Evolution of Frequency Modulation

EDWIN H. ARMSTRONG

SOME 60 years ago the electric-power industry began the development of a system of distribution which all are now agreed was not the right system. I am referring of course to the low-voltage d-c system. The inevitableness of its replacement by the high-voltage a-c system is now obvious to everyone, although the literature of the transition stage reflects a period of violently conflicting opinion.

A part of the radio industry, in fact by far the largest part, is about to pass through a similar transition. It has become obvious that the present system of broadcasting is not the best, and that its faults are readily curable by the introduction of new technical methods. The characteristics of this new system are such as to provide practically perfect solutions of most of the troubles of the present structure.

Embracing the substance of lectures presented before many AIEE Sections and other groups, and particularly of an address delivered at the 1940 AIEE Pacific Coast convention, this article by the inventor indicates briefly how the frequency-modulation system of radio communication differs from the present amplitude-modulation system, traces the history of this new system, points out its advantages over the amplitude-modulation system, and indicates the extent of its probable applications in the future.

These faults are, specifically referring to the broadcast industry: the interruption or marring of the transmission by natural (lightning) or man-made static; the inability either to transmit the full musical range because of a lack of available channel space in the frequency spectrum, or to transmit that part which can be transmitted with full fidelity; the drastic mutual curtailment of the service ranges of two stations on the same wave lengths, even though separated hundreds of miles; and the distortion of the reproduction at certain points in the transmission paths by a phenomenon of propagation known as selective side-band fading. These difficulties and disabilities of present-day broadcasting are about to disappear with the introduction of a new system which has become popularly known as "frequency modulation," although much more is involved than a method of modulation per se.[1] Some 15 broadcast stations employing this system are now in operation and some hundreds are projected.

The problems solved are not merely technical ones. Since the system is primarily adapted for use in the ultra-high-frequency part of the spectrum, so much new frequency space becomes practically available that it has become possible to allot channel facilities to every town in the country. The factor that determines whether a community may have a station to serve its local needs is no longer the availability of channel space, but the economic ability of the community to support it. The development of local broadcast service within these smaller communities will play an increasingly important part in the broadcasting of the future.

MODULATION

Modulation in radio signaling is the process of changing some characteristic of the radio wave in accordance with the intelligence to be transmitted. The earliest form of modulation was the interruption or the breaking up of the radiated energy into the long and short pulses of the Morse code by means of a telegraph key, although in those days the term "modulation" was not used. Subsequently, with the introduction of continuous-wave generators, as distinguished from the "damped" wave or spark type of transmitter, it became possible to superimpose the characteristics of the voice or music on the radio wave. The method employed followed closely upon an early form of wire telephone transmission in which the strength of a current flowing through the line was varied in accordance with the tones of the voice, the number of times per second the direct current was "modulated" above and below its normal value corresponding to the frequency of the tone to be transmitted (considering, for example, a single tone), and the magnitude of the change corresponding to its loudness. In the earliest form of radio telephony the strength of the antenna current at the transmitter (in this case alternating several hundred thousand or more times per second) was varied in amplitude by a microphone connected in the path of the current. At the receiver, in the circuits of which currents corresponding in form to those transmitted were flowing, the variations in the amplitude of the high-frequency current were converted by means of a rectifying detector into currents corresponding in frequency and amplitude to those which the microphone would have created were it "modulating" a direct current. These currents may be observed in an ordinary telephone receiver.

The difficulties of handling large antenna currents by either a single microphone or a group of microphones led to various proposals for another form of modulation known then as "wave length" modulation. In this method, the amplitude of the antenna current remained unchanged, but the wave length or frequency was periodically increased above and decreased below a certain resting value,

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1. For numbered references see list at end of article.

the number of times per second the frequency was swung about the midpoint being determined by the frequency of the tone to be transmitted, and the extent of the change above and below (or the "deviation" from) the mid-frequency point being proportional to the strength or loudness of the tone. It was proposed to effect this kind of modulation at the transmitter by changing the inductance or capacitance of the circuit controlling the frequency of the oscillation generator by means of some electrostatic or electromagnetic microphone. Since no change in amplitude of the radio wave was produced, the transmission could not be received by the ordinary means. It was proposed to effect reception of waves with this type of modulation by causing the changes in frequency in the received wave to produce changes in amplitude by the use of mistuned selective circuits so that as the incoming variable-frequency current came closer into or receded farther from the resonant frequency of the selective circuit, the amplitude of the currents therein would be correspondingly varied and so could be detected by the usual rectifying means. No practical success attended these proposals, and the literature attests the fact that the early art struggled on with amplitude modulation. About 1914 the advent of the vacuum-tube modulator so completely solved the problems of amplitude modulation that for almost a decade frequency modulation was forgotten.

In 1922 the possibility of its use as a means of reducing the band width required to transmit a given range of frequencies was examined mathematically by Carson[2] who dispelled the illusion that a saving in spectrum space could be obtained over that required by the amplitude-modulation method. Carson proved that at least the same and usually a greater space was required by the frequency-modulation method. Other conclusions unfavorable to the frequency-modulation method were reached. The principal conclusions were subsequently confirmed by other mathematical treatments.

"STATIC"

The major problem of radio signaling for about 30 years has been the interference caused by various forms of natural and man-made electrical disturbances. While radio communication has always been subject to disturbances during lightning storms, the introduction of the vacuum-tube amplifier and the regenerative circuit in 1912 made the problem an ever-present one, as almost any signal could be received, however weak, provided it could be separated from the disturbing impulses which likewise, however weak, were always present. With the coming of broadcasting, which brought the location of the receiving system into areas where high levels of "man-made static" existed, and with the improvements in the sensitivity of the receivers themselves, which finally reached a point where fluctuations in the flow of electrons in the early stages of the amplifier circuits became capable of producing disturbances, the noise problem became the all-pervading one in the art.

Realization of the nature of the problem by those engaged in its study developed slowly. Following the introduction of the new methods of reception in 1912, a vast amount of work was done on the theory that the disturbing waves of natural origin were different in kind from those used in signaling and that circuit arrangements could be devised to differentiate between them. The patent literature of the art of this time furnishes an illuminating illustration of the amount of ingenuity that can be exercised along lines of unsound theory.

