Coaxial Cable System for Television Transmission*

By M. E. STRIEBY

THE reports which have been made on the progress in television development increase the expectation that the broadcasting of visual programs will soon be realized. In anticipation of that result, the Bell Laboratories has been engaged for some time in the development of wire line circuits for transmitting television signals between studios and broadcasting transmitters, or between cities, as may some day be required if television follows in the footsteps of sound program broadcasting.

The wide frequency bands required for television and the dearth of available frequencies appear to force the broadcasting of television signals into the ultra-high frequency range. At these high frequencies, the coverage which can be obtained from a broadcasting station is very limited as compared to that obtainable in the sound broadcasting frequency range. Hence, if television programs are to reach large sections of the country simultaneously, the provision of interconnections between large numbers of television broadcasting transmitters will become even more important than it is today for sound broadcasting.

Coaxial cables have received much publicity as transmission lines for television. The original conception and use of the coaxial form of cable was first as a low frequency submarine conductor and later as a lead-in for radio antennas. The idea of a coaxial cable or other medium for the transmission of very broad frequency bands originated in the course of telephone development in America.[1] The first lengths of such cable for broad-band transmission were made here and its first use for the transmission of a large number of simultaneous telephone conversations was between New York and Philadelphia.[2] In this country the important reason for developing coaxial cable systems was, and still is, that they appear to offer material economies in the provision of large groups of long distance telephone facilities. Television has been secondary.

Recently experiments have been made on the transmission of television signals over the coaxial cable between New York and Philadelphia. This cable contains two coaxial conductor units within

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a lead sheath about 7/8" in diameter as indicated in Fig. 1. Two coaxial units were provided because, for long distance telephone operation four-wire operation is preferable, one coaxial being employed for transmission east to west and the other west to east. Each coaxial unit is made up of a 13-gauge inner conductor on which hard rubber disks have been placed at intervals of 3/4 of an inch. The outer metallic tube is made up of 9 overlapping copper tapes so designed that they form essentially a solid copper tube about 20 mils in thickness and .267" in inside diameter.

The transmission loss of this circuit as a function of frequency is shown on Fig. 2 together with the portion of the attenuation that is contributed by conductance losses. Inasmuch as the intention is to use these conductors at very high frequencies, a high grade insulating material was used with the result that the conductance losses are small.

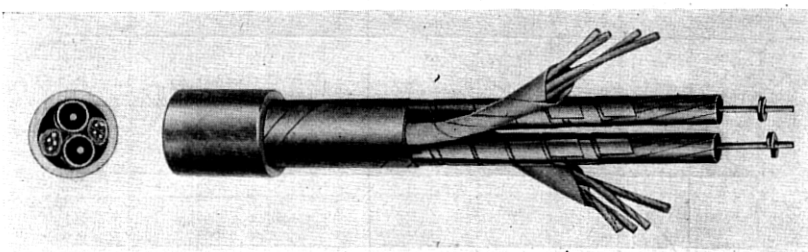

Fig. 1—Section of the New York-Philadelphia coaxial cable.

It should be noted that the attenuation increases very nearly as the square root of the frequency.

In order to transmit high frequencies over long distances, a great deal of amplification is obviously required. The New York-Philadelphia cable was initially equipped to handle a band of one million cycles. Its overall attenuation at a million cycles is approximately 600 decibels. In order to reduce this to a usable amount 10 repeater points were provided at intervals of about 10 miles each having an amplification at the top frequency of about 60 decibels. These repeaters were so designed that they provided less gain at low frequencies than at the high frequencies, in approximately the same degree as the line had less attenuation. To make up for certain cumulative irregularities an equalizer was built and added to the overall circuit. The net result was a transmission path which had approximately zero loss over the whole band which it was desired to use from 60 kc. to 1000 kc. as shown in Fig. 3.

Another complicating factor is, however, involved, as is the case with all long wire circuits, namely, the variation encountered with changes in temperature. The loss in a 10-mile repeater section varies materially from summer to winter. If the cable is hung overhead, this variation is about as shown in Fig. 4 and amounts to a change of about ± 7 per cent in the attenuation. If the line is buried underground at the normal depth used for telephone cables, the actual variation is about one-third as much. Automatic transmission regulators were developed to compensate for these changes. These

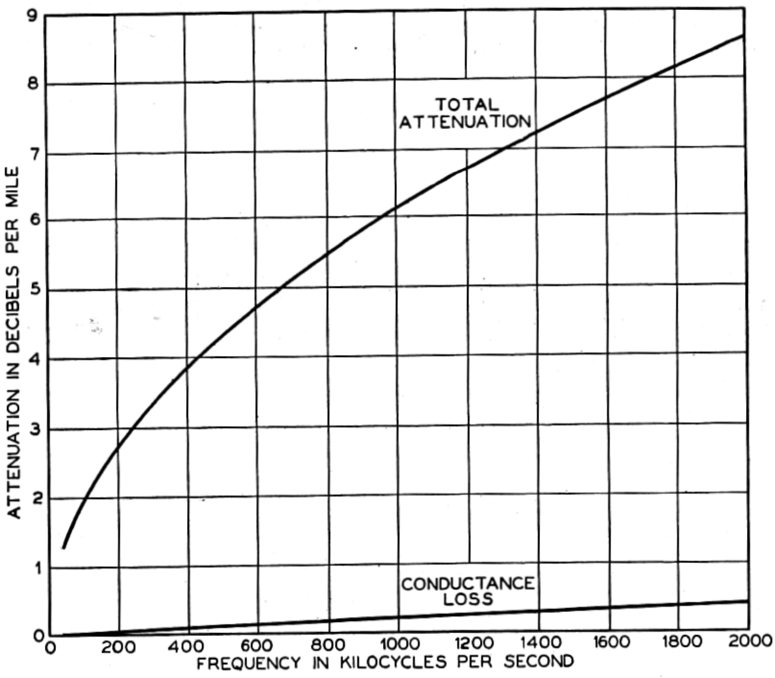

Fig. 2—Attenuation per mile of the New York-Philadelphia coaxial cable. Also the proportion of that attenuation due to conductance losses.

