AN ALL SOLID-STATE SSB-AM CARS BAND SYSTEM

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1. INTRODUCTION

Single-sideband amplitude modulation (SSB-AM) is well established as the signal processing method which assures minimum spectrum occupancy. Already four decades ago it became the generally accepted standard of multichannel telephone transmission in the form of frequency-division multiplex, first used on open-wire lines and cables, and later on microwave links. The last decade witnessed the transition to virtually exclusive use of SSB-AM on a world-wide basis in another segment of communications where frequency spectrum is at a premium, namely, short-wave radio telephony. This became feasible after an impressive arsenal of technological solutions for the rather difficult inherent problems of SSB-AM radio transmission became available. The December 1956 special issue of the Proceedings of the IRE on single-sideband techniques makes one of the most interesting readings on this subject. It might come as a surprise to some that one of the articles in that issue describes an experimental 24-channel telephone system using SSB-AM for beyond-the-horizon UHF transmission [1]. Not too long after that, in 1960, came a proposal for the use of SSB-AM on line-of-sight radio relay links [2]. This would quadruple the transmission capacity as compared to the most advanced FM radio relay telephone systems in use today. The main problem to be solved to this end is that of linear power amplification at microwave frequencies. Technological implementation, therefore, came first at lower frequencies where linear power amplifiers are available at higher output levels. SSB-AM 120-channel telephone systems operating in the 400-410 and 420-430 MHz bands were installed in the mid 60's to establish a high-quality commercial telephone link between West Berlin and the Federal Republic of Germany [3].

The first proposal for the use of SSB-AM for TV transmission at microwave frequencies was made in 1959 [4]. It envisaged TV broadcasting in the 12 GHz band, as a means of substantially increasing the number of TV programs in the Federal Republic of Germany*.

*In view of the population distribution the VHF and UHF channels offer satisfactory coverage for only three simultaneously broadcasted TV programs in that country and, as a matter of fact, in most of Europe.

Systematic studies and experimental investigations of this problem area have been carried out [5] in the course of which the feasibility of an SSB-AM microwave transmitter has been established [6].

The use of SSB-AM for microwave transmission of TV channel groups intended for CATV distribution started on an experimental basis in 1966 [7]. Frequencies in the 18 GHz range were used and transmission was on a group basis; i.e., the TV channels to be transmitted were multiplexed at VHF frequencies and transmitted with a single, broadband microwave transmitter (refer to Fig. 2). Experience gained from these experiments and the subsequent development of a new system version for the 12.7-12.95 GHz CARS band [8] were instrumental in formulating the FCC rules for SSB-AM transmission in this band [9]. Thirty six regular and two "auxiliary" channels are assigned. This is the maximum usable capacity of links without intermediate repeaters. If one or more intermediate repeaters are needed, the transmission capacity is reduced to a total of nineteen channels.

The system design to be described in this paper fully conforms with the aforementioned FCC rules [9] and is based on the microwave solid-state technology developed at Fairchild for use in communication systems. As will be shown, the selected system configuration enhances transmission performance, flexibility of use, and reliability.

This paper is limited to the description of the overall system design. Technical data are specified in such a way as to facilitate their use for performance calculations of planned links using generally established procedures. Propagation aspects are treated only to the extent not covered in the existing literature on CARS band systems.

The feasibility of the described SSB-AM CARS band system design was experimentally verified in the Spring of 1970. A system model was since repeatedly demonstrated in the laboratory, simulating link lengths of up to 10 miles. FCC type acceptance tests are in preparation and the first field tests are to be carried out in 1971.

2. CHOICE OF MICROWAVE SIGNAL PROCESSING SCHEME AND SYSTEM CONFIGURATION

The signal processing scheme is selected for the advantages it offers. The reasons for preferring SSB-AM were as follows:

- This is the signal processing scheme with the minimum bandwidth requirement on a per channel basis. The occupied spectrum width in microwave CARS band transmission is the same as in VHF cable transmission. The 250 MHz wide CARS band can thus accommodate the entire 50-300 MHz bandwidth envisaged for future cable systems (refer to Fig. 1).