It was finally realized that the nature of these disturbances is that of a spectrum which contains all component frequencies, some of which always coincide with those being used in any particular case for transmitting the signal. Carson placed the matter on a quantitative basis in 1925.[3] Subsequently it was shown that many of the man-made disturbances are similar in make-up to those of natural origin and finally that the constitution of the disturbances originating in the irregularities of the motion of the electrons in tubes and circuits is likewise that of a spectrum. The amount of energy absorbed by any electrical system subjected to disturbances of this character depends on the width of the frequency band passed by the selective circuits of the system. Consequently it became a principle of design to make the admittance band of a receiver just sufficiently wide to pass the frequency components necessary to convey the signal, and no wider. The presence of the residual noise came to be accepted as a necessary evil.

Subsequent to the publication of the 1925 Carson article,[3] it occurred to the writer that the use of a system of signaling in which only changes in frequency of a transmitted wave could be observed in a receiver (which was made nonresponsive to amplitude changes) might furnish a means of distinguishing between the desired and undesired currents. An experimental investigation under actual working conditions using a receiver provided with a device for limiting out amplitude changes led to the conclusion that the currents set up in the receiving system by the waves of natural origin were modulated in frequency as well as in amplitude and that no major improvement could be thus effected. These observations were made with the frequency band width of the transmission and reception kept to the narrowest possible limits.

During the course of this work, however, an observation was made which seemed to indicate that the changes in frequency of the disturbing currents were limited in extent. This suggested the idea that if the transmitted wave were modulated widely in frequency and if the receiver were made nonresponsive to amplitude changes, feebly responsive to small changes in frequency, and fully responsive only to the wide frequency changes of the signal, a means of differentiating between desired and undesired currents might be found. With this relatively crude conception of a possible solution the necessary experimental work was undertaken. It resulted in the discovery of a new principle in noise reduction, the application of which furnishes an interesting conflict with the principle that had been the guide to the art for years. In accordance with this principle it was found that in a frequency-modulation system which is not responsive to amplitude changes within its working limits (noise not greater than one-half the signaling current), the wider the band used in trans-

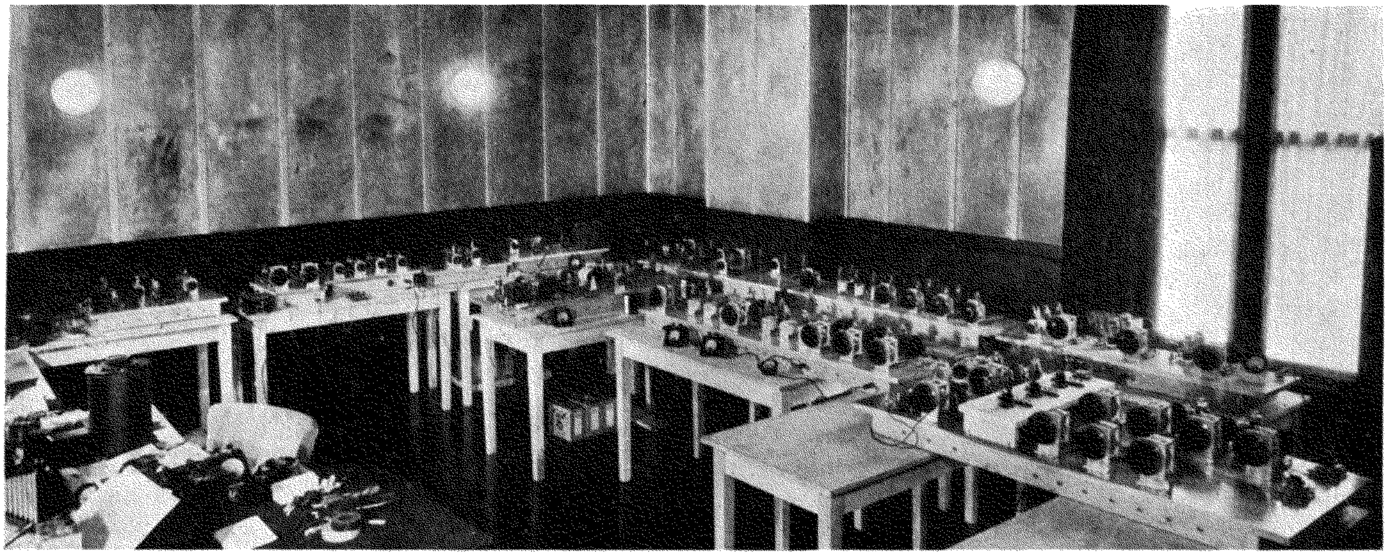


Figure 1. Frequency-modulator setup in shielded room used in early experimental work

mitting the signal the better the signal-to-noise ratio. The power gain of the signal-to-noise ratio increases as the square of the frequency band width used, and gains of a thousandfold or more can be realized in practice. Now the actual mechanism of the process by which the gain is achieved is much more involved than the foregoing explanation would indicate. It may be treated in various ways, but it is beyond the scope of this article to examine it in detail. A full explanation may be found in the writer's paper[1] presented before the Institute of Radio Engineers in 1935. The recent AIEE paper by Everitt likewise contains a detailed explanation.[4] Further reference to this process will be made hereinafter.

TRANSMITTING AND RECEIVING METHODS

In order to carry out the experimental investigation just mentioned, it was necessary to produce both transmitting and receiving equipment. An extensive experience with the known methods of obtaining frequency-modulated signals and their shortcomings led to the development of a new method which gave a complete solution to the problem of producing large frequency changes of a carrier at the relatively high frequencies where of necessity the new system had to operate in order to find available channel space. This method consists in employing the modulating current to shift the phase of a current derived from a source of fixed phase and frequency (usually about 200 kilocycles) by an amount directly proportional to the amplitude of the modulating current and inversely proportional to its frequency. The resulting phase shift is then multiplied several thousandfold by means of a series of frequency multipliers. By keeping the initial phase shift below 30 degrees substantial linearity can be obtained. Some three to five thousandfold multiplication is required in order to give an over-all frequency swing of 150,000 cycles at a transmitting frequency of 40 megacycles. Since it is desirable to perform the initial phase-shifting operation at a frequency of the order of 200,000 cycles the multiplication is carried out in two stages. The first stage usually converts its 200-kilocycle input to 12.8 megacycles; this frequency then is heterodyned with a frequency differing from 12.8 megacycles by a submultiple of the frequency which it is desired to transmit. Where the transmitter frequency is of the order of 40 megacycles the submultiple frequency may be of the order of 600 to 900 kilocycles. This current is then passed through a second series of multipliers until the desired output frequency is obtained, where its power is increased to any required amount by a series of amplifiers.

