 miles (27 km.) apart. Since the present repeater points on cables are about 50 miles (80 km.) apart, it will be necessary to add on the average two new repeater points between existing repeaters. The total amount of apparatus at these new repeater points, however, does not bulk very large, because a repeater handling 12 channels will be no larger than the older type voice repeaters

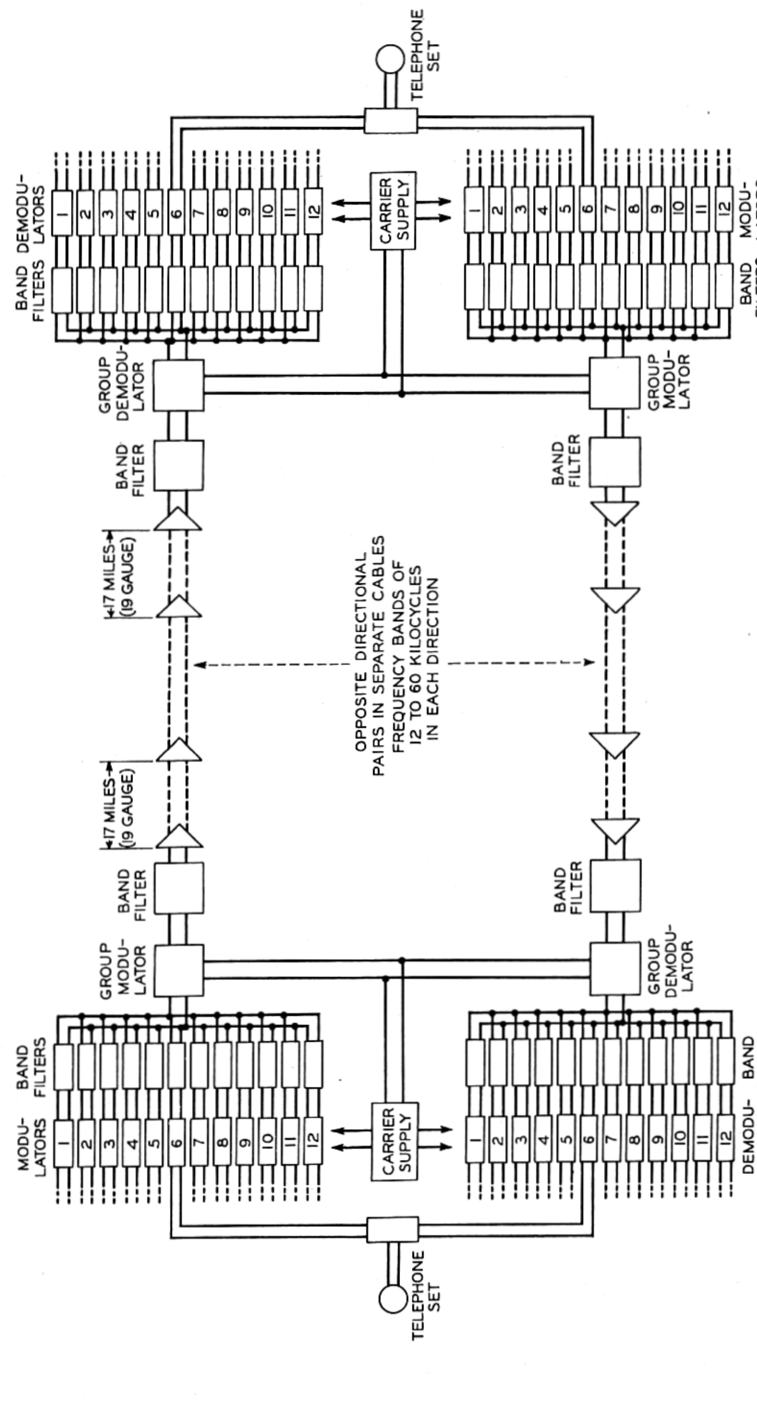

Fig. 11—Schematic representation of the broad-band cable carrier system, which supplies 12 channels in each direction.

handling only one channel. The present plans call for these intermediate repeater stations to be substantially non-attended. The electrical units employed in a cable carrier system are shown schematically in Fig. 11.