regulators depend, for their operation, on the transmission of a pilot channel. At each point where it is desired to regulate the transmission, the pilot channel is selected by a very narrow band filter and its amplitude used to control an automatic device which changes the gain of the repeater until the amplitude of the pilot at the output of the repeater reaches a certain predetermined value. The regulators on the New York-Philadelphia circuit have operated with such accuracy that it has been unnecessary to make manual adjustments to take care of temperature changes.

The repeaters used along this route were novel in that most of them were placed in small iron boxes located at convenient points along the line. Power for their operation was transmitted at sixty cycles over the coaxial cable itself. Figure 5 shows one such unattended repeater located near Dunellen, New Jersey.

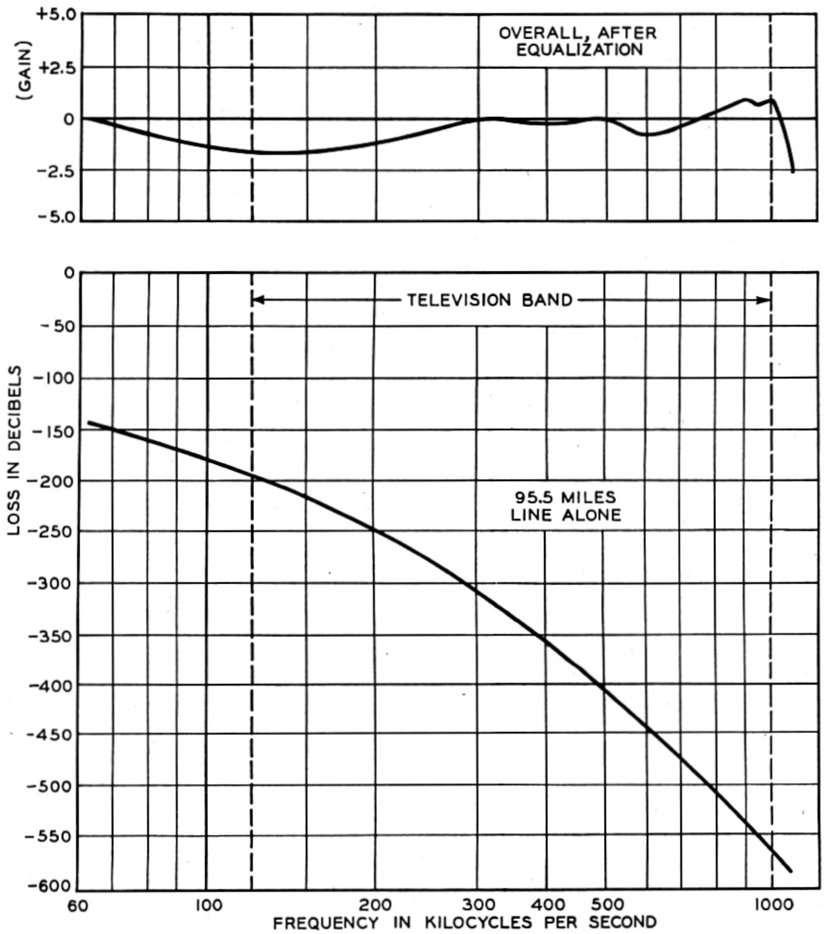

Fig. 3—Overall attenuation of the New York-Philadelphia cable without repeaters and the net attenuation after repeaters and equalizers had been provided.

The coaxial system between New York and Philadelphia was designed to provide 240 telephone circuits. Skeleton terminal apparatus was installed at New York and Philadelphia to test out such operation. This apparatus has been described [2, 3, 4] in various papers and will not be discussed here. Suffice it to say that methods and equipment have been developed which enable a wide band to be split up so as to obtain hundreds of telephone channels.

For television transmission a quite different problem existed—namely, can very wide band systems be used for the long distance transmission of these complicated signals? In planning tests to be significant of the operation of the cable system for such signals, it was important to obtain as nearly as possible an ideal television signal and as nearly as possible an ideal television receiver. In this

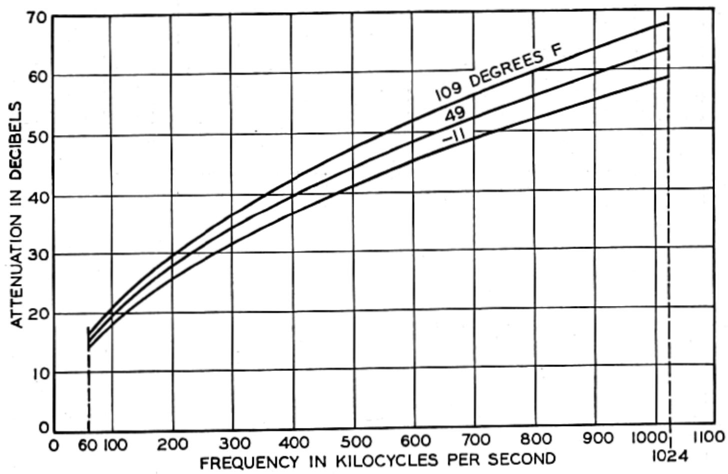

Fig. 4—Attenuation of the New York-Philadelphia type of cable under widely different temperature conditions.

way it was hoped that any defects in the cable transmission itself could be discovered.