The receiving equipment follows amplitude-modulation

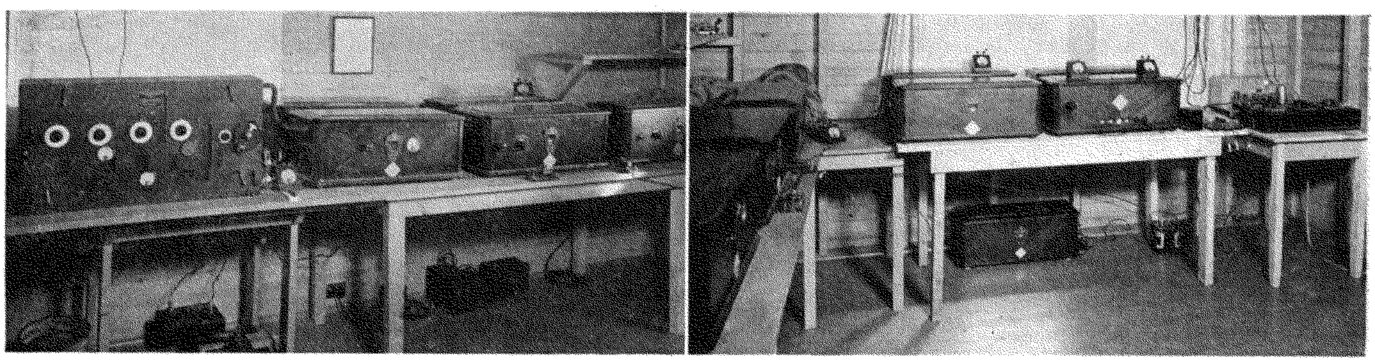


Figure 2. Early experimental frequency-modulation receiving equipment

practice along certain general lines. The superheterodyne method of reception is employed with two additional pieces of apparatus. The first detector or converter of the superheterodyne and the intermediate-frequency amplifier follow standard practice with the exception that the intermediate amplifier has a much broader frequency-band width and greater amplification than in the ordinary amplitude-modulation system. One of the two additional pieces of apparatus is a device for removing changes in amplitude from the received wave so that only pure frequency-modulated current is passed on for detection. This device is generally an overloaded vacuum-tube amplifier in which the screen and plate voltages are reduced to cause the tube to give a limited output; hence it is commonly referred to as a "limiter". It is connected to the output of the intermediate-frequency amplifier and usually requires several volts to be applied to its grid for effective operation. The second device is an arrangement of circuits in which the transmission characteristics with respect to frequency vary linearly over the range of the intermediate frequency through which the signal sweeps. It is placed after the limiter and before the detector, and its function is to convert the frequency changes linearly into amplitude changes. The name "discriminator" is commonly applied to this kind of device. Usually a differential or balanced type of detector is employed.

FIELD TESTS

The many years of research required to test out the principle were carried out in the Marcellus Hartley Research Laboratory at Columbia University, New York, N. Y. Since both ends of the system of necessity had to be under simultaneous observation, the transmitting and receiving equipment were located in adjoining rooms, the distance over which signals were transmitted being some 50 feet. During the winter of 1933–34 the system was demonstrated in the laboratory to the executives and engineers of the Radio Corporation of America for several months. Laboratory experiments in the "static eliminator" field being subject to quite justifiable suspicion, the transmitting equipment was removed from Columbia in the spring of 1934 and installed at the National Broadcasting Company's station located at the top of the Empire State Building in New York. This station had a 2-kw 44-megacycle transmitter which was originally intended for television, but which was not in use at the time. It was modified so as to transmit the wide-band frequency-modulation signals. Two modulators of the type heretofore described are shown in figure 1. They were located in a shielded room adjacent to the power-amplifier equipment and hence could be operated in the open as shown. The receiving system was located at Westhampton Beach, Long Island, about 70 miles from New York City. Figure 2 shows the receiving equipment as installed there in June 1934. The excellence of the results obtained in the initial tests surpassed all expectations, perfectly quiet reception being secured through the heaviest thunderstorms when all the standard broadcast services had been rendered utterly useless. As Westhampton Beach was obviously too favorable a site, the receiver was removed in July to Haddonfield, N. J., near Camden, a distance of about 85 miles from New York, where successful operation likewise was obtained.

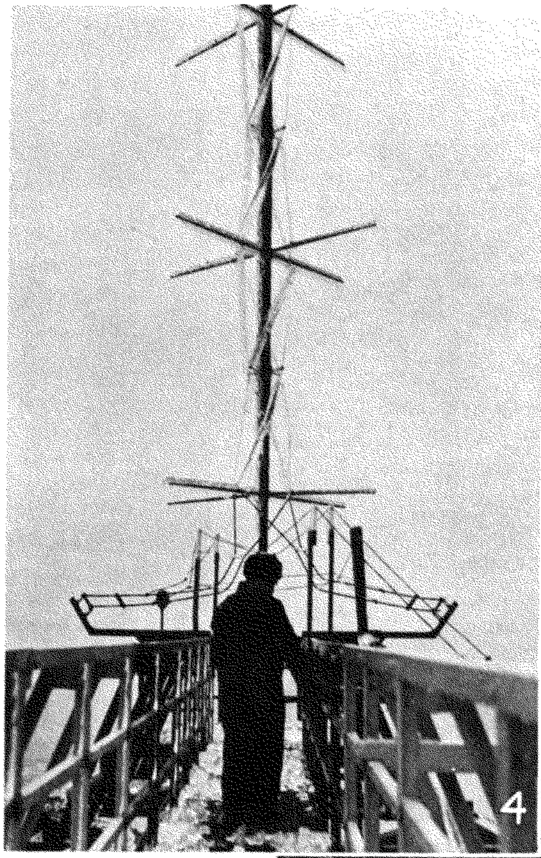
In all these tests much greater improvement in the signal-to-noise ratio was obtained than the thousandfold gain heretofore referred to, as in addition to the improvement due to the use of frequency modulation much less static is encountered on the ultrahigh frequencies than in the standard broadcast band. A pleasant surprise was the establishment of the fact that ultrahigh-frequency transmission, contrary to the accepted belief, did not stop abruptly at the horizon (about 45 miles for the Empire State tower) but could be successfully received up to at least three horizons. The complete absence of all the effects of selective side-band fading from which the standard band suffers was proved, and all the fears of limited coverage were set at rest.