Some idea of the possibilities of this carrier cable system may be formed from the results of a trial installation made on a laboratory-scale. In one case, we had circuits as long as 7,500 miles (12,000 km.) set up, over which we carried on satisfactory conversations. The total attenuation over some of these circuits was such as to require power amplifications of 12,000 db, which corresponds to a power ratio of 10^{1200} to 1. This amplification was applied at nearly 400 points.

Broad-Band System for Open-Wire Lines

In the Bell System, as you know, along many toll routes, there is still much open-wire construction, aggregating tens of thousands of miles. At the present time, many thousands of miles of open-wire lines are equipped with 3-channel two-way carrier systems. These systems employ frequencies up to about 30,000 cycles, and with the regular voice frequency circuit provide facilities for four simultaneous conversations over one pair of wires. This might appear to be an efficient use of the wire plant, but the proposed system employs an additional frequency range from about 30,000 cycles to perhaps 150,000 cycles, adding 12 channels in each direction to a pair of wires. This will furnish a total of sixteen simultaneous conversations over a pair of wires.

Extending the frequency range accentuates the problem of crosstalk and some of the other problems of interference, but it is our present feeling that a substantial number of the pairs on a suitably constructed pole line can be rearranged for operation by this broad-band method. Figure 12 shows schematically the arrangement of apparatus at a terminal to provide these sixteen talking circuits, and Fig. 13 shows diagrammatically the arrangement of apparatus at a repeater station.

Since increased frequency means higher line attenuations with corresponding higher amplification, the use of higher frequencies means additional repeaters on the line, so that the line currents will not at any point be attenuated below a certain level. The present proposal is to provide repeater spacing of approximately 75 miles, instead of the 150 miles used on the present open-wire carrier systems.

Coaxial Cable System

This is the most radical of the broad-band developments that we have attempted to develop practically. Instead of several pairs

