A DOUBLE SIDE-BAND AMPLITUDE-MODULATED MULTIPLEX SYSTEM FOR USE OVER MICROWAVE RADIO

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Microwave communications is one of today's most rapidly expanding fields in the radio art. Its inherent characteristics fit well into the communication needs of expanding industry. One of its important advantages over conventional communication means is the capability of handling numerous voice frequency channels over a single radio frequency carrier. This capability is made possible by the wide bandwidth which is available and can be transmitted at ultra high frequencies.

To make use of the transmitter bandwidth, multiplexing methods must be used to arrange the various audio channels so that they all can be transmitted simultaneously over one uhf carrier and be recovered at the receiving end without interference to each other. To accomplish this, a number of systems are being used.

Pulse time division multiplexing shares the radio channel among the various audio channels on a time basis. The intelligence in each audio channel is sampled and used to vary the position, width, or amplitude of a transmitted radio frequency pulse corresponding to that particular audio channel. When done at a sufficiently high rate, these pulses adequately carry the intelligence, and associated commutating and demodulation circuits at the receiving end recover the intelligence on each audio channel.

Frequency division multiplexing simultaneously transmits all audio channels over the radio carrier, but each channel is translated to a separate band of frequencies such that one channel will not interfere with another. Suitable filters at the receiving end, separate the channels, and demodulators translate each back into the original audio frequencies.

The frequency translating process is usually accomplished by either amplitude or frequency modulation of higher frequency carriers ranging from 5 kc/s to 1 mc/s. If am is used, either single side band suppressed carrier, or conventional double side-band, transmitted carrier can be used.

In both frequency and time division multiplexing, the resulting multiplex signal is used to either amplitude or frequency modulate the radio carrier at ultra high frequency.

In the initial design stages of the Westinghouse FJ Multiplexing Equipment, all the various methods were considered. Each has certain inherent advantages and disadvantages and the design goal of the particular equipment in hand must govern the choice.

The decision to employ frequency division rather than time division was based on several fundamental objections to time division circuits and performance. First, it was desirable to avoid unnecessary common elements which would increase the possibility of simultaneous loss of all audio channels. The commutating or timing circuit of time division is subject to this hazard in contrast to frequency division, where the various channels have no such common element.

A second reason is that for equivalent number of audio channels, time division methods of multiplex often result in a wider transmitted radio frequency bandwidth. With emphasis on spectrum conservation, it was felt that equipment using a more limited bandwidth would have a longer design life.

Also influencing the decision was the goal to have the equipment as versatile as possible for both long and short haul and for both limited and multi-drop services. The complexity and cost of the channel drop and party line provisions appeared greater for time division schemes than for frequency division.

In choosing a basic multiplexing system, it is the end result of all factors that is important in establishing a reliable communications system. The successful system must not only have good initial performance but must be easy to adjust, operate and maintain. It should be stable and as simple as possible. A system capable of extremely low thermal noise performance is of no avail if the inter-modulation, cross talk, or power supply hum is sizable, if the channels are unstable in frequency, or the system requires frequent and painstaking adjustment.

Although each had certain unique advantages, it was decided that the simplest system providing the best balance among all factors and still meeting low cost and high performance requirements was the conventional double side-band, transmitted carrier, amplitude modulation system.

Market analysis indicated that 30 voice frequency channels plus an underived service channel, would provide sufficient facilities for present and immediate future needs. The frequencies for the 30 channels were selected within an octave range to give the best balance between thermal noise and inter-modulation products. They were chosen such that the second harmonic of the lowest channel (305 kc) falls above the highest channel (595 kc). This means that not only the direct harmonics but sums and differences of the various carriers also fall completely outside the multiplex band. Fig. 1 shows a spectrum analysis of some representative channels. Of course, third harmonic distortion which is the source of $(2f_1-f_2)$ type interference and adjacent channel interference are still a source of noise, and circuits must be designed to minimize this type of distortion.

These higher multiplex frequencies, in contrast to conventional telephone carriers of 100 kc and lower, would require greater rf deviation to prevent decreasing the per-channel modulation index which would increase the signal-to-thermal noise ratio over lower but harmonically related frequencies; however, even with a somewhat lower modulation index, the improvement in inter-modulation noise justifies the octave frequency choice. The circuits are easier to adjust and maintain and still give a very good signal-to-total noise ratio. The thirty Type FJ Multiplex channels are assigned frequencies spaced 10 kc apart from 305 kc to 595 kc. The actual channel is 6 kc ($\pm$3 kc) with a 4 kc guard band. See Fig. 2.