Signal Generator

Although television implies the transmission of an actual scene it is much more satisfactory for engineering studies to transmit a motion picture, since exactly the same picture can then be transmitted over and over again as the circuit elements are changed or adjusted. Moreover, it was decided to use mechanical scanning to obtain the most nearly perfect signal possible, and with this form of scanning a film can be much more brightly illuminated than an actual scene and hence is much easier to use. Because of these factors a motion picture film was chosen as the material for the recent experiments.

The scanning disk used in these tests was developed under the direction of Dr. H. E. Ives at the Bell Telephone Laboratories. It consists of a six-foot disk with a circle of 240 lenses near its outer edge.

The arrangement is indicated schematically in Fig. 6. Light from a powerful incandescent lamp behind the disk, passing through one lens at a time, is focussed by the lens to form on the film a small dot of

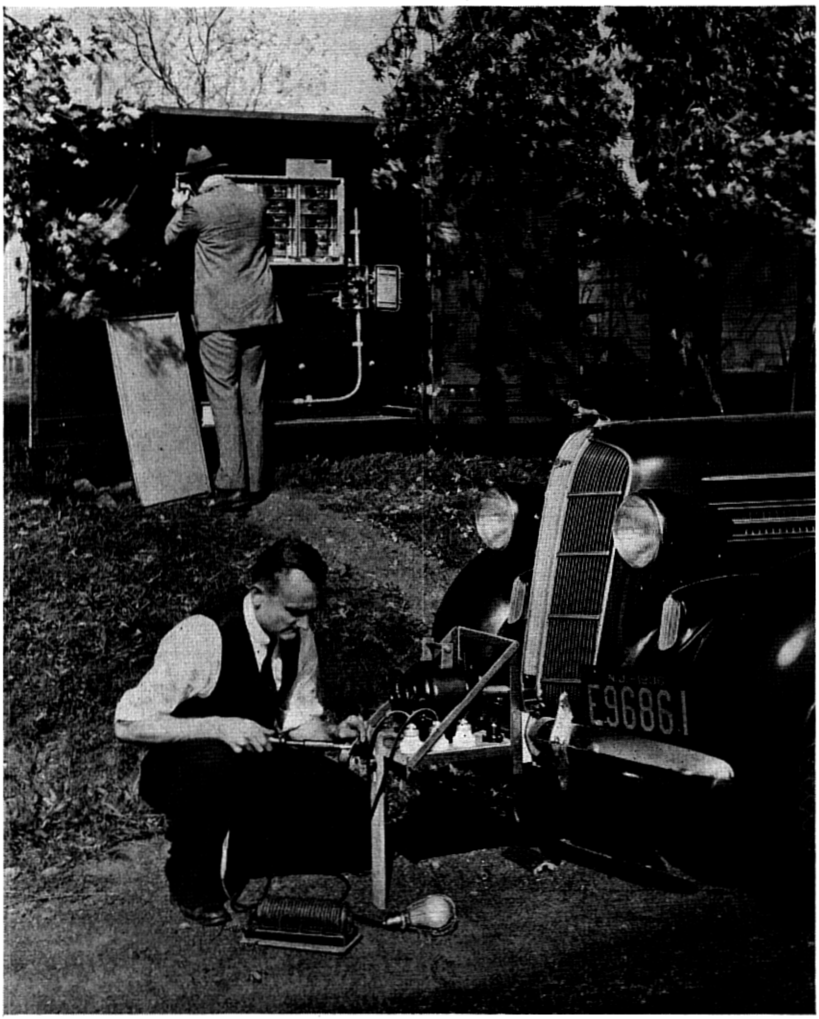

Fig. 5—Repeater near Dunellen, New Jersey.

light about three thousandths of an inch square. The lenses in the disk are spaced by a distance equal to the width of the picture, or a little less than an inch, and as the disk rotates, each spot is moved rapidly across the picture. The film is carried at a uniform rate downward behind the disk at such a speed that the successive holes throw their light in successive rows across the picture one above another. The film moves one frame for each revolution of the disk. A photosensitive surface mounted behind the film picks up the light transmitted through it, and produces a complex electric current corresponding to the variations of light in the picture. Figure 7 is a photograph of the housing in which the disk is mounted. This

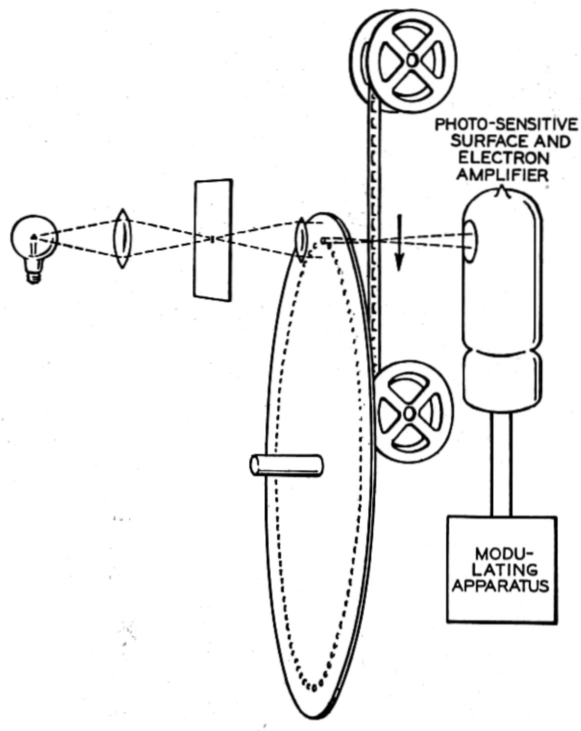

Fig. 6—Schematic diagram of the mechanical scanning arrangement used for television testing.