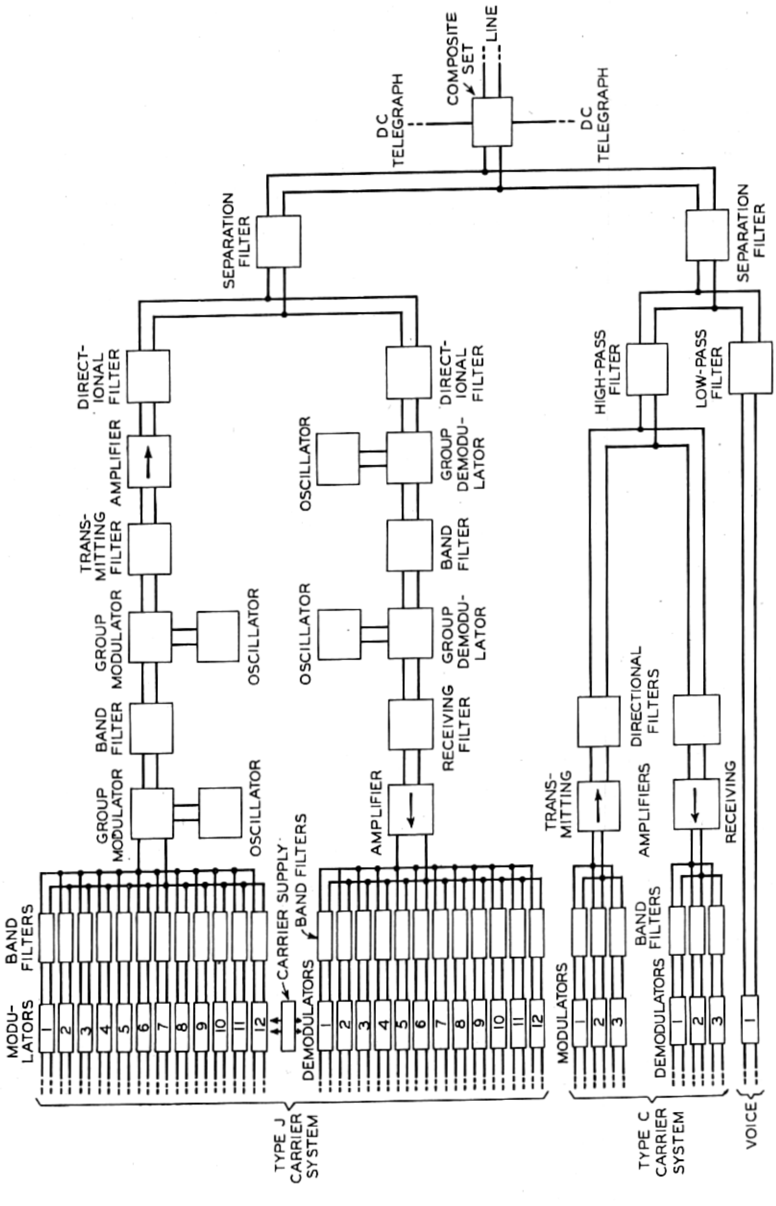

Fig. 12—The broad-band open-wire circuit superimposes twelve two-way circuits on a single pair of wires that also carries three two-way carrier channels at lower frequencies and a two-way voice circuit.