The various services are provided by three independent units — the Voice Panel, the Telegraph Transmitter and the Telegraph Receiver. The voice and telegraph units are basically the same, each operating on any one of the 30 assigned multiplex channel frequencies, except that the voice panel is an integral, two-way package complete with signaling and telephone termination, whereas the telegraph panels are one-way and do not include signaling. Depending upon the service required, either a voice or a telegraph panel is used.

The Voice Panel is a complete multiplex unit for either a terminal or drop. The panel contains the power supply, transmitter, receiver, signaling and ringdown circuits, telephone hybrid for 2 or 4 wire termination, and it can be connected for either private or party line service. Figs. 3 and 4 show the Voice Panel and Fig. 5 shows the block diagram of the Voice Panel.

The modulation is accomplished in a mixer type circuit, the carrier being applied to the grid and the audio signal to the screen of a 6BA6 modulator tube. The carrier oscillator is crystal controlled and temperature compensated to a stability better than .02 per cent from -30^{o} to $+70^{o}$ C.

Signaling is accomplished in the channel by the incoming a-c ringdown (or d-c) shifting the channel carrier by 1000 cycles. The dual fm-am demodulator applies the resulting discriminator voltage to the ringing relay. A 60 cycle ringing source is provided on the panel. The shifting of the carrier does not affect the channel operation, overall distortion still being less than 5 per cent. This means that the shift can be used for telephone supervisory, vhf control, etc. with a satisfactory talking circuit in either the shifted or normal position.

The channel filters are plug-in and by means of padding capacitors and a tapped coil, cover the entire range from 305 to 595 kc. A typical filter response curve is shown in Fig. 6. An audio equalizing circuit flattens the overall channel response to be within 3 db from 300 to 3000 cycles. Filters as well as the other equipment are temperature compensated over the range -30^{o}C to $+70^{o}$C. Fig. 7 shows the multiplex frequency output of the voice panel when modulated as a private line; output is shown on both a time and spectrum basis.

In frequency division systems of party line operation, a heterodyne might develop from more than one carrier on the same frequency if all were on continuously. This is usually avoided by using suppressed carrier, push-to-talk, or voice controlled relays on channel carriers. In the FJ equipment it was felt desirable to avoid the nuisance of push-to-talk and the clipping and clicking often incurred with voice controlled relays. As a result, a system is used whereby the channel carrier is normally "off" with no audio input signal and the amplitude of the carrier is increased in direct proportion to the audio input level. Since both the carrier and its modulation are a direct function of the audio input level, essentially constant modulation occurs at all levels of input. The modulation is set at about 85 per cent. Fig. 8 shows the output signal at various input levels on both a time and spectrum basis.

Since there is no avc action applied to the receiver, the channel noise level runs about 10 db lower under conditions of no signal and no carrier than under the private line type of operation where the carrier is transmitted even during noise measurements. Signal/noise measurements are referenced to average modulation on a flat, per channel basis, that is, with a 1000 cycle sine tone 30 per cent modulating the channel. The transmitter level is set, such that under expected input voice levels, the peak output voltage will not exceed that produced by an 80 per cent modulated, private line panel where the carrier is transmitted continuously. With no input signal the carrier is squelched to approximately 45 db below average level.

It should be noted that the use of average modulation as a reference level results in a 6 to 10 db lower signal-to-noise ratio figure than with a 60 or 100 per cent modulation reference, which is quite often used on commercial equipment.

It is felt, however, that the average modulation reference is a much more realistic basis with respect to resulting performance. When a voice channel is set up for signal-to-noise tests at 100 per cent modulation by a sine tone, the channel cannot be modulated by voice without overmodulation; the gain control must be reduced for normal voice operation which, of course, invalidates the S/N ratio measurement. RETMA Committees are preparing a standard method of conducting signal-to-noise ratios which will be fair to the various multiplexing systems.

On 2-wire party line service, it is necessary to prevent feed through of receiver-to-transmitter from hybrid unbalance which would cause echo effects. In the FJ system this is prevented by causing the received signal to produce a squelch on the transmitter which is proportional to the amplitude of the received signal and is sufficient to prevent transmission of the feed through signal. Local input telephone signal is, of course, of sufficient amplitude to overcome the squelch and operate the transmitter. Even with normal squelch applied, a dynamic range of 30 db is obtained. At exceptionally noisy locations, noise cancelling microphones may be required and in extreme cases the squelch can be re-adjusted to prevent carrier emission from background noise at some reduction in dynamic range.