scanning arrangement produced a picture of 240 lines, 24 frames per second. It was recognized that 24 frames per second were not sufficient to avoid flicker but this choice simplified the scanning apparatus and it was believed would not interfere with engineering tests.

Signal Frequency Range

In order to understand what frequency is required to transmit an image scanned in this way consider the diagram shown in Fig. 8.

Of course, actual television will not ordinarily deal with such a picture, but by means of it an approximate visualization of the problem can be obtained. A desired definition of 240 lines was chosen and it was decided that the requirement would be to transmit square picture elements as indicated in the figure. The shape of the picture which

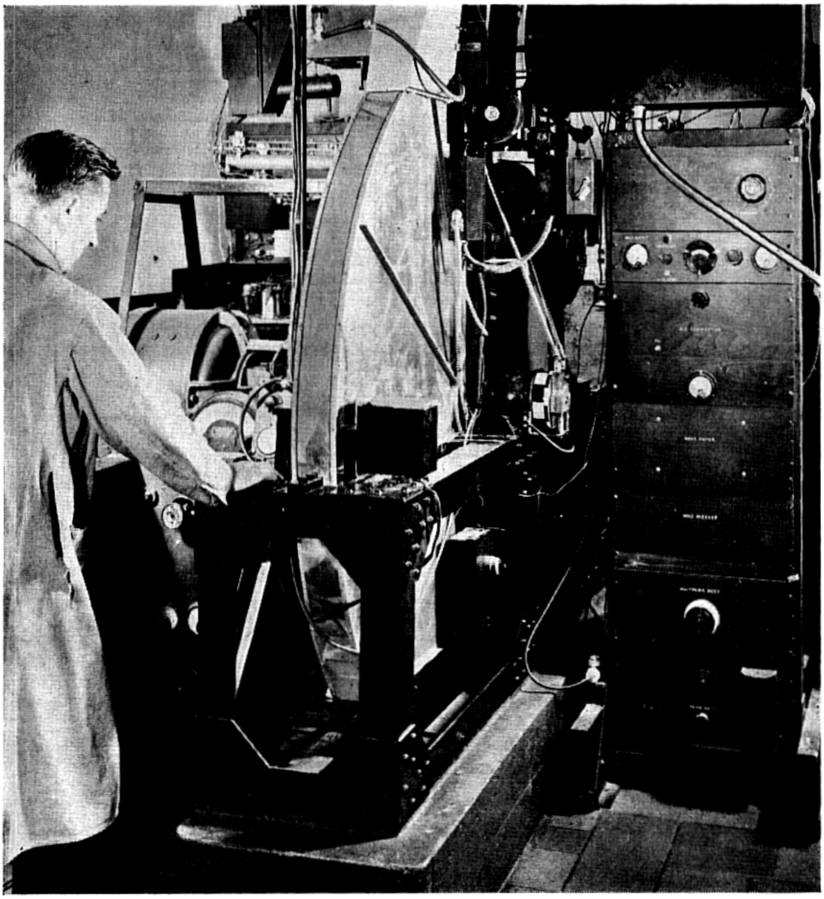

Fig. 7—Photograph of the mechanical scanning disk and associated experimental apparatus.

it was convenient to use with this scanning disk is wider than it is high in the ratio of 7 : 6. This differs somewhat from the standard aspect ratio of 4 : 3, but is easily taken into account. The total number of picture elements in a frame is then $240^2 \times \frac{7}{6} = 67200$.

If the smallest picture element to be transmitted is a single block then the distribution of light and shade over the block is unimportant. The average brightness over the block is what counts. Obviously, a simple approximation is a sine wave as shown at the bottom of the picture. This wave has ½ cycle for each block and is as high a frequency as there is any profit in transmitting for this diagram.

The top frequency needed for such a picture can then be calculated. The number of square elements in the picture computed above is

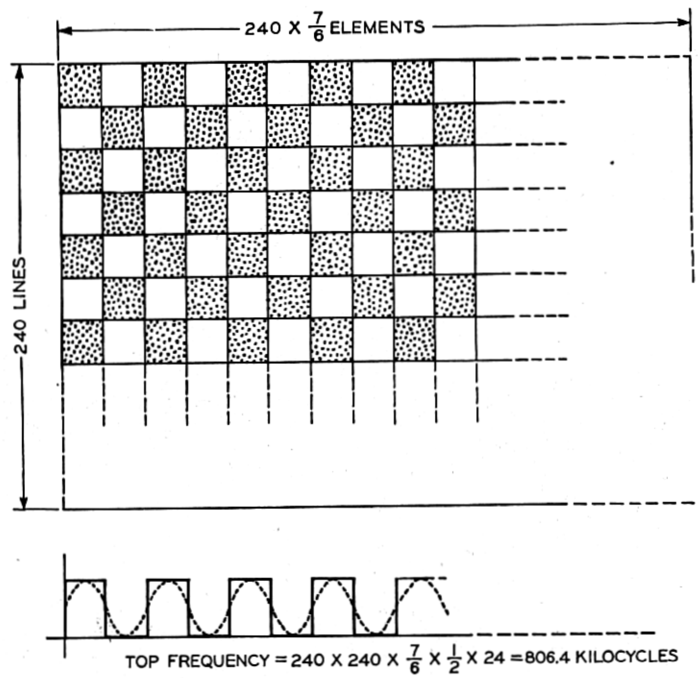

Fig. 8—Diagram illustrating the resolution of an image into picture elements and the derivation of maximum frequency required for transmission.