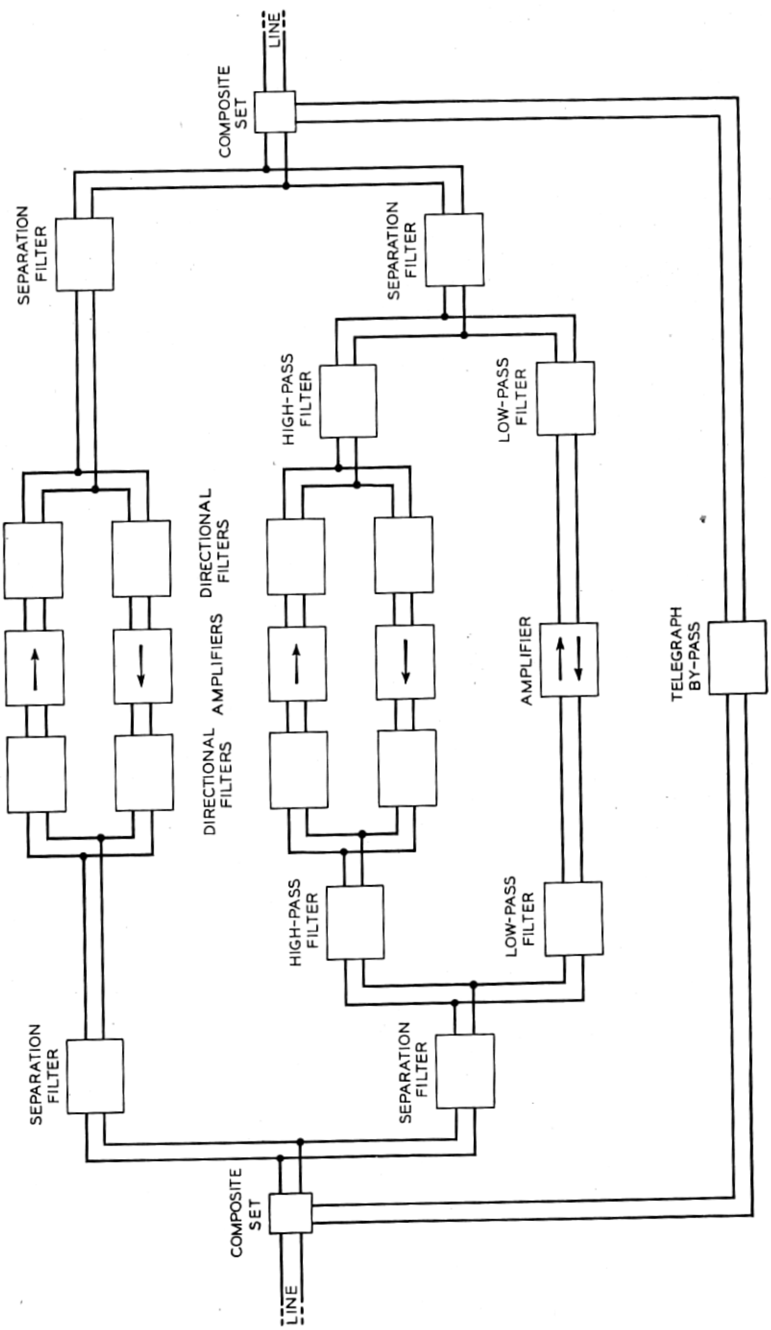

Fig. 13—Block schematic of a repeater station for a broad-band open-wire circuit.

carrying what are now considered moderately high frequencies, this new system employs a single circuit carrying a very broad frequency band. There are many ways in which conducting systems of this type may be constructed. In this connection, of course, facility of

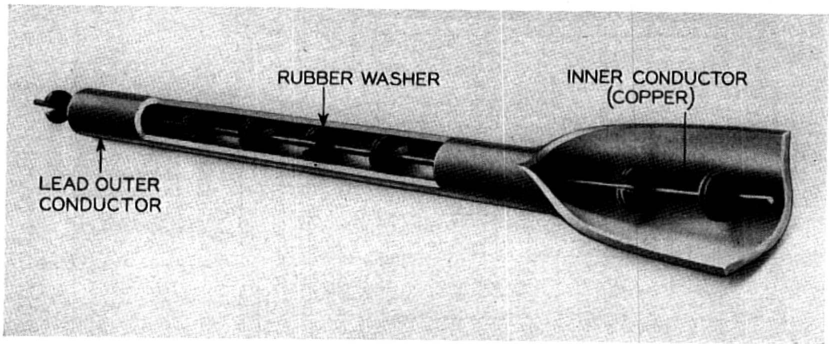

Fig. 14—One of the experimental coaxial structures.

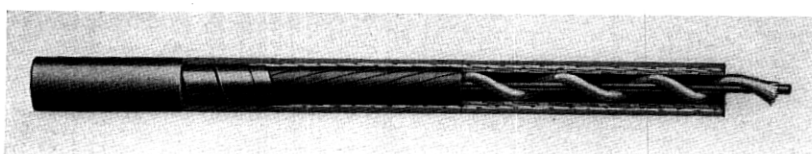

Fig. 15—Another experimental coaxial structure.

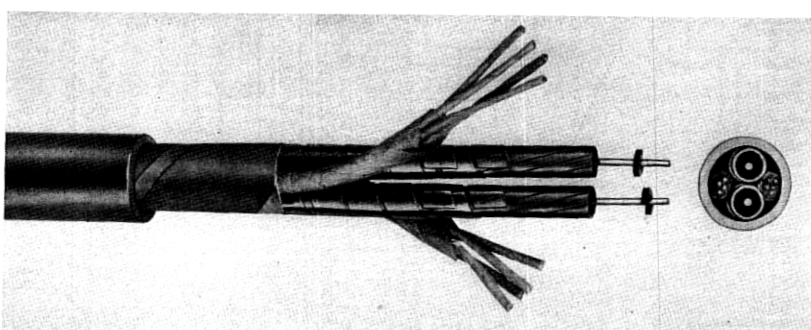

Fig. 16—The coaxial cable employed on the experimental installation between New York and Philadelphia.

manufacture and ability to withstand the handling incidental to installation, must be considered as well as electrical performance. Some of the experimental types of structure are shown in Figs. 14 and 15. In a field trial between New York and Philadelphia, over a