The performance of the voice proportional carrier system is identical to regular party line telephone with two minor exceptions. First, with normal background noise and with no one talking on the party line, and if the local telephone noise and radio thermal noise is low, the telephone circuit is noticeably quiet due to the total absence of background noise from other "off hook" transmitters, which are squelched off.

The second effect occurs when there is a very high background noise level at one or more "off hook" way stations which may cause those carriers to transmit a low level signal. A number of these signals would create low level noise. However, because of the proportional squelch circuit, each carrier tends to squelch every other carrier. Further, when any transmitter is normally voice modulated, all the party line receivers increase their squelch on their associated transmitter, which prevents transmission of local background noise. Thus, even high background noise from a number of "off hook" way stations does not interfere with the intelligibility of party line communications.

As a result, normal two-way conversation is produced with any party able to interrupt any other at any time. Beats produced by simultaneous operation of two carriers cannot be heard by either of the talking parties since the radio circuit is a 4-wire device. A third party listening might occasionally discern a low frequency carrier beat except that it is difficult to distinguish it from normal interference produced by the two parties talking at once, as on any voice frequency party line.

The time constant of the carrier starting is about 5 milliseconds such that there is no discernible clipping effect of the first syllable. The carrier drop-off time constant holds the carrier on through normal syllable and word sequence and drops off slowly enough not to produce thumps or clicks.

Signaling is performed by carrier shift, the carrier being keyed on in the shifted position by the signaling relay contacts. Total channel distortion is under 5 per cent and the response is flat within 3 db from 300 to 3000 cycles.

The independent telegraph transmitter also uses double side-band amplitude modulation for services requiring tone such as frequency telemetering, facsimile, etc. The same circuits are used as in the voice panel, except that because of the stringent inter-modulation and distortion requirements for audio sub-multiplexing by up to 15 audio tones, a negative feed back loop has been added to the transmitter to keep the total harmonic distortion well below 1 per cent. With no signaling required or provided, the detector is straight am.

Fig. 9 shows the telegraph power supply, transmitters and receivers. Figs. 10 and 11 show the block diagrams of the Type FD Telegraph Transmitter and Receiver. With proper adapters plugged in, and the strapping completed on the terminal board, the units can be used for any service requiring a keyed carrier or a carrier modulated from 6 to 3000 cycles. This modulation range allows direct modulation and demodulation of the carrier by the low frequencies used in frequency telemetering without the necessity of pulse counting or pulse keying. With the carrier being transmitted, there is no frequency reference stability problem in connection with frequency telemetering.

Protective remote and transfer trip relaying used on high voltage transmission lines requires high speed operation of the connecting channel. Because of the 6 kc bandwidth, the response time of the FJ Telegraph Units is limited primarily by the relay operation time, and trip operations can be completed in 4 to 6 milliseconds.

An example of a simple multiplex system over a two hop microwave circuit is shown in Fig. 12. Two terminals of Type FR Microwave and one FR Repeater carry one private telephone line, one party telephone line, 2 telegraph circuits east and 2 telegraph circuits west. The voice frequency service channel and alarm circuit drop at every station.

