Sky-Wave F-M Receiver

Multipath reception, generally considered more troublesome for f-m than a-m, is explained and a receiver capable of such reception described. Simulated cochannel tests indicate that transatlantic f-m broadcasting is possible with a 150-kc bandwidth

By L. B. ARGUIMBAU and J. GRANLUND

Department of Electrical Engineering*
Massachusetts Institute of Technology
Cambridge, Massachusetts

AT THE PRESENT TIME there are two main technical obstacles to completely reliable transatlantic communication, noise and multipath fading. In a sense these difficulties are merely two aspects of the same problem, that of trying to receive a desired signal in the presence of unwanted disturbances. The disturbances may consist of atmospheric noise, signals from other transmitters or signals from the desired transmitter that arrive from subsidiary transmission paths and interfere with the main signal.

A-M Interference

It has been known for a long time that with amplitude modulation the signal-to-noise ratio is not essentially modified by the detection process. Thus if we wish to suppress interference by 40 decibels in the output of a receiver we must make sure that there is a similar difference in level between the radio-frequency signals. In the case of multipath interference the situation is not quite so serious because in practice the interference from a delayed version of the same audio signal is not usually so bothersome as a totally new signal. However, when the desired and undesired signals are of comparable magnitude, the envelope distortion becomes intolerable.

By the use of proper frequency-modulation equipment and present standards it is possible to reduce the effect of interference by thirty-odd decibels. These facts might

lead one to feel that frequency modulation could be substituted for amplitude modulation under multipath conditions with great advantage.

Early experiments[1, 2] indicated that the contrary is true, that frequency modulation is more highly susceptible to multipath interference than is amplitude modulation. The results were very bad when the signals from the various paths became of comparable magnitude.

This result was not surprising because it has usually been assumed that the advantages of frequency modulation only apply when the signal exceeds the interference by a considerable amount, perhaps by two or three to one. This idea of a threshold perhaps arose from the difficulties of computing the interference from ratios near unity and from the fact that with heavy interference receivers depart from our idealized notions of what they should do.

In the case of multipath transmission, or deep selective fading, the desired signal and the interference are likely to be of comparable

magnitude. It is not safe, therefore, to assume a two- or three-to-one voltage ratio.

Average vs. Instantaneous Frequency

It has been shown by the writers[3, 4, 5, 6] that no such threshold or necessity for difference in level actually exists if a receiver is carefully designed. The reasons for this can be summarized briefly. If two signals of constant but different frequency and of nearly equal amplitude are superposed their sum has an average frequency which is exactly the frequency of the larger signal. However, the instantaneous frequency varies widely. Most of the time the frequency is very nearly the average frequency of the two signals. However, when the two signals are near phase opposition the phase of their sum jumps by approximately 180 degrees in a very short time interval. This gives rise to a frequency spike or impulse. The nature of the frequency variations has been studied carefully by several writers.[7, 8, 9] If two signals of frequencies f_1 and f_2 differ in amplitude by a small frac-
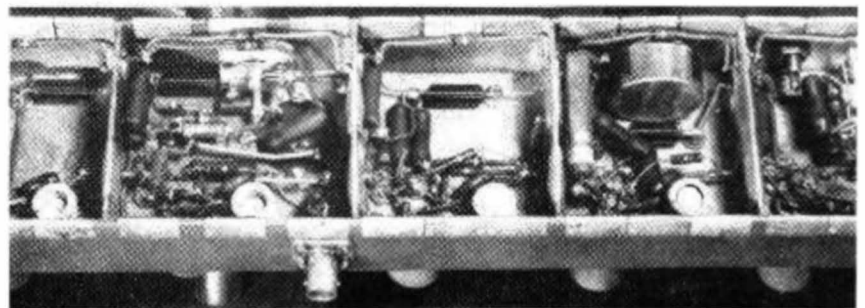
Portion of the receiver built into a 10-cm waveguide for good shielding

tion, $1-a$, then the instantaneous frequency may vary over a bandwidth of approximately $2\left(\dfrac{f_1 - f_2}{1 - a}\right)$ For example, if the two signals differ in frequency by 150 kilocycles and in amplitude by 5 percent a band of around 6 megacycles may be covered.