67,200. As each of these elements represents ½ cycle, this figure is divided by 2, giving 33,600 cycles per frame. As similar frames are reproduced 24 times a second, the result is 24 × 33,600 or 806,400 cycles per second. In a real moving picture, other frequency components may exist at all other frequencies from 800 kc. down to and including direct current. The direct current or zero frequency component controls the general level of brightness of the picture. Where the general level of brightness changes slowly, it results in a component of very low frequency. A composite picture can be imagined which will produce a pronounced component at any given frequency, hence, it is deemed important to transmit the entire band from 0 to 806 kc.

Receiving Device

At the receiving end an effort was made to obtain as high a degree of fidelity of reproduction as possible. No small factor in the success of the recent experiment was the special cathode ray tube, designed by Dr. C. J. Davisson and used at the receiving end to display the transmitted picture. Some of the features of this tube are indicated schematically in Fig. 9. A stream of electrons from the cathode passes through a series of electron lenses which focus a narrow beam on an aperture .006″ square. Between the lenses and the aperture, however, are two modulating plates connected to the incoming circuit in such a way that there appear on these plates potentials varying according to the voltage of the incoming signals. The effect of

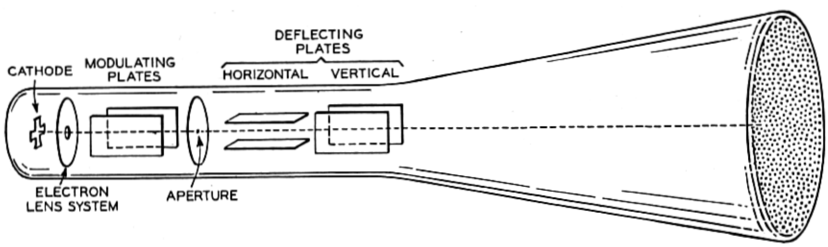

Fig. 9—Schematic diagram of the special cathode ray tube used for viewing transmitted images.

potential on these plates is to deflect the electron beam, and the conditions are such that at maximum strength of signal practically the entire stream of electrons passes through the hole and forms a brilliant spot of light on the front of the tube. As the signal decreases in strength, the electron stream is more and more deflected; less electrons pass through the aperture, and the illumination on the sensitized end of the tube decreases.

In addition to these modulating plates, and placed between the aperture and the front of the tube, are two other pairs of plates mounted in planes at right angles to each other. The potential on one of these sets of plates, controlled by a frequency of 5760 cycles, which is the frequency at which successive lines are scanned, varies in such a way that the beam of electrons passing through the aperture is swept across the front of the tube from left to right, exactly in synchronism with the scanning beam at the sending end. After the beam reaches the farther side of the picture, the potential on the plates is suddenly changed, and the beam is rapidly moved back to begin the next line. Due to a black mask down the far side of the film being scanned, there is no signal during this very short period while the voltage on the plates is changed, and thus the electron beam is deflected from the aperture and is not visible on the front of the tube during its return.

The potential on the other pair of plates is controlled at a frequency of 24 cycles per second, which is the rate of scanning successive frames. The effect of the potential on these plates is to deflect the electron beam downward in synchronism with the motion of the film at the sending end. This results in the passage of the electron beam across the front of the tube in successive rows, one below another. After the last row has been scanned, the voltage on the plates is changed and returns to the value that causes the beam to appear at the top line of the tube. A properly synchronized blanking-out pulse is introduced between successive frames of the film, so that no signal is received during this interval, and thus the passage of the electron beam from the bottom to the top of the frame is not visible.

Figure 10 is a photograph of one of these cathode ray tubes. Due to its superior design, the image is very sharp over the entire field and a wide range of brightness is secured. The chief factors in its success are the sharp focusing by the electron lenses, the linear deflection of the beam at the aperture, and the great length of the tube, which makes it necessary to deflect the electron beam over only a narrow angle to cover the 7 × 8 inch field. Since this trial was a test to determine the capabilities of the system, such matters as size and cost, which would be important with commercial receivers, were not controlling.

Modulation System

The frequency band which was generated at the sending end as noted above was 0 to 806 kc. The coaxial cable system used could not transmit this band, because repeaters were not designed to pass frequencies below about 60 kc. This limitation was incorporated in the original design because the cable offers insufficient shielding to various disturbances at low frequencies. For television transmission it was necessary, therefore, to raise the television signal band to a higher frequency position before attempting transmission over the line. A number of considerations led to the decision to raise the entire frequency band 144 kc. for transmission over the coaxial cable.

Where such a wide frequency band is to be raised by an amount less than the width of the band itself, a single modulation is not generally satisfactory. The products of modulation include the original frequency band as well as the upper and lower sidebands, so that there will be a confusing jumble of frequencies in the modulator output. For this reason a double modulation method was used for the recent experiments.