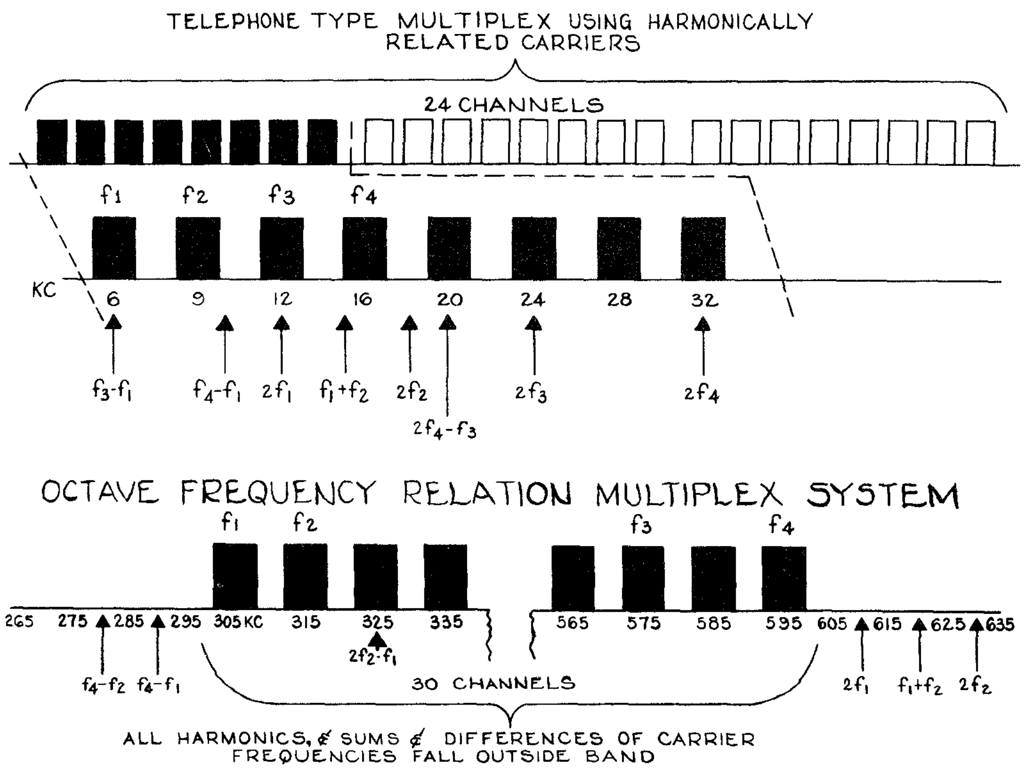

Fig. 1 - Comparison of harmonic type crosstalk in two multiplex systems.

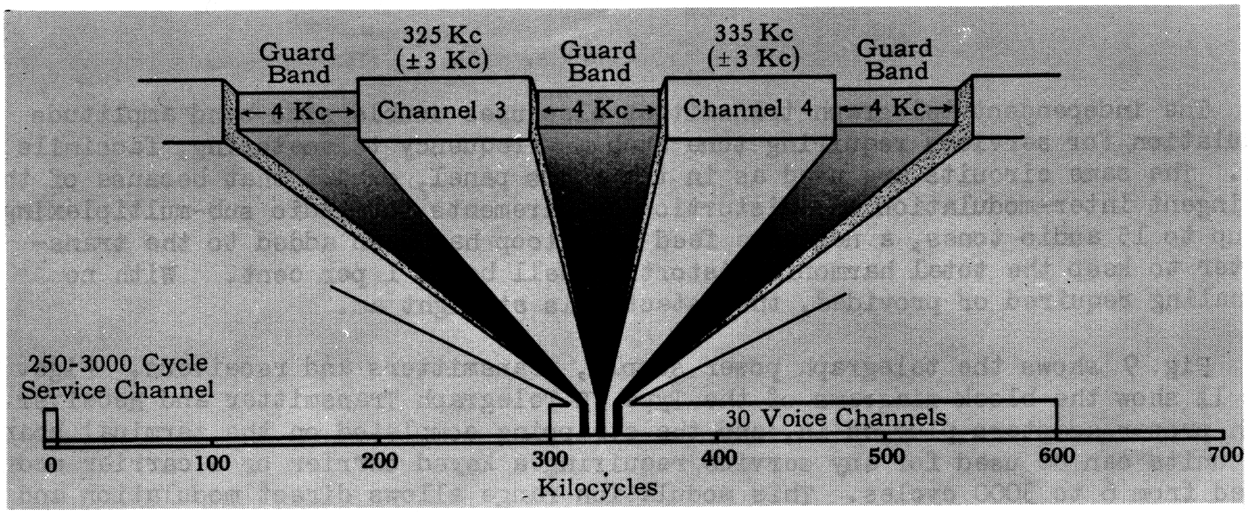

Fig. 2 - Allocation of type FJ multiplex frequencies.