- When planning a radio system which is to be used with an existing cable system, it is advantageous to use the same channel multiplexing scheme in both cases. The SSB-AM CARS band system to be described takes the VHF channels directly from the frequency range required for cable transmission and puts them directly back into the same VHF frequency range (Fig. 1).

- It is always advantageous to use the simplest possible signal processing scheme consistent with the required transmission performance. The straightforward up-conversion/down-conversion scheme of SSB-AM (Fig. 1) is undoubtedly the simplest available.

Accordingly, SSB-AM was selected because it assures, on one hand, maximum spectrum usage and, on the other hand, the simplest possible transition from cable to radio transmission and vice versa.

The main difficulty in implementing analog AM systems, in general, lies in the non-linear transfer characteristic of the transmitter or amplifier output stage [10]. As a consequence, the tolerable amount of non-linear distortion determines the maximum usable power output which is in most cases one or two orders of magnitude below the saturated output power. This is a serious disadvantage of analog AM as compared to all other signal processing schemes which operate at saturated output power levels.

Figure 2 illustrates the most logical first approach to an SSB-AM CARS band link which consists of using a single, broadband transmitter-receiver pair for the simultaneous transmission of several VHF channels. The specific example used in Fig. 2 and for most of the following system considerations is that of a 6-channel head-end link with alternate channel transmission. The case of contiguous 12-channel transmission is treated later. However, all of the following considerations of multichannel transmissions apply irrespective of channel arrangement or transmission capacity.

Since the output power of the transmitter cannot be arbitrarily increased due to technological and economical constraints, the multichannel transmission performance must be considered for a predetermined available transmitter output level. It becomes immediately clear that under these conditions both the signal-to-noise ratio, S/N, and the relative cross-modulation level, -XM, deteriorate as the number of transmitted VHF channels, n, increases.

The deterioration of the S/N ratio with increasing transmission capacity is due to the fact that in a broadband group transmitter the available power output is shared by the simultaneously transmitted signals such that the available power per channel, P_{ch}, becomes