Of course the frequency spectrum of two superposed signals is merely the sum of the spectra of the two signals and is not widened by linear superposition. However, the amplitude of the combined signal varies from the sum of the two amplitudes to the difference. Our 5-percent example corresponds to an amplitude variation of 39 to 1. If this amplitude variation is removed the resultant constant-amplitude signal has a spectrum corresponding to the variation of instantaneous frequency and in our numerical case covers at least a six-megacycle band.

In order to receive a desired signal in the presence of deep fading or interference we may make a receiver that gives a rectified output which varies linearly with frequency over the widened band regardless of input amplitude. This

should be followed by a de-emphasis circuit and a filter arranged to remove the ultrasonic components generated by the interference.

The Receiver

In order to illustrate the principles involved it may be useful to describe the special features of a receiver designed to separate a signal and noise differing by only a half decibel (5 percent in voltage). In order to give a very good check on the theory, the receiver design has been kept ultraconservative. No effort has been made to use one vacuum tube where three will work as well. The receiver was built in 10-centimeter waveguide, not because this was necessary but because it eliminated shielding problems. The general scheme of the receiver is indicated in Fig. 1.

There is little unconventional in the early portions up to the limiter. This part must supply a signal of fair peak amplitude to the limiter. Furthermore it must have adequate selectivity but must have a very nearly constant response over its 150-kilocycle pass band. This requirement prevents the relative

amplitudes of the signal and interference from changing while their frequencies vary. Failure to use due care at this point may cause the signal and interference to interchange during the audio cycle. In the particular receiver under discussion the response was kept within one percent over this range.

The limiter section consists of four stages, one of which is shown in Fig. 2. It is capable of removing the 39-to-1 variations in amplitude corresponding to the 5-percent margin even when these occur at a 150-kilocycle rate. In fact, such amplitude variations are reduced to something like one percent, a total 70-decibel reduction of amplitude variations. The limiter has a flat response over a bandwidth of 6 megacycles centered at 13.

The discriminator circuit is shown in Fig. 3. This rather unconventional arrangement was used in preference to the more usual Foster-Seeley circuit. Its chief relative advantage is that it is much less subject to diagonal clipping by the detectors. The single radio-frequency bypass capacitor, C, is alternately charged and discharged
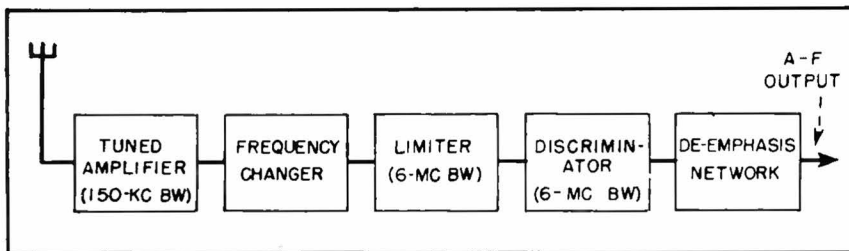

FIG. 1—Block diagram of long-distance f-m receiver showing the main circuit elements and bandwidths required
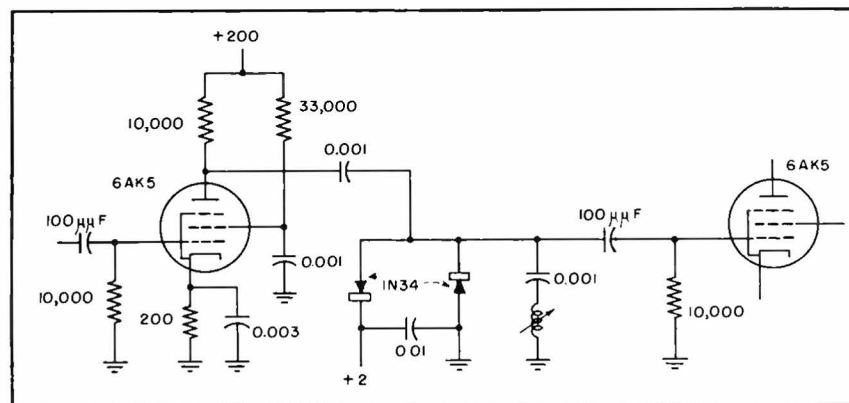