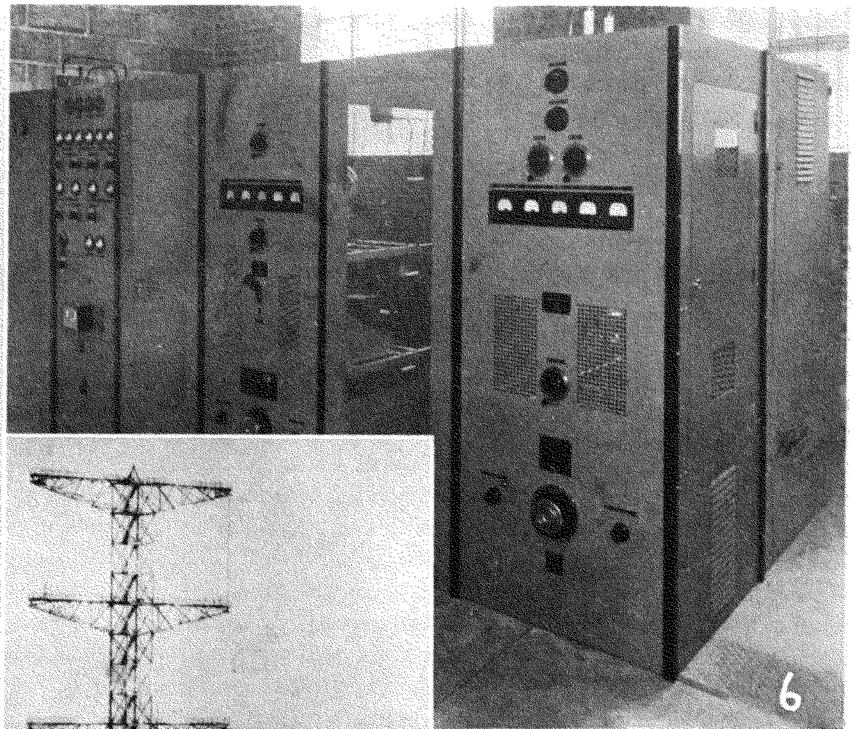
Up to this point the development of the system had proceeded in a normal way, similarly to the pattern followed in the introduction of many other inventions into American radio. However, numberless objections began to be raised regarding the utility of the new system; and although for over a year and a half tests were conducted under all conceivable conditions and repeated demonstrations and comparisons with the existing broadcast system carried out, the Radio Corporation declined to put the invention into public use. The Empire State transmitter was withdrawn from further frequency-modulation tests.

Work therefore was transferred to an amateur station W2AG located in Yonkers, N. Y. This station was equipped by its owner, C. R. Runyon, to operate on 110 megacycles and was used to demonstrate the system to the Institute of Radio Engineers in November 1935, on the occasion of the presentation of a paper[1] describing the system.

Next, application was made to the Federal Communications Commission for permission to construct a high-power 40-megacycle transmitter the success or failure of which would remove from the realm of academic discussion all questions concerning the efficacy of the system. The necessary authoritv was obtained at the end of 1936 and construction was started in the spring of 1937. The erection was completed and testing started in the fall of 1938. In the intervening time scores of demonstrations carried out from the Yonkers station, W2AG, were made to the representatives of the broadcast industry. As a result of these the Yankee Network decided to enter the field and proceeded with the construction of a station near Worcester, Mass. (Mt. Asnebumskit, Paxton). At about the same time, the management of Station WDRC at Hartford, Conn., entered the field with the erection of a station on Meriden Mountain, Meriden, Conn. Shortly thereafter the General Electric Company, as a result of the W2AG demonstrations, became interested and carried out and published the results of a long series of tests confirming the conclusions arrived at during the Empire State field tests.

The Alpine transmitter was ready for preliminary testing during the summer of 1938. All expectations were more than fulfilled and in the summer of 1939 the sta-