Fig. 10—Photograph of one of the special cathode ray receiving tubes.

The modulating scheme employed can be followed with the help of Fig. 11, which shows the two modulating steps at the sending end and the two demodulating steps at the receiving end in four lines beginning at the top. A carrier of 2376 kc. is used for the first modulation, which results in a lower sideband from 1570 to 2376 kc. and an upper sideband from 2376 to 3182. The carrier itself is eliminated in the balanced modulator. The output of this modulation is passed through a filter, but because the two sidebands touch each other at 2376 kc., the filter cannot cut off all the upper sideband. At the output of this filter there is thus the lower sideband plus a small amount of the lower part of the upper sideband. The upper sidebands from all subsequent modulations are readily eliminated by filters because of the wide separation.

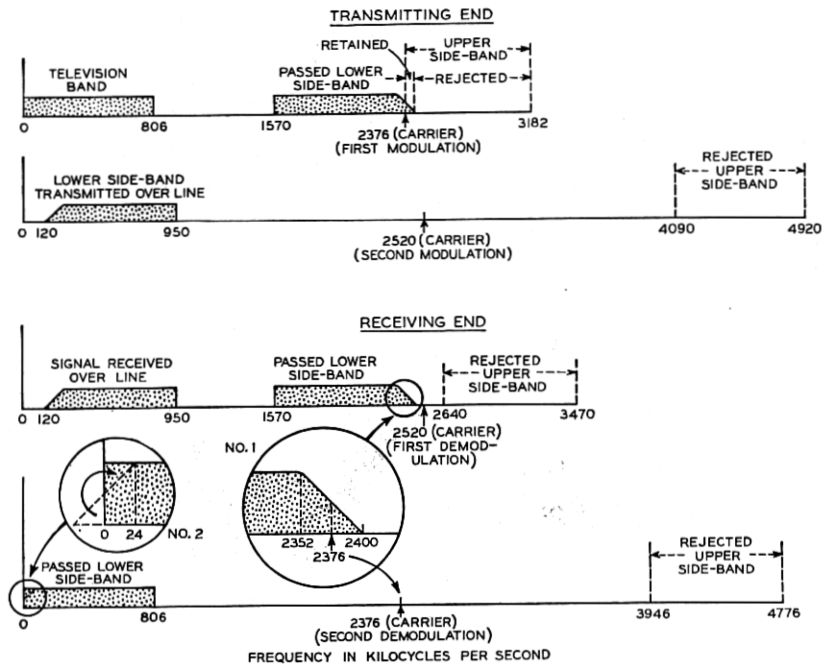

Fig. 11—Schematic diagram illustrating the processes of modulation and demodulation used in transmitting television signals over the coaxial line.

The carrier for the second modulation is 2520 kc., and the lower sideband extends from 950 down to 144 kc. plus a vestigial upper sideband remaining from the first modulation which extends down to 120 kc. The high-pass filter following this modulation is accurately designed to pass with controlled attenuation a group of frequencies just above 144 kc. and the vestigial sideband. The resulting single sideband, extending from 120 to 950 kc., is then passed over the coaxial cable.

At Philadelphia the received signal, together with a carrier of 2520 kc., is applied to the first demodulator, and the lower sideband, from 2400 down to 1570, is passed to the second demodulator where a carrier of 2376 kc. is applied. The lowest frequency of the lower sideband, 1570 kc., is converted to 806 kc., becoming the highest frequency of the final demodulated band. The frequencies from 2352 to 2400 kc. of the sideband before the second demodulation have been attenuated somewhat by the high-pass filter following the second modulator, and the second demodulating carrier, 2376 kc., falls in the middle of this attenuated band as shown in inset No. 1. Frequencies extending about 24 kc. above the carrier are inverted by the demodulation, and superimposed upon the corresponding frequencies just below the carrier. The magnitude and phase of these components are proportioned by the high-pass filter and an equalizer so that the overall result, when they are superimposed, is an essentially flat transmission band from 0 to 806 kc.

The above steps of modulation involved a number of difficulties. In the first place the signal level must be carefully controlled so that on the one hand it does not sink into the background noise, while on the other hand it must not be raised to such high levels that unwanted modulation products are produced in too great magnitude. The first modulator presents some special problems. It must accommodate all frequencies from 0 to 806 kc. In order to eliminate the carrier, it must be balanced to a very high degree—about 80 db in this case. The reason the carrier must be so completely wiped out is that the 0 frequency component of the signal is identical with the carrier at the output and hence the true d-c. value of the signal must be exceptionally free from carrier interference.

Referring to Fig. 12, the next piece of apparatus is a band filter to eliminate the video signal and cut off the top edge of the band. Then follows the 2nd modulator which is quite conventional. A low-pass filter is next and is very important as it performs part of the function of cutting off and adjusting the vestigial sideband. Then follows an amplifier, a predistorting network to partially equalize the amplitudes of the different components of the signal, an aperture equalizer to correct for the fact that the scanning spot is of finite size, a terminal equalizer to make up for irregularities in the overall setup and other amplifiers.

The carrier apparatus at the sending end is shown on Fig. 13. It is mounted in rather conventional form except for the 1st modulator which was arranged to minimize the effect of low-frequency vibrations. At the receiving end about the same apparatus is required in the inverse order and will not be discussed in detail.