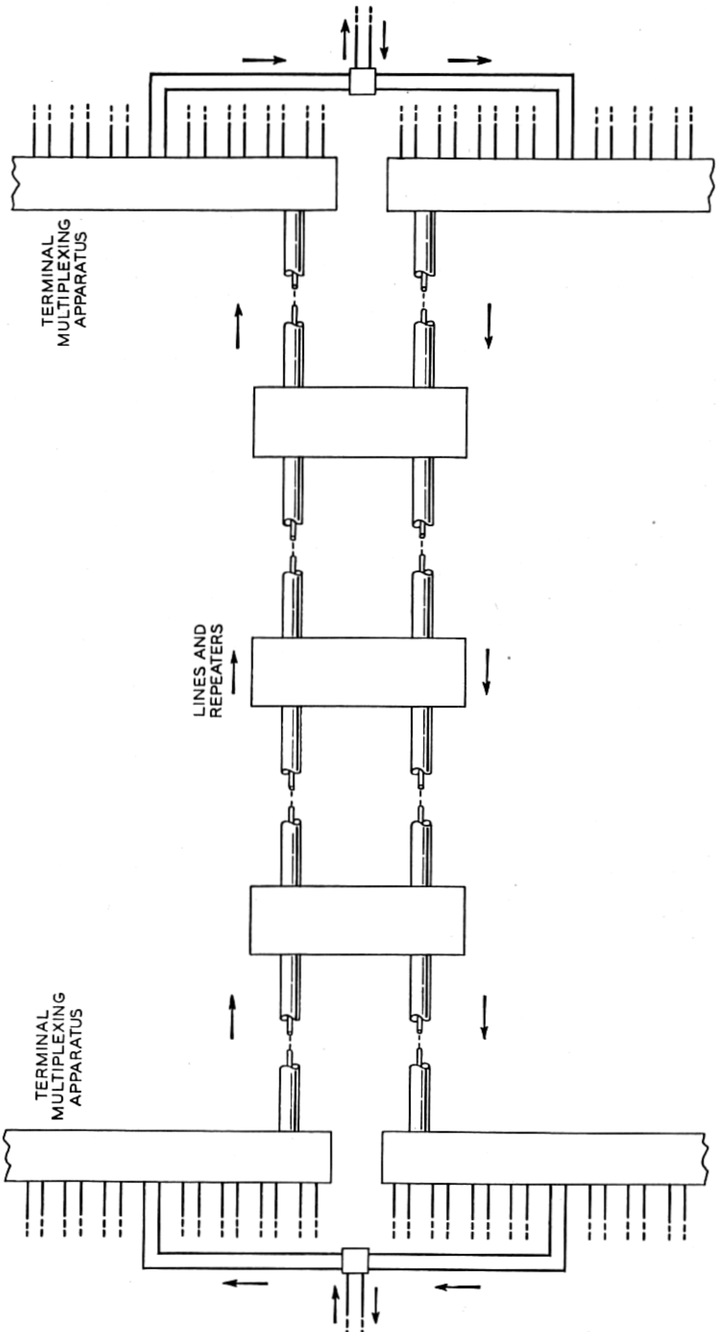

Fig. 17—Block schematic of the coaxial system.