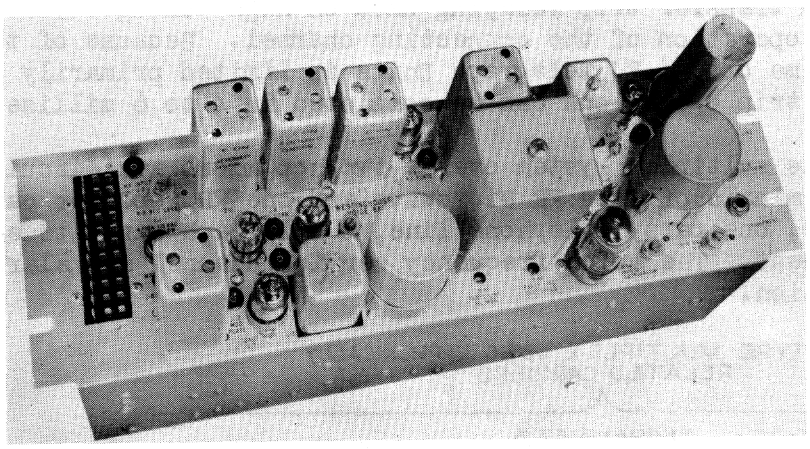

Fig. 3 - Type FJ voice panel - front view.

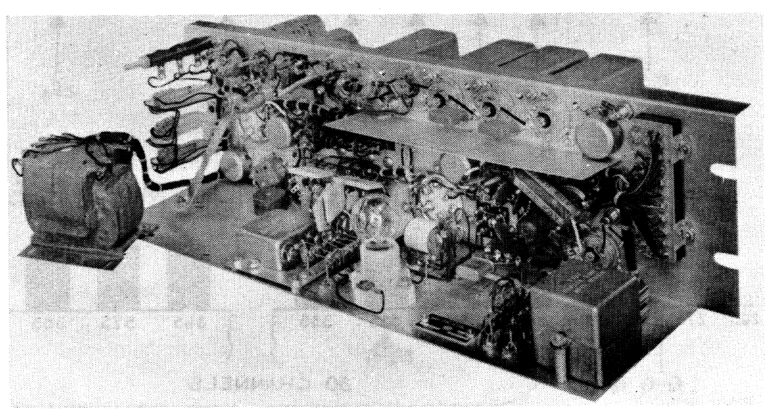

Fig. 4 - Type FJ voice panel - rear view.

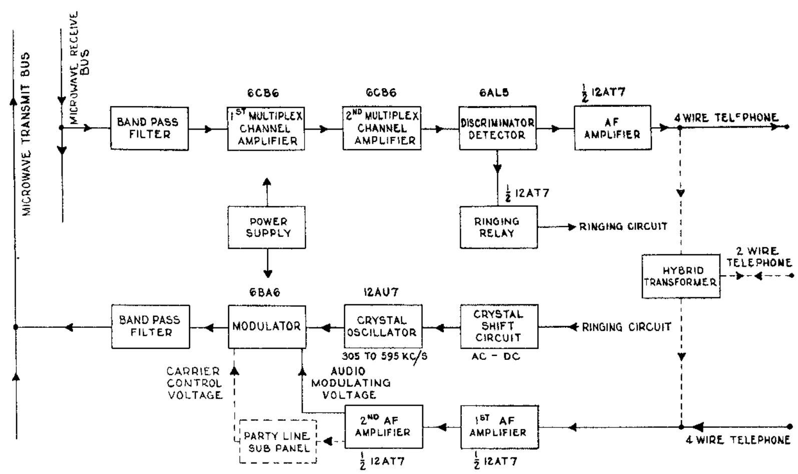

Fig. 5 - Block diagram - type FJ voice panel.

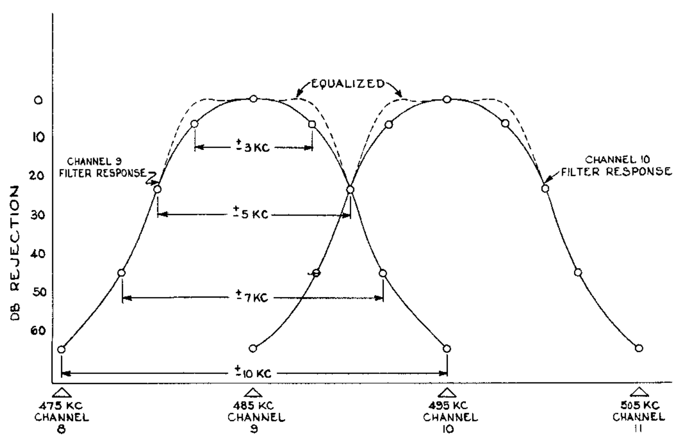

Fig. 6 - FJ voice panel filter response.