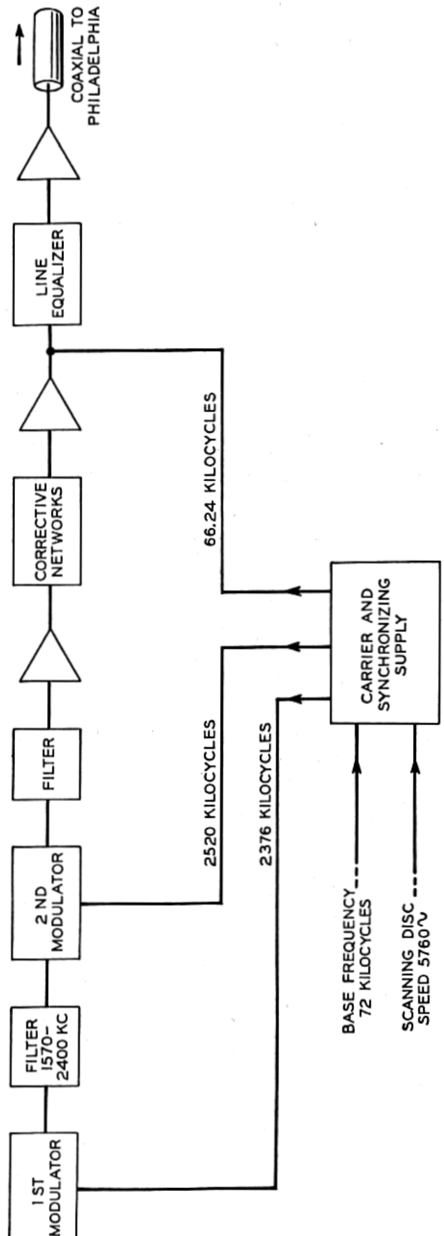

Fig. 12—Block diagram of the transmitting carrier television terminal at New York.

Carrier Supply

Another important feature of this system was the provision of accurately spaced carriers for the various modulating operations. The Bell System 4 kc. standard was used to produce a 72 kc. (18th harmonic) base frequency signal which could be transmitted over the line

Fig. 13—Photograph of the transmitting carrier television terminal with associated sound apparatus.

and so tie the transmitting and receiving ends together. From this, by harmonic generation, the carriers used in the two steps of modulation were produced, being the 33rd and 35th harmonics.

To synchronize the scanning at the receiving end with the transmitting disk required another direct tie. The disk is driven by a d-c.

motor and its speed cannot be kept very constant. By means of an auxiliary lamp and photocell, the frequency with which one scanning line followed another—approximately 5760 per second—was obtained. This was modulated with the 72 kc. mentioned above and transmitted over the line as a lower sideband at 66.24 kc. At the receiving end by demodulation, the exact line speed is obtained and used to drive the horizontal sweep. The vertical sweep is obtained by generating the 240th subharmonic of this—namely 24 c.p.s.

Line Equalization and Test Results

Returning now to the line transmission problem, the signals which might be transmitted in the general case are indicated in Fig. 14. They include the pilot channels used for automatic transmission regulation at 60 kc. and 1024 kc. For convenience, one telephone channel with a carrier at 64 kc. is indicated as an order wire, and a

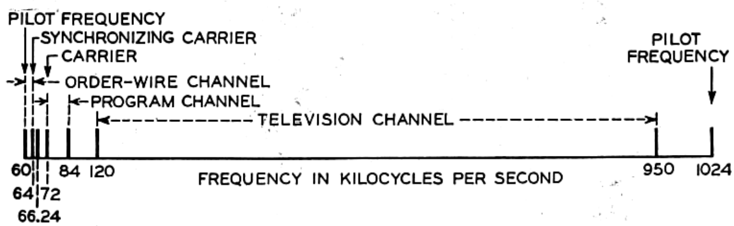

Fig. 14—Frequency allocation for a television transmission system with associated control circuits.

wide-band program channel with carrier at 84 kc. to transmit the sound. These, of course, could be provided with ordinary telephone facilities. The base frequency of 72 kc. and the disk synchronizing sideband at 66.24 are also included. For the television signal itself the band from 120 to 950 kc. is provided. Actually in the tests to Philadelphia, automatic regulation was not needed and a separate wire line was used for synchronization.

It was necessary to provide networks and equalizers to insure that the coaxial line did not distort the ultimate image due to unequal attenuation, resulting in amplitude distortion, or to unequal time of transmission, causing phase distortion. The actual attenuation characteristics of the line [5] and the overall result were shown above in Fig. 3. The requirements for phase distortion are rather difficult to meet. The details in the scanned picture result in various frequencies of the electrical signal, and if these details are to appear in the reproduced picture in the same relative position as in the scanned picture, it is essential that all frequencies be received in very closely the same relative time relationship as they are generated. Referring back to Fig. 8, it was assumed that no picture element could be displaced by more than about half its width. This led to the decision to hold frequencies between 806,000 and 3000 cycles to a delay distortion of about 0.3 microsecond. For a similar degradation of detail in the vertical direction, the permissible delay distortion is 280 times as great which, in a system of this type, is very easily obtained. The actual circuit roughly met these requirements as indicated by Fig. 15,