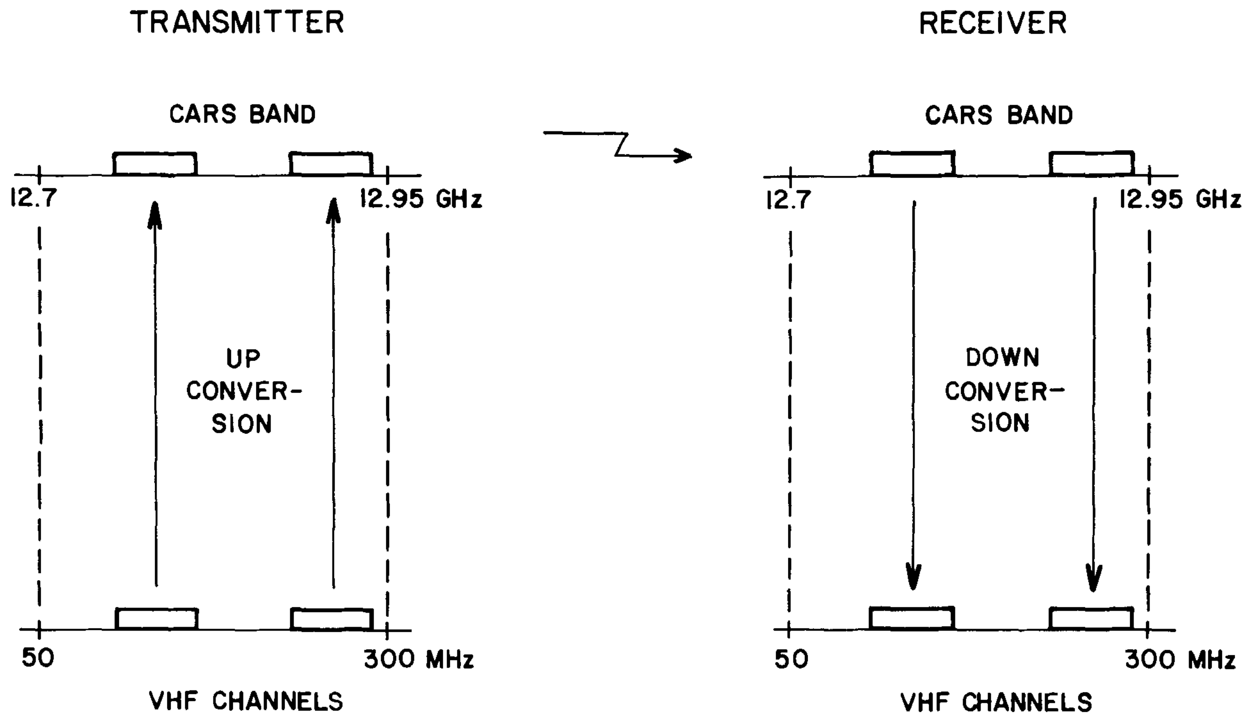


Fig. 1. SIGNAL PROCESSING SCHEME OF THE CARS BAND SSB-AM SYSTEM.

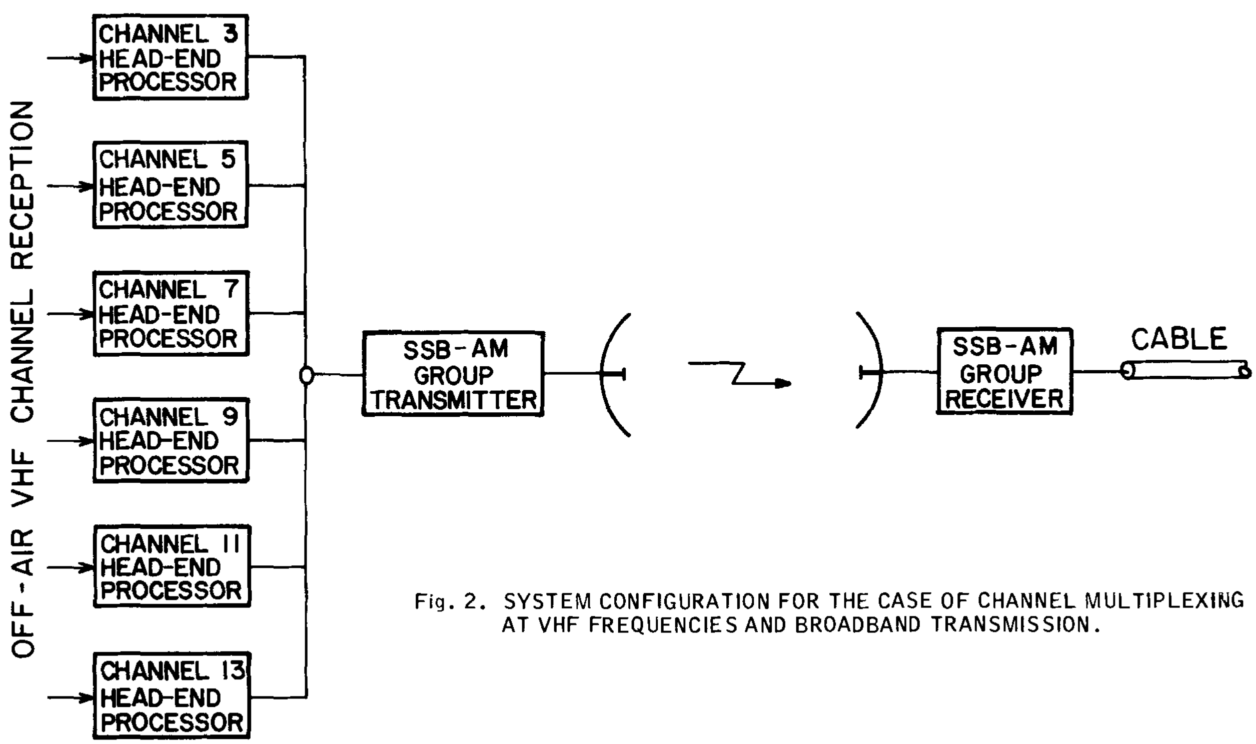


Fig. 2. SYSTEM CONFIGURATION FOR THE CASE OF CHANNEL MULTIPLEXING AT VHF FREQUENCIES AND BROADBAND TRANSMISSION.