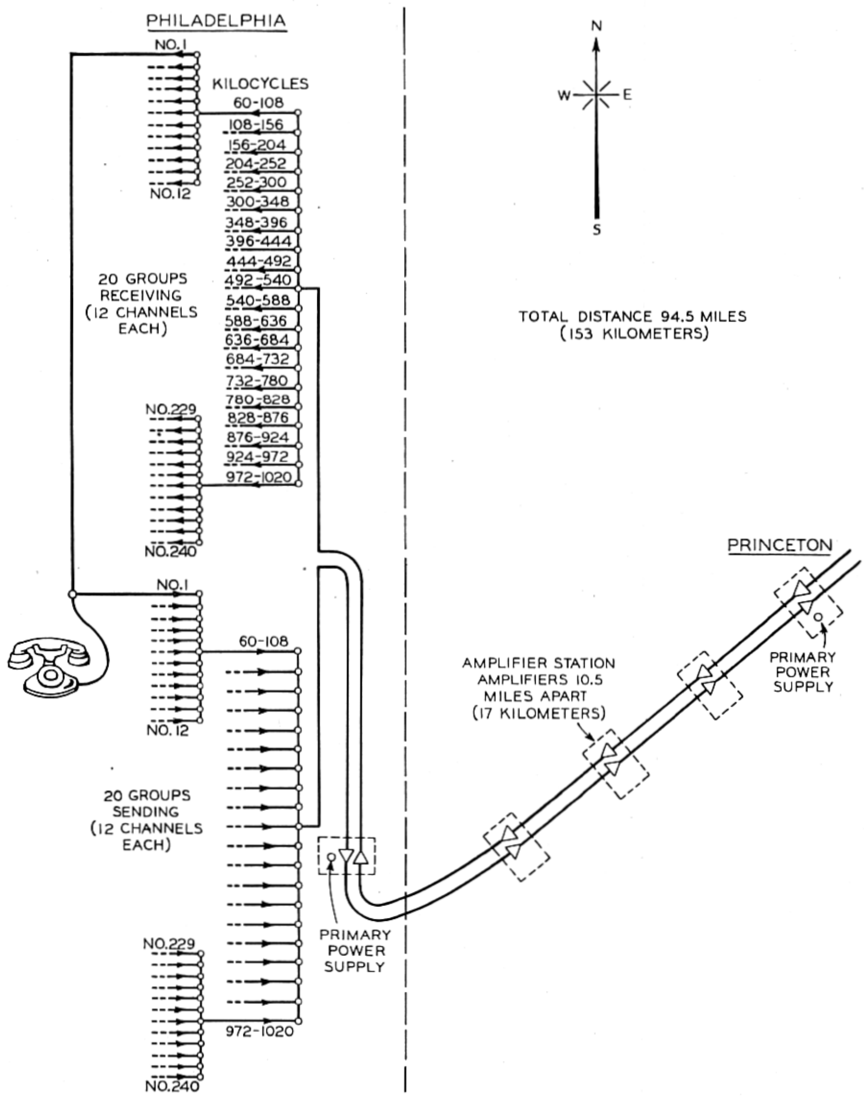

Fig 18—Schematic representation of the coaxial system.