FIG. 2—Representative limiter stage. There are four similar stages used in the prototype receiver to reduce amplitude variations
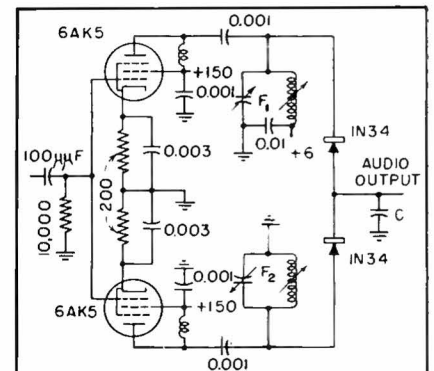

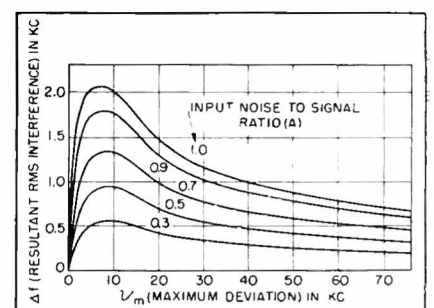FIG. 3—Discriminator with no resistors in active circuits

FIG. 4—Interference as a function of transmitter deviation

by the crystal diodes as they take turns in conducting. The rates of charging and discharging the capacitor are alike. It must be remembered that diagonal clipping is a serious problem in the present receiver, since its output must follow faithfully the extremely rapid fluctuations of instantaneous frequency.

It will be noticed that no resistors are indicated in the active part of the detector circuit, either in the two tank circuits or shunting the bypass capacitor, C. Under these loss-free conditions the output varies linearly with frequency between f_1 and f_2, the resonant frequencies of the two tank circuits. The alignment procedure consists simply of tuning the two tuned circuits so that $f_2 - f_1$ is the desired bandwidth, and $\frac{1}{2}(f_2 + f_1)$ is the desired center frequency.

A necessary condition for proper operation is that both diodes conduct during each radio-frequency cycle. If this condition is fulfilled, the output at a particular frequency is proportional to the bias (6 volts in this circuit). The output is not proportional to the instantaneous signal amplitude. Thus it is seen that a limiter stage is incorporated in the discriminator.

RMS Interference

In the foregoing paragraphs we have indicated that with an ideal receiver, interference can be kept very small. It is not difficult to show that the signal-to-noise ratio at the output of the receiver is increased relative to that at the input by a factor very roughly equal to the ratio of peak frequency deviation to de-emphasis frequency, as long as the signal is greater than the interference.

A somewhat more careful analysis gives the results shown in Fig. 4. These curves were computed for the case in which a sinusoidally modulated signal is interfering with an unmodulated signal. The abscissas show the peak deviation of the interfering signal and the ordinates show the equivalent peak frequency deviation of the resultant root-mean-square interference. Notice that the largest interference is about 2 kc, a value which should be compared with the peak swing of
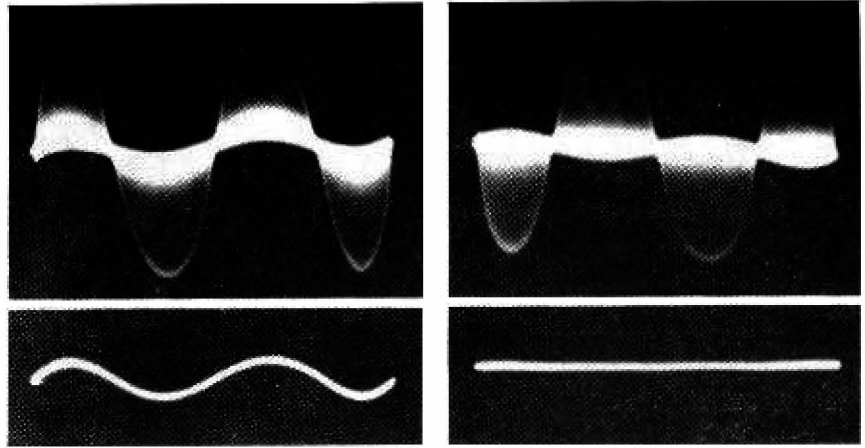