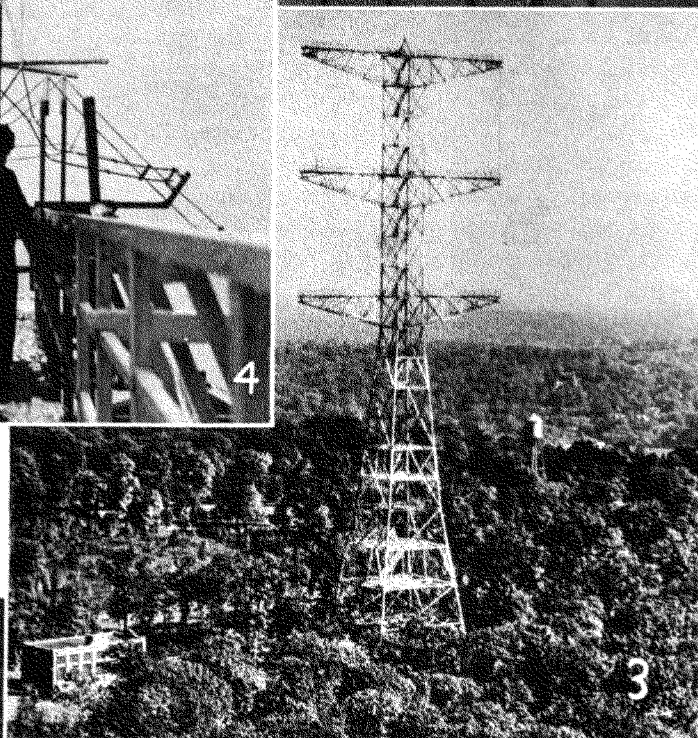
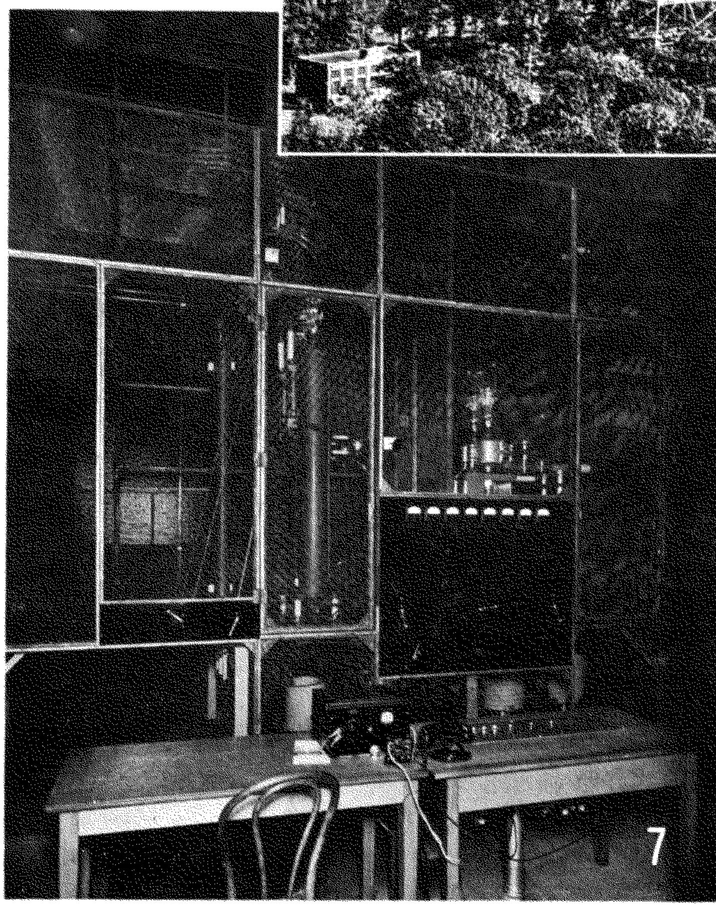
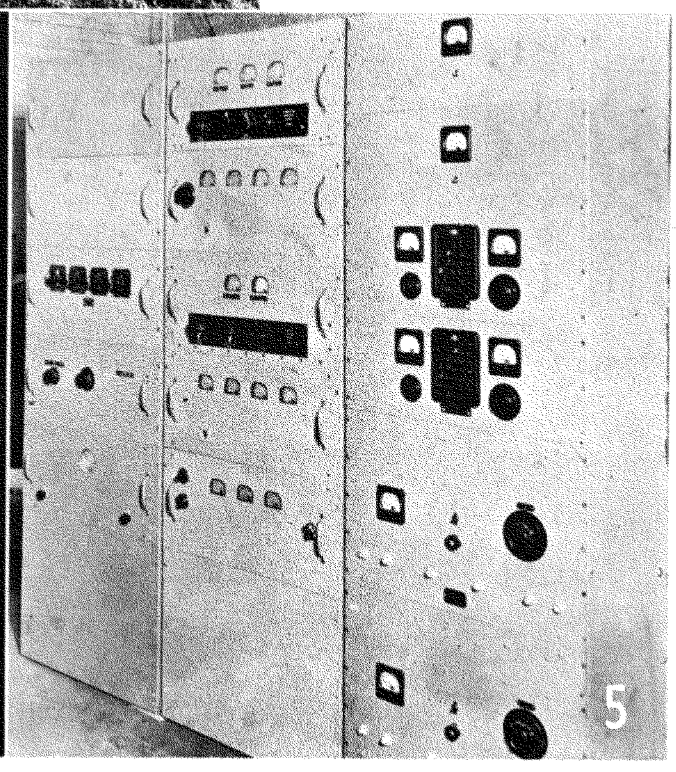


Figure 7. Last two power - amplifier stages

Figures 3–6. Frequency-modulation transmitter built at Alpine, N. J., by the author during 1937–38; note antenna between extremities of two upper arms (3); antenna structure, after a sleet storm (4); modulating equipment (5); frequency multipliers and low-power amplifiers (6)





tion was placed on a regular operating schedule. A general idea of the transmitter as originally installed is given by figures 3 to 7. Since height above the surrounding terrain is of primary importance in ultrahigh-frequency transmission, the site selected was on the cliffs on the west side of the Hudson River known as the Palisades. A point about 500 feet above the river 17 miles north of New York in the village of Alpine was chosen. The antenna structure of the Alpine station is illustrated in figures 3 and 4. The height of the tower above grade is 400 feet. The length of the three cross arms is 150 feet and their vertical separation slightly over 80 feet. The radiating members of the antenna consist of a series of seven pairs of crossed rods about 11 feet long which are mounted on a boom supported between the tips of the two upper arms. These crossed rods or "turnstiles" are separated slightly less than half a wave length and are fed by a series of transmission lines which wind around the supporting member. The whole antenna is fed by an open-wire transmission line of about 500 ohms impedance which runs vertically through the center of the tower and horizontally over to the transmitter building for a total distance of about 700 feet. The efficiency of transmission appears to be of the order of 90 per cent.

The modulating equipment, similar in type to the "bread board" setup of figure 1, is shown in figure 5. The modulator is entirely contained in the center rack, the left-hand rack housing the ordinary line amplifiers, and the right-hand rack housing the power-supply equipment for operating the modulator and other units. Figure 6 shows a further series of frequency multipliers and low-power amplifiers for raising the power to a level of 1 kw at 40 megacycles. The last two power stages employ water-cooled tubes which raise the power respectively to 3 kw and to 40 kw. Figure 7 shows these amplifiers as installed in a shielded cage, which is necessary for the protection of the operating staff from the high field strength. The modulating and low-power units shown in these illustrations were built by the Radio Engineering Laboratories and the two high-power amplifier units by the RCA Manufacturing Company.

In the summer of 1939 the Paxton (figure 8) and Meriden transmitters were completed; and when they and the Alpine transmitter were placed on a regular operating schedule so that their performance could be observed daily, the broadcasting industry became convinced that a change was imminent. A dozen more stations were constructed and applications for over 150 more were on file with the Federal Communications Commission by the fall of 1939, when it was alleged that improper standards were being employed and that a band width narrower than 200 kilocyles could be employed more effectively. The granting of further construction permits was suspended pending an investigation by the Commission of this question and the question of providing additional channel space to accommodate the large number of applications for licenses. A public hearing by the Commission in March 1940, resulted in the approval of the 200-kilocycle band, the rearrangement of the allocation plan to increase substantially the assignment of channel space (42–50 megacycles) and the decision to grant commercial licenses. The Communications Commission has now resumed the issuance of licenses, and some 15 permits for commercial instead of merely experimental operation, have now been granted.