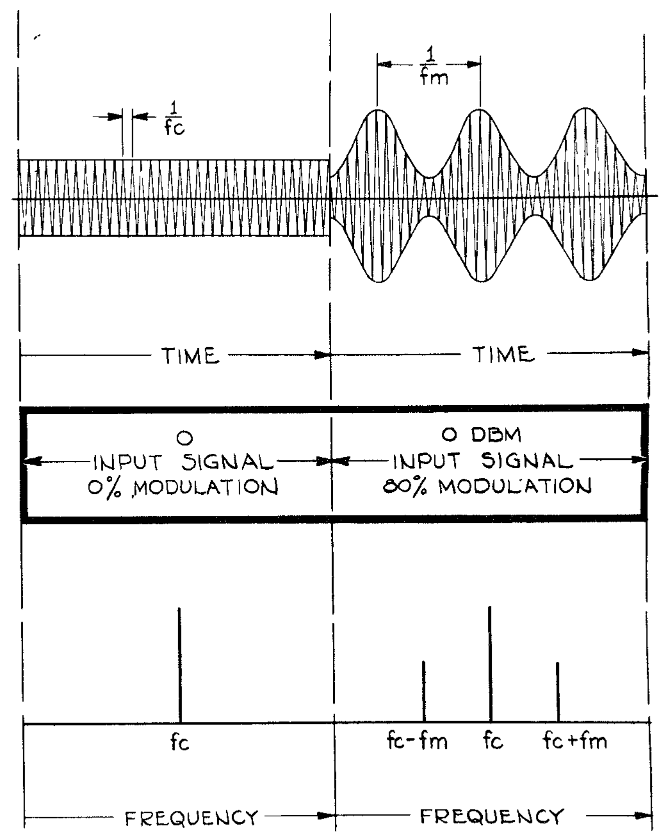

Fig. 7 - Output of FJ voice panel in private line operation on a time and frequency basis.

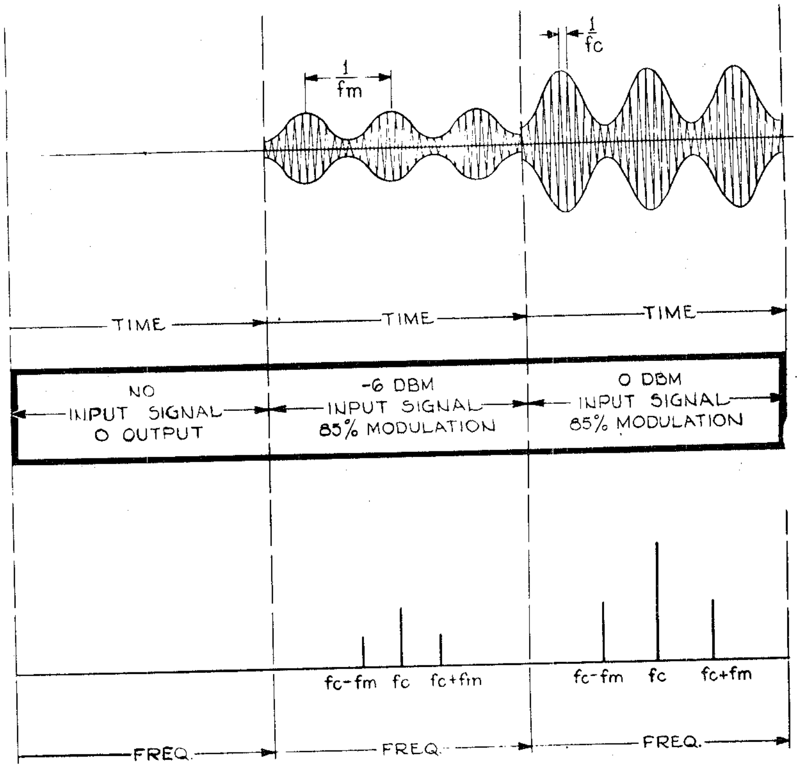

Fig. 8 - Output of FJ voice panel in private line operation on a time and frequency basis.

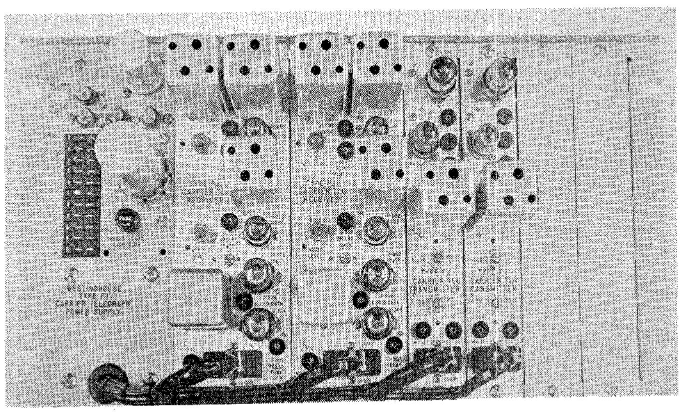

Fig. 9 - Type FJ telegraph assembly - power supply, two transmitters, two receivers.