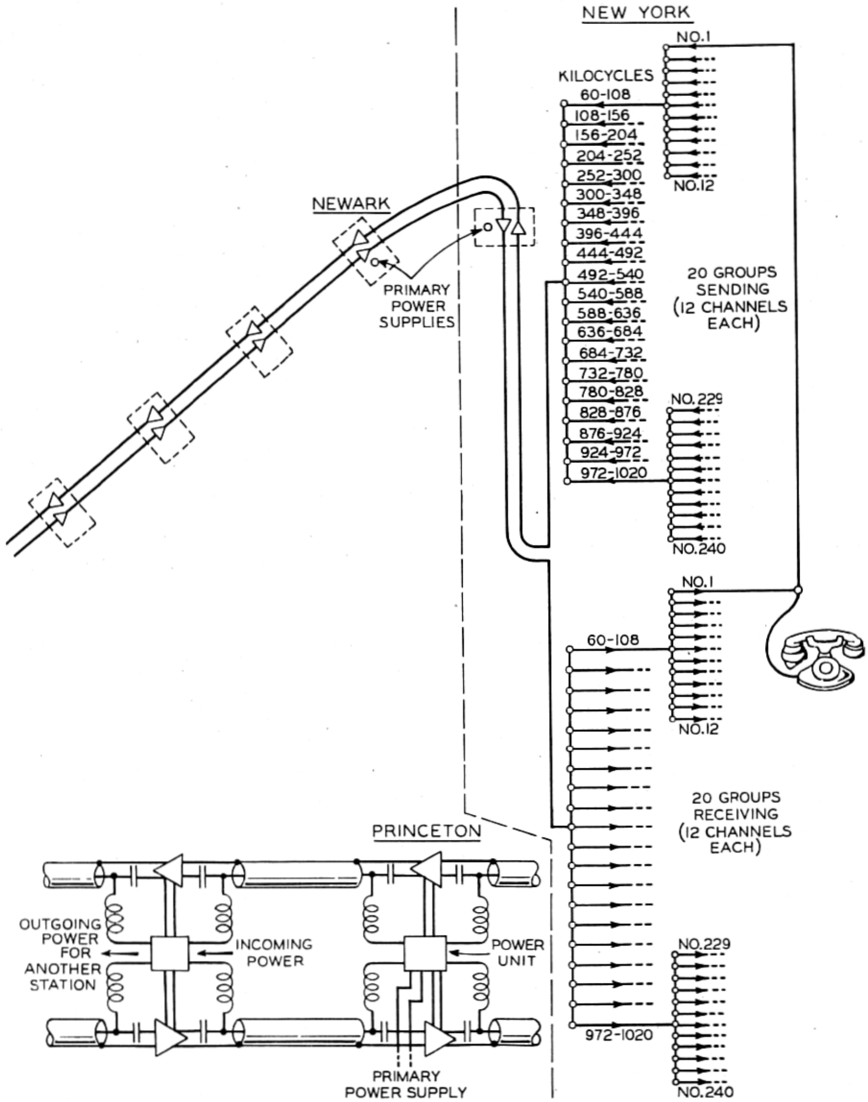

Fig. 18—*Continued from page 140.*

distance of about 95 miles (153 km.), we are employing two coaxial structures within a single lead sheath so as to provide transmission in each direction. The complete structure is shown in Fig. 16. Some of the space within the circular lead sheath is filled with ordinary cable pairs which are tapped out at repeater points for testing and trial purposes. Repeaters are being provided along this coaxial circuit at intervals of about 10 miles (16 km.), which allows frequencies up to about 1,000,000 cycles to be transmitted. Figures 17 and 18 show schematically this coaxial broad-band system.

At each repeater point there is a single amplifier for each coaxial unit, that is, one for each direction of transmission. This amplifier handles the entire number of simultaneous conversations obtainable, which is 240 for the million-cycle band. The amplifiers are equipped with automatic regulating arrangements to adjust the amplification to correspond to the attenuation of the cable as the temperature changes. As you would expect, the attenuation variations with temperature are not the same at different frequencies, but the regulating system meets this condition.

Development of means for combining and separating the channels at the terminals is an interesting feature. Some of our engineers have termed the means employed "unit group." The twelve carrier channels employed in both the cable and open-wire broad-band systems are provided in a unit called a "12-channel terminal." The coaxial system employs essentially the same 12-channel terminal, but it employs twenty of them to provide the total of 240 channels. The output of one 12-channel terminal is put directly on the line, but the outputs of the other nineteen are modulated a second time, and raised to successive positions in the frequency spectrum.

The use of double modulation has two principal advantages. In the first place it simplifies the apparatus by requiring fewer different carrier frequencies, and since it employs a channel terminal that is used by all broad-band systems, considerable economies in production are secured. The chief advantage of double modulation in the coaxial system, however, is that it simplifies the separation of the side-bands resulting from modulation, which is necessary because only one of the side-bands is transmitted. If only a single modulation were employed, the two sidebands of the upper carrier frequency would be separated by only about .05% of the carrier frequency, while with double modulation the narrowest separation is about ten times this amount.

With such a coordinated program of broad-band telephony, toll transmission takes on a new appearance. Not only will the provision of additional channels be simplified by the availability of these new systems, but the cost per channel should be somewhat decreased. At the same time the quality of the circuits, from the standpoint of voice transmission, has been improved, so that a multiple gain is obtained.

Lecturer's Note: The lecturer wishes to acknowledge his indebtedness to a number of members of Bell Telephone Laboratories' staff. In particular, he wishes to thank Messrs. H. A. Affel, A. B. Clark and P. C. Jones for their assistance in preparing this material.