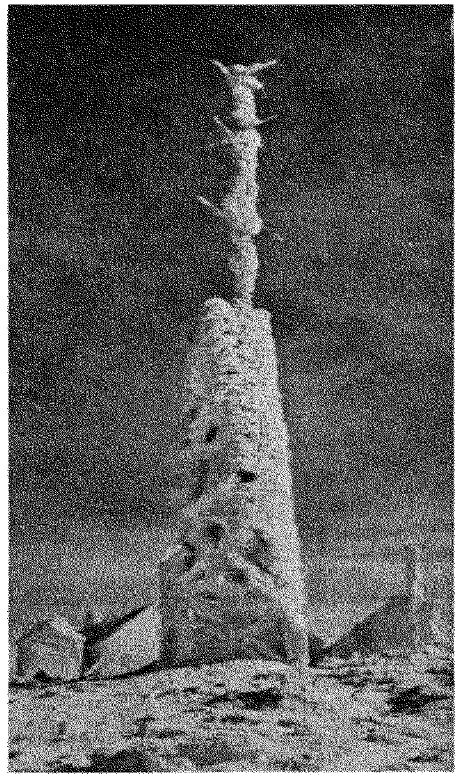
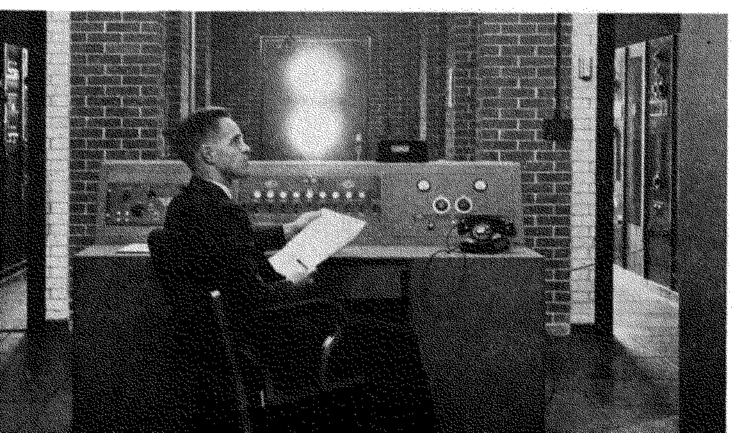


Figure 9. Winter condition of experimental frequency-modulation antenna atop Mount Washington, N. H.

Figure 8. Interior of Paxton, Mass., transmitter building



RELAYING

At the present time the wire-line facilities available for linking radio stations into networks are limited to the transmission of a frequency range up to about 5,000 or 6,000 cycles and have a residual noise level considerably greater than that required for the full dynamic range of even ordinary studio orchestral productions. Approximately the same limitation is imposed on the present-day radio stations by the lack of available frequency space and by the noise problem which results when receiver circuits and speaker systems are adapted to reproduce the full audio range of 15,000 cycles. These limitations are not imposed on the frequency-modulation system since the band width used is much in excess of the range of frequencies to be transmitted and the low noise level permits the effective reproduction of the weakest overtones. Residual noise in the transmitting equipment is now better than −70 decibels, so that the signal-to-noise ratio over a large part of the service range of a high-power station can be held below this level. Since the bottleneck, at the present time and perhaps for a long time to come, lies in the wire connecting links, various radio relaying projects have been started.

The first of these was initiated by the Yankee Network to transmit the programs originating in its Boston studios to the top of Mt. Asnebumskit. The air-line distance is approximately 45 miles. Preliminary estimates of the cost of construction of the type of wire line required were in the neighborhood of $70,000, with doubtful guarantees of the noise level. The problem was solved by the use of a frequency-modulated 250-watt 130-megacycle transmitter located on the roof of the six-story studio building, arranged with a directional antenna to beam the transmission toward Paxton. At the receiving end a directional array likewise adds to the efficiency of the circuit.

The initial cost of the installation was a fraction of the estimated cost of the line, its maintenance cost is negligible, and its performance far better than could be obtained with any line facilities that could be furnished, even at the cost mentioned. The circuit has been in operation for over a year and has functioned perfectly through even the heaviest thunderstorms. Experience with this circuit has indicated ways of cutting the cost markedly. A second relay project which the Yankee Network is carrying out is the construction of relay stations to rebroadcast the Paxton transmissions. The first of these to be erected is located at the summit of Mt. Washington in northern New Hampshire, about 130 miles from Paxton. For over six months of the year the climate at the summit of this mountain is one of the severest in the world, winds of over 200 miles an hour with extremely low temperatures being frequently encountered together with a type of ice formation that imposes great mechanical stresses on the antenna structures. Two years ago a 100-foot tower was erected and a small transmitter installed to determine the practicability of the operation of ultrahigh-frequency transmission from an antenna the normal winter condition of which is shown in figure 9. Two winters' experience has resulted in a solution of the problems involved and a one-kilowatt frequency-modulation transmitter is now installed on the mountain (to be increased to ten kilowatts in the spring); regular operation will begin about November 15. The performance of this station will be watched with much interest throughout the radio world. A similar station located on a mountain in northern Vermont will complete the coverage of the northern half of New England. Several similar networks are projected in the southern Atlantic and the Pacific Coast states.

Another relaying circuit is now in daily operation between Alpine, N. J., and Meriden Mountain, Conn., and Alpine and Helderburg Mountain, N. Y., the station of the General Electric Company near Albany. The distances involved are about 70 and 130 miles, respectively. At the Helderburg station reception is effected in the ordinary way, and the recovered audio signaling current at a remotely located receiver is sent over a telephone line to the transmitter where remodulation occurs in the ordinary manner. At the Meriden station the 42.8 megacycles of the Alpine transmission is converted to the Meriden frequency of 43.4 megacycles and amplified up to excite the final power amplifier without the necessity of creating any audio-frequency current in the process. It has been found possible to do this with the receiving antenna located within 100 feet of the transmitting antenna, and the elimination of the processes of detection and remodulation has resulted in the removal of the distortion incident to these operations.

The future undoubtedly will see the introduction of chains of relaying stations equipped with highly directional antenna arrays operating on frequencies considerably higher than those used in broadcasting.

TRANSMITTING AND RECEIVING EQUIPMENT

Great improvement and simplification has been effected in the design of both transmitting and receiving equipment since the building of the initial transmitter at Alpine. It has been found possible to eliminate the intermediate water-cooled power stage and to drive the final 50-kw amplifier directly by a 2-kw air-cooled amplifier stage, this in turn being driven by a pair of 250-watt high-amplification beam tubes, all operating on 40 megacycles. The beam tubes are readily driven by a pair of triplers operating with a power output of 10 to 20 watts. Perfectly stable and reliable operation is obtained with this arrangement of the exciter stages. Figure 10 shows a complete modulating and exciter unit (2 kw). Figure 11 shows the 50-kw amplifier unit for the Paxton station during construction. These units together with the power-supply racks for the high-power amplifier are all that is required for the production of 50 kw of frequency-modulated power.