$$P_{ch} = \frac{P_{tot}}{n}$$

where P_{tot} is the total available transmitter power and n the number of transmitted channels. The S/N ratio of each channel in a group of n channels, $(S/N)_n$, expressed in dB, thus equals

$$(S/N)_n = (S/N)_{n=1} - 10 \log n$$

where $(S/N)_{n=1}$ is the S/N ratio for single-channel transmission and n the number of simultaneously transmitted channels. As illustrative, numerical examples consider a 5-channel system and a 12-channel system. The S/N ratio in each VHF channel of the former system will be $10 \log 5 = 7$ dB lower than for a single channel system. The corresponding difference for the 12-channel system is $10 \log 12 = 10.8$ dB

The relative cross-modulation level, -XM, expressed in dB, increases with the increasing transmission capacity by the following amount [10]:

$$20 \log (n-1)$$

where n is again the number of transmitted channels. This means that the cross-modulation level in each channel of a 5-channel system will be $20 \log 4 = 12$ dB higher than in a 2-channel system; the corresponding difference for a 12-channel system amounting to $20 \log 11 = 20.8$ dB . Comparison with a single-channel system is meaningless since, by definition, there is no cross-modulation in that case. However, the 3rd order intermodulation specifications for single-channel transmission are much easier to satisfy than the cross-modulation specifications for even a two-channel system.

The above considerations lead to the conclusion that from the viewpoint of transmission performance it is preferable to use a separate microwave transmitter for each channel and multiplex them into a common antenna as illustrated in Fig. 3. The implementation of such a transmitter solution is described in the next section.

On the receiving end there is no need to use a separate microwave receiver for each channel because the group receiver approach, illustrated in Fig. 2, is satisfactory from the viewpoint of both S/N ratio and cross-modulation. The latter is, of course, more critical but the receiver operates at levels which are substantially lower with respect to saturation than is the case in the transmitter. A study based on considerations reported at the 1970 NCTA Convention showed that acceptable cross-modulation levels can be obtained with existing microwave mixer technology [11].

3. SYSTEM BLOCK DIAGRAM

3.1 Transmitter

Figure 4 shows the block diagram of the transmitter. The simplest possible solution has been adopted. There is only one active microwave circuit in the signal path, namely the upper-sideband parametric up-converter which directly delivers the required output power. Such a solution is undoubtedly the most advantageous one from the viewpoint of distortion because it minimizes the number of sources thereof.

The additional important advantage of the adopted transmitter configuration is that it lends itself best to an all solid-state implementation. The source of microwave power, the up-converter pump, is a CW oscillator with output power in the 1.5 - 2.0 W range. It consists of two cascaded silicon avalanche diode (IMPATT) oscillators with 1 W nominal power output each and a DC-to-RF conversion efficiency of better than 5% which is higher than the efficiency of commercially available klystrons in the same frequency range*. The avalanche diodes and the power combining scheme were developed at Fairchild. The power combining efficiency of the composite oscillator is virtually 100%. For a description of these techniques and more details on the obtained results it is referred to publications at the 1969 International Solid-State Circuits Conference [12] and at the 1971 International Microwave Symposium [13].

The advantage of the described transmitter over any other configuration can be fully appreciated only after the available alternatives have been considered in some detail. They all involve power amplification. Unfortunately, non-linear distortion in available microwave power amplifiers for CARS band frequencies, tube or solid state, is by no means lower than in a properly designed high-level up-converter. While it is true that there are several promising approaches for linearizing the tube and transistor amplifier transfer characteristics in the VHF to lower microwave frequency ranges, there apparently is as yet no practical solution available at CARS-band frequencies. This subject matter is, therefore, not treated here and references to publications are omitted.

*The second generation up-converter pumps will use GaAs avalanche diodes whose efficiency is around 10%.