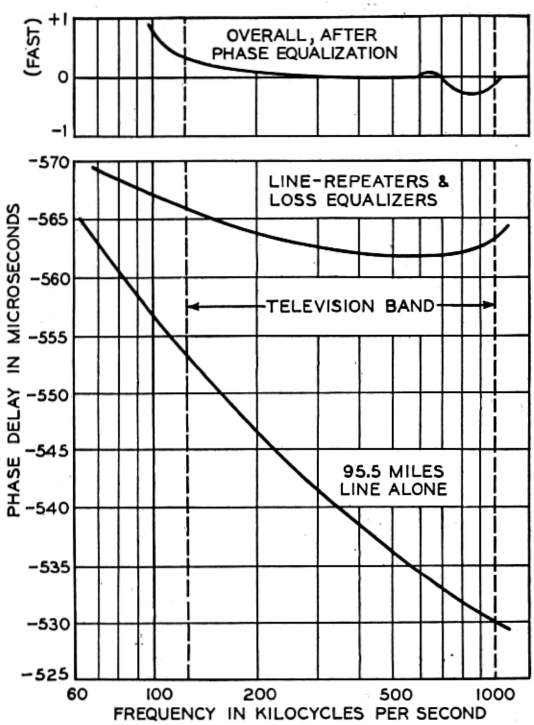

Fig. 15—Phase delay of New York-Philadelphia television circuit.

which shows the phase delay characteristics of the line, repeaters and equalizers, and of the overall circuit at the frequencies used for transmission.

Noise or interference is very annoying in television transmission; and pattern, or single frequency interference, is particularly objectionable. The permissible noise or interference depends on the amplitude range of the reproduced picture. During these experiments, it was found that a substantially linear response could be obtained over a signal current range of about 20 db—a brightness ratio of 10 to 1.

The actual reproduced pictures considerably exceeded this range; in fact a brightness ratio of 50 or 100 to 1 was realized. In these tests it was found desirable to hold random interference down about 40 db below the maximum signal, and pattern interference down at least 15 db more.

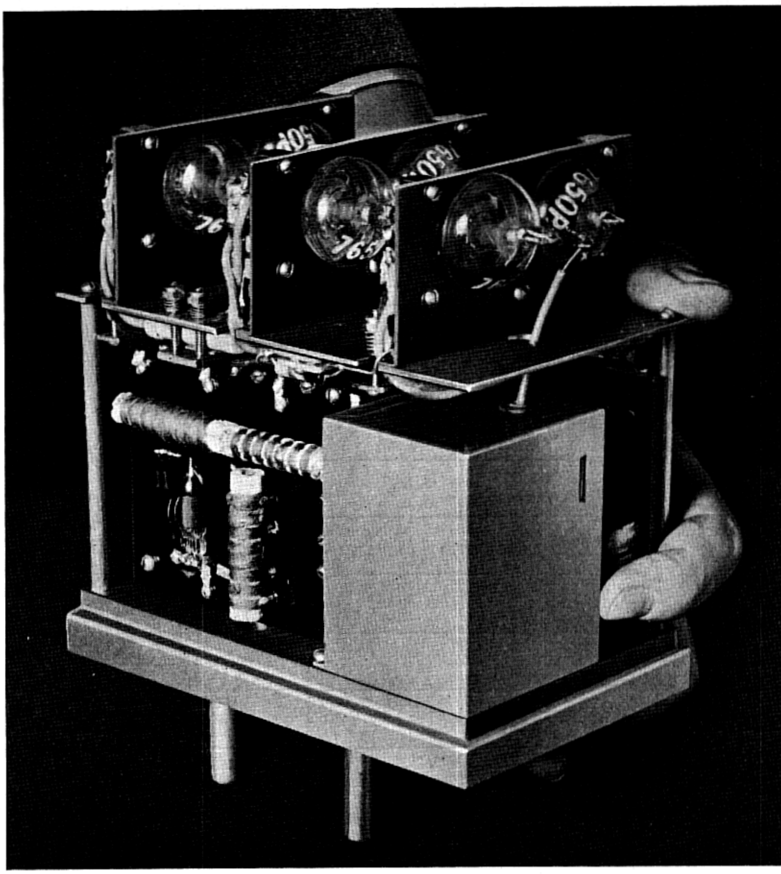

Fig. 16—Photograph of a two million cycle amplifier under development for experiments on the coaxial cable.

The engineers who worked on the system, and outside experts who observed it, expressed the opinion that the reproduced pictures in Philadelphia were substantially the same as those seen on a similar receiving device in New York, thus showing that the cable system itself introduced no appreciable distortion.

Conclusion

As a result of the experimental transmission of the pictures over the coaxial cable from New York to Philadelphia it has been proved that wide-band signals of the type required for television can be satisfactorily transmitted over a coaxial cable system, and that in such transmission the distortion introduced by the wire line circuits can be made so small as to be inappreciable, in its effect on the received picture.

The work on these very wide-band systems has only begun and repeaters and terminal apparatus are now under development capable of handling wider bands of frequency. At the present time work is under way on a two-million cycle system for telephone transmission and a trial installation is being made between New York and Princeton. The system will transmit a frequency band of about two million cycles corresponding to a capacity of 480 telephone circuits. Repeaters on this system will be about 5 miles apart and will consist of unattended boxes somewhat smaller than the one-million cycle repeaters illustrated above and placed either in manholes or on poles along the route. Within these boxes there are placed two amplifiers, one for eastbound transmission, the other for westbound, together with the necessary filters and power supply apparatus. The actual amplifiers themselves are quite small compact units one of which is shown in Fig. 16. Two megacycles, of course, is not a sufficiently wide band to transmit the present R.M.A. standard 441-line television signal, but is a logical step toward more economical telephone circuits. Development is also under way on amplifiers capable of transmitting three megacycle bands of frequency, which should amply satisfy the requirements for transmitting the 441-line television signals now envisioned as standard by the television industry.

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