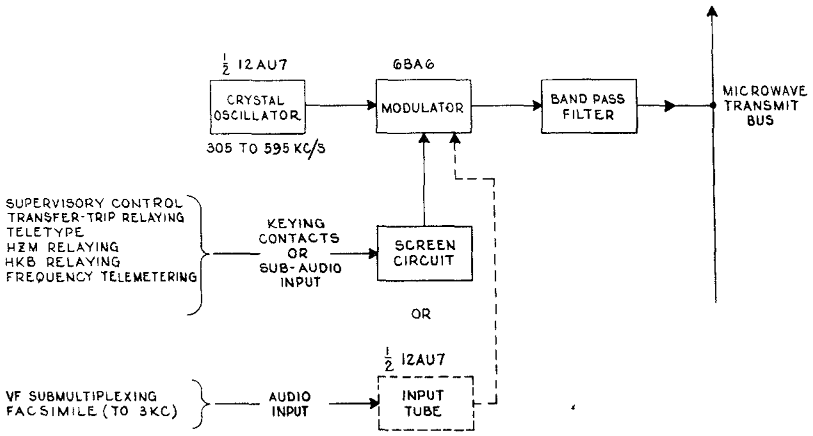

Fig. 10 - Block diagram - FJ telegraph transmitter.

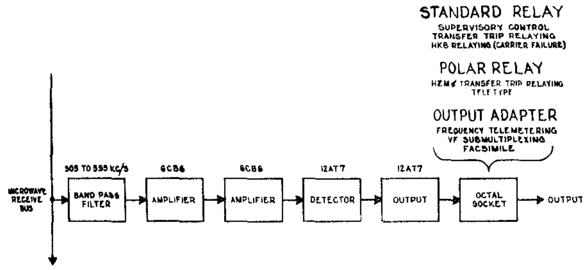

Fig. 11 - Block diagram -FJ telegragh receiver.

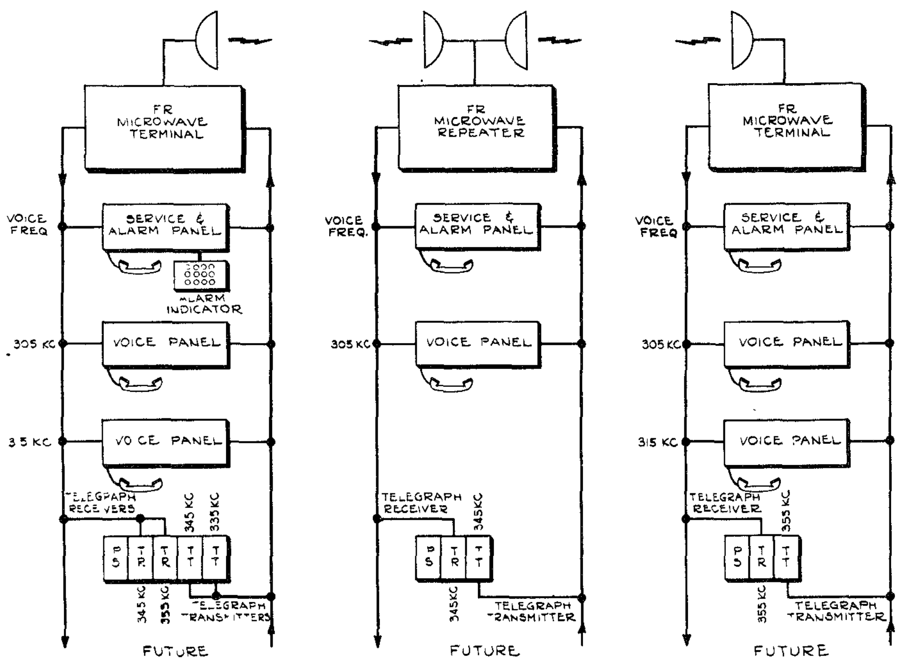

Fig. 12 - Example of FJ multiplex system.