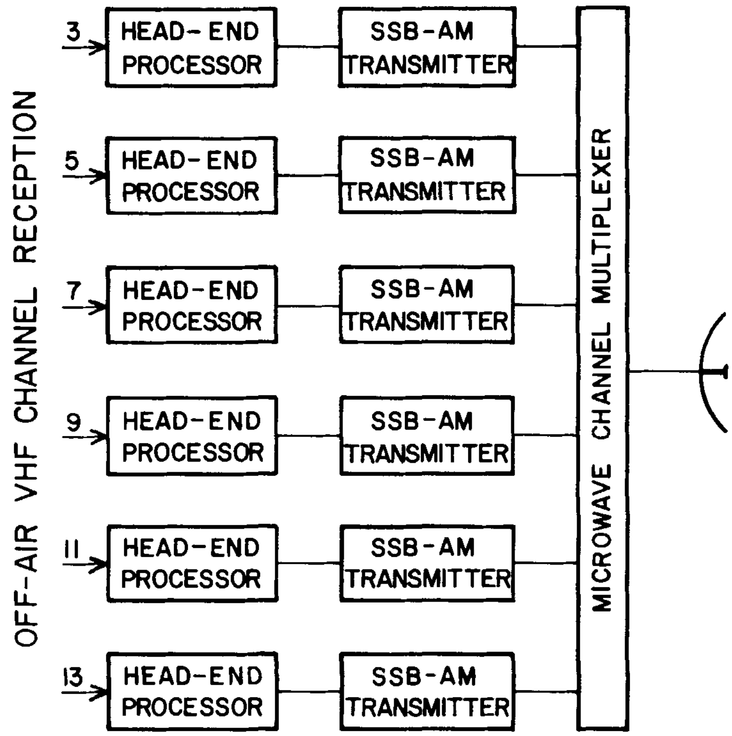


Fig. 3. TRANSMITTER CONFIGURATION WITH CHANNEL MULTIPLEXING AT CARS-BAND FREQUENCIES

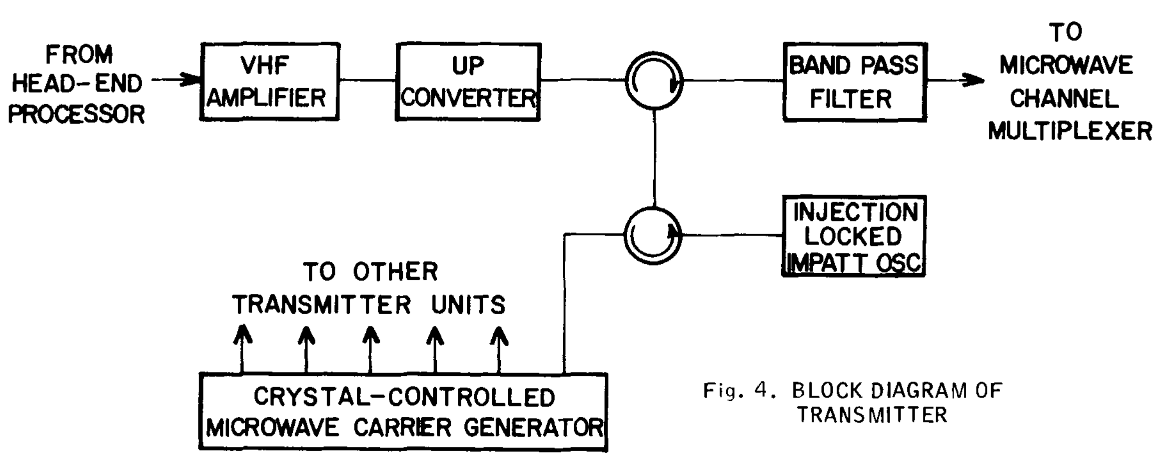


Fig. 4. BLOCK DIAGRAM OF TRANSMITTER

As can be seen in Fig. 4, a crystal-controlled microwave generator is used as the common carrier source for the entire multichannel transmitter group. It consists of a low-power crystal controlled multiplier source, a standard Fairchild product for use in microwave communication systems, followed by an injection locked avalanche diode oscillator which functions as power amplifier. Its output power is split to in turn injection lock all the up-converter pumps of the transmitter group. The purpose of this arrangement is to keep all the up-converter pumps in synchronism, which is indispensable because, as pointed out before, a group microwave receiver is used in the described system.