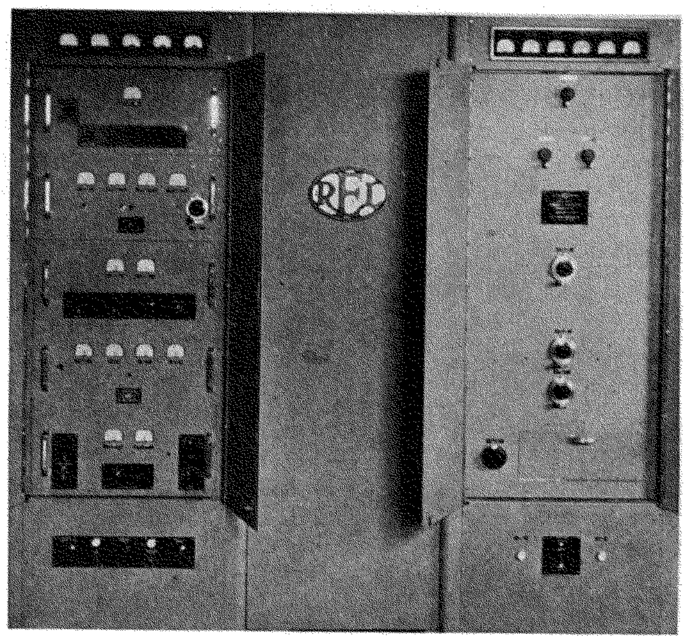


Figure 10. Modulating and power amplifier units of complete two-kilowatt transmitter

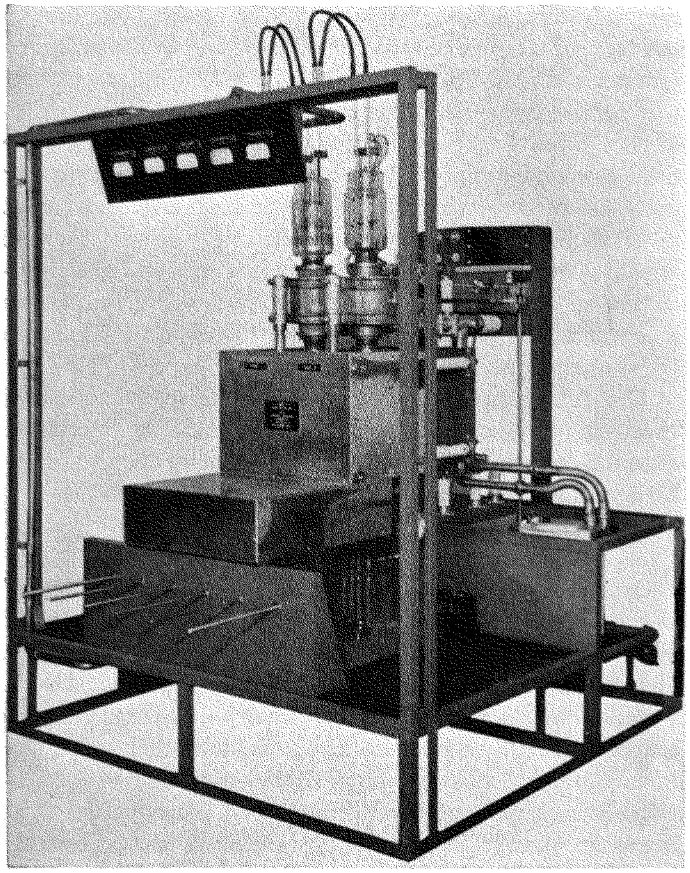


Figure 11. Power-amplifier unit of 50-kw frequency-modulation transmitter before mounting in shielded room

Similar progress has been made in receiver design, figure 12 showing a general-purpose receiver which operates effectively on a field strength of about ten microvolts per meter and gives an undistorted audio output of about 15 watts (a few watts only is necessary for home reception). Ten tubes are used, but with the production of double-purpose tubes specially designed to meet the requirements of this type of receiver further reduction in the number of tubes and parts is possible.

At the present time intensive commercial development of both transmitting and receiving equipment is under way, the General Electric Company and the Western Electric Company being now in position to supply transmitters and some dozen receiver manufacturers having on the market sets adapted to receive both the frequency-modulation and standard-broadcast amplitude-modulation transmissions.

SOME UNIQUE CHARACTERISTICS

There are some characteristics that are unique in the frequency-modulation system which have no counterpart in amplitude modulation. It is, of course, well known that when the carriers of two amplitude-modulated transmitters are sufficiently close in frequency to produce an audible beat, the service range of each of them is limited to that distance at which the field strength of the distant station becomes approximately equal to one per cent of the field strength of the local station. As a consequence, the service area of each station is greatly restricted; in fact, the service area of the two stations combined is but a small percentage of the area rendered useless for that frequency by the presence thereon of the two interfering stations.

With the wide-band frequency-modulation system, however, comparable interference between two transmissions does not appear until the field strength of the interfering station rises to a level of between 25 and 50 per cent of the field strength of the local one. The reason for this lies in the fact that while the interfering signal, in beating with the current of the local station under such conditions, may be producing a large change in the amplitude of the voltage applied to the current limiter, the system is substantially immune to such variations in amplitude. The only way in which the interfering signal can make its presence manifest is by superimposing some modulation of frequency on the frequency variations of the local signal. Under the conditions this "cross modulation" or phase shift superimposed upon the signaling current is limited to something of the order of a 30-degree change in phase, and the characteristics of the wide-band receiver are such that at least within the range of best audibility a phase shift of thousands of degrees in the signaling current is necessary to produce full modulation. Hence the 30-degree interfering phase shift superimposed upon the signaling current will produce little change in the rectified or detected current. As a consequence, the interference area in territory served by two frequency-modulation stations on the same channel is greatly reduced, as compared with amplitude modulation, and becomes, in fact, less than the area usefully served.

This property of the system, coupled with the fact that the propagation limits of ultrahigh frequencies are more sharply defined than those of the present broadcast frequencies, makes it possible to operate stations occupying the same channel space with much less geographical separation. Where desirable, it will be found practical to operate stations from 25 to 50 miles apart.