FIG. 5—Simulated transatlantic reception showing unfiltered (above) and filtered (below) signals with input noise-to-signal ratio 0.9 (left) and 1.1 (right)

75 kc. Notice that the ratio corresponds to a suppression of 36-to-1 or about 31 decibels.

Although these results were computed for cochannel interference with only the interference modulated, they are directly applicable to multipath conditions provided the abscissas are found by multiplying the peak signal deviation by twice the sine of half the audio delay angle between the paths. In the worst case this means that the abscissas are doubled without change in the ordinates.

In order to simulate a transatlantic link an ultrasonic mercury delay line[10] corresponding to about 100 miles of space or a half millisecond was paralleled with a capacitive attenuator. When it was tried out with amplitude-modulated signals the combination gave the selective fading that is so characteristic of transatlantic reception.

Under frequency-modulation conditions the results given by Fig. 4 checked fairly closely. Listening tests showed that reception comparable to local broadcast quality is possible as long as the level difference between the paths is less than a half decibel. The chief interference observable is a relatively high-pitched swishing noise, the audible residue of the frequency spikes.

When more than two paths are present the results are similar unless the peak value of the interference exceeds the strongest path. Even in this case the resultant interference is not very bad unless the total interference exceeds the largest signal by something like fifty

percent. A small excess is tolerable.

Although the receiver was primarily designed to suppress selective fading it is of course applicable to the common-channel conditions of interference between two different stations. Figure 5 shows the output of the receiver during such a test, before and after passing the detected output through the de-emphasis and filter circuits.

The results described indicate that technically it should be possible to establish a high-fidelity transatlantic link for relaying speech and music with a freedom from interference comparable to that associated with local reception. The question of the desirability of doing this depends upon whether or not the 150-kc channel width can be spared in the short-wave band.

REFERENCES

(1) Murray G. Crosby, Frequency Modulation Propagation Characteristics, *Proc. IRE*, 24, p 898, June 1936.
(2) Murray G. Crosby, Observation of Frequency-Modulation Propagation on 26 Megacycles, *Proc. IRE*, 29, p 398, July 1941.
(3) L. B. Arguimbau and J. Granlund, The Possibility of Transatlantic Transmission by Means of Frequency Modulation, *Atti del Congresso Internazionale*—Rome, September-October 1947.
(4) L. B. Arguimbau and J. Granlund, The Possibility of Transatlantic Communication by Means of Frequency Modulation, *Proc. NEC*, Chicago, November 1947.
(5) Massachusetts Institute of Technology, Research Laboratory of Electronics, *Quarterly Report*; July 1947.
(6) L. B. Arguimbau, "Vacuum Tube Circuits", John Wiley and Son, New York, p 530, 1948.
(7) S. T. Meyers, Nonlinearity in Frequency-Modulation Radio System Due to Multipath Propagation, *Proc. IRE*, 34, p 256, 1946.
(8) M. S. Corrington, Frequency Modulation Distortion Caused by Common and Adjacent Channel Interference, *RCA Review*, 7, p 522, 1946.
(9) F. L. H. M. Stumpers, Interference Problems in Frequency Modulation, *Philips Research Reports*, 2, p 136, 1947.
(10) H. B. Huntington, On Ultrasonic Propagation through Mercury Tubes, *J. Acous. Soc. Am.*, 20, No. 4, July 1948.