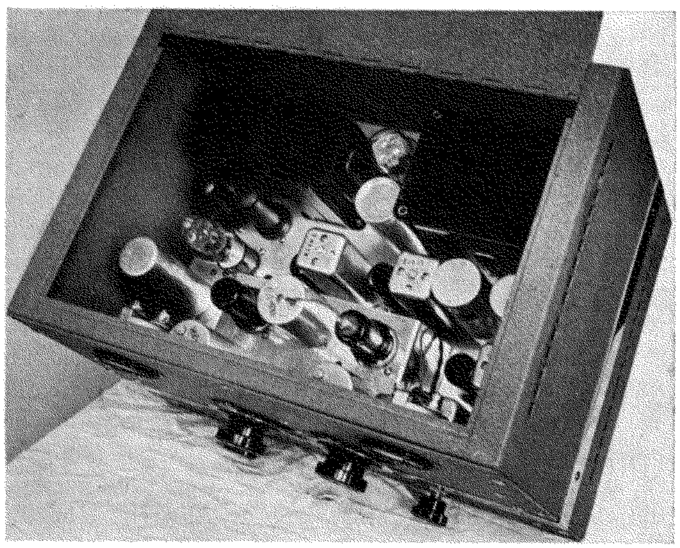


Figure 12. General-purpose frequency-modulation receiver having an undistorted audio output of about 15 watts

There is likewise a fundamental difference in the factors that govern distortion in the amplitude- and frequency-modulation equipment. Provided the circuit constants are properly designed for the frequency of the signaling currents, distortion in an amplitude-modulated transmitter or receiver depends principally on the linearity of the characteristics of the vacuum tubes employed. In frequency modulation, distortion is practically independent of the linearity of all the tubes that handle radio-frequency current and is dependent only on the phase shift introduced by the circuit components. These can be more readily designed and maintained to keep distortion below a desired limit. As a consequence, not only can aural effects be transmitted and reproduced with great fidelity, but the system is well adapted for multiplexing. It has been found possible to transmit simultaneously both an aural and facsimile program without interference between the two, the facsimile transmission being carried out on a channel of superaudible frequency. This was accomplished as early as 1934 over a distance of 85 miles in the original tests using the two-kilowatt transmitter at the Empire State Building in New York.

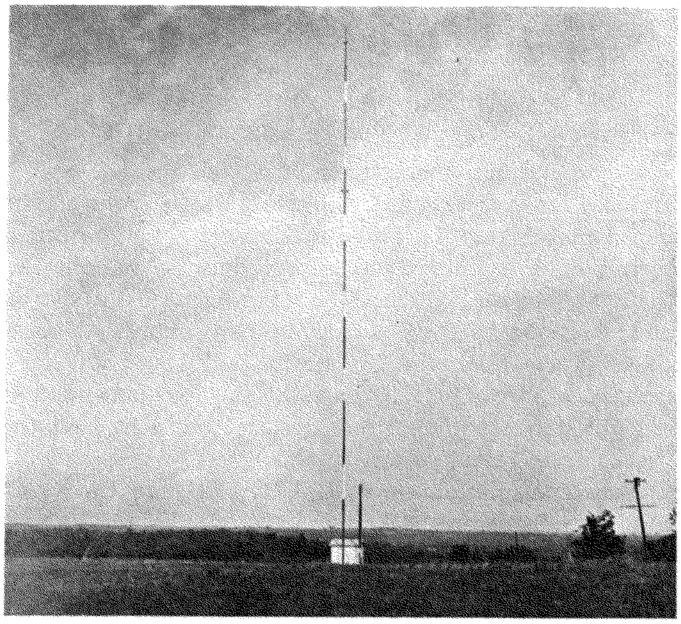


Figure 14. Connecticut State Police system: two-way 250-watt station at Wilton, Conn.

APPLICATION TO SERVICES OTHER THAN BROADCASTING

The system has important applications to various types of emergency communication services. Since the transmission of intelligible speech requires a much smaller range of frequencies than the full musical range—in fact a range of perhaps only 250 to 3,500 cycles—a smaller deviation of the transmitted frequency may be employed. It has been found practicable to make use of a total band width of 40 kilocycles in police service, and several installations are now operating effectively.

The largest project at the present time is that undertaken by the Connecticut State Police, who have in operation nine fixed stations and approximately 200 mobile stations equipped for two-way operation. The fixed stations are located on hill tops and have 250 watts power output. The car transmitters have approximately 25 watts power output. Thirty-mile communication between the cars and the fixed stations and five- to ten-mile communication between cars is easily obtained. This system was designed by Professor Daniel E. Noble (A'32) of the University of Connecticut. (See figures 13 and 14.)

The next largest project to be undertaken is in the city of Chicago, where some 200 mobile 25-watt car units are being installed. Numerous other projects for police services and for emergency-service use by power companies are being made, and it is doubtful if many new installations employing amplitude modulation will be made in the future. It is, of course, needless to say that there are many important military uses. In fact, in practically all ultrahigh-frequency applications where weight or portability is not too great a factor, the frequency-modulation system has found increasing use. The one important field where progress has been inexplicably slow has been television, where its advantages, particularly on the sound channel, could be effectively utilized. A limited use has been made in the relaying of the television sight channel.

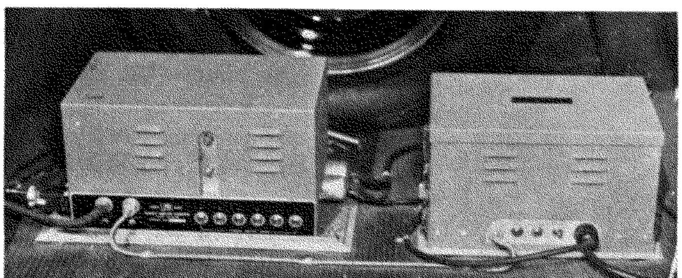


Figure 13. Transmitter (left) and receiver in rear interior of car, Connecticut State Police system

CONCLUSION

Five years ago the writer said[1] that "the conclusion is inescapable that it is technically possible to furnish a broadcast service over the primary areas of stations of the present-day broadcast system which is very greatly superior to that now rendered by these stations." With the cost of transmitting equipment for the new system already below the cost of the equipment of the standard broadcast type (for the same power output) and with the cost of broadcast receivers approaching levels that will permit large-scale production and distribution, the conclusion is likewise inescapable that within the next five years the existing broadcast system will be largely superseded.

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