3.2 Receiver

The block diagram of the group receiver is shown in Fig. 5. It uses a conventional RF head consisting of a band-pass filter, a mixer, and a crystal-controlled multiplier source as local oscillator. Means for establishing synchronism between the latter and the microwave carrier generator of the transmitter, which is needed in the case of locally broadcasted channel transmission, can be added. A pilot signal derived from the microwave carrier generator is then inserted at the transmitting end in the frequency space the FCC reserved for this purpose [9]. At the receiving end, this pilot signal is filtered out and used to control the frequency of the local oscillator.

The receiver of Fig. 5 employs a separate AGC VHF amplifier in each channel. While the concept of a group receiver can be implemented all the way down to the VHF output, automatic gain control on a group basis is likely to prove impractical for many applications. This statement does not refer to problems of AGC circuit design but to multipath propagation effects in the form of frequency selective fading which would manifest itself as an irregular, frequency-dependent and time-varying amplitude distortion over the whole receiver bandwidth or portions thereof. These amplitude variations can amount to several dB. In general, the wider the occupied transmission bandwidth, the more pronounced this effect becomes. The bandwidth of a 12-channel SSB-AM CARS band system transmitting the standard VHF channels, for example, equals 162 MHz or, on a percentage basis, 1.25% approximately. This is by no means negligible as compared to frequency separations of frequency diversity systems operating in the microwave region which exploit the frequency dependency of multipath fading to reduce outage time due to such fading*.

*A discussion of multipath fading, published in the Lenkurt Demodulator [14] includes the statement that most frequency diversity systems have frequency separations of 2-5% of the lower frequency.

The problem of frequency selective fading at frequencies above 10 GHz has received very little attention, most likely due to the fact that the most severe fadings,which limit the usable path length at these frequencies,are caused by heavy rainfall. However, there is ample evidence [15,16] that the multipath fading problem in the CARS band is a real one whenever systems of considerable bandwidth are used. Systematic propagation studies would be necessary in order to determine a "safe" upper limit for the usable system bandwidth. An estimate based on the above quoted publications [15,16] leads to the conclusion that the danger of frequency selective fading must not be disregarded for SSB-AM systems occupying a substantial portion of the CARS band frequency spectrum. In practical terms, AGC on a group basis might be sufficiently safe only for small groups of contiguous channels, such as the five-channel group of VHF channels 2-6 (bandwidth: 34 MHz) or even the seven-channel group of VHF channels 7-13 (bandwidth: 42 MHz).

The above discussion, although limited to the SSB-AM system, should not be misinterpreted as being pertinent to this system alone. Severe multipath fading will significantly affect any wideband analog transmission system. The degree of this effect and the most suitable solution of the resulting problems will depend on the particular system. For the SSB-AM system under discussion, it is believed that the receiver configuration of Fig. 5 represents a technically and economically sound solution based on readily available technology. Of course, if signal processing is needed at the receiving site, as well, this can be easily accomplished by using head-end processors instead of AGC amplifiers.

3.3 Contiguous Channel Transmission

So far, the system configuration has been illustrated only in terms of alternate channel transmission (Figs. 2-5). To transmit a group of contiguous signals requires simply connecting two corresponding alternate-channel transmitter groups to a common antenna with two polarizations. The same applies to the receiving end. This solution is illustrated in Fig. 6 for a 12-channel capacity, but the principle applies also to other transmission capacities.

The adopted solution is attractive not only from the viewpoint of microwave channel multiplexing, which would be prohibitively complicated and expensive if a single polarization were used for the entire group of contiguous channels, but also from the viewpoint of suppressing adjacent channel interference due to third order intermodulation products. Figure 7 is referred to for an explanation. It shows the carrier frequencies of channel 10 and their third order intermodulation products as they appear in the CARS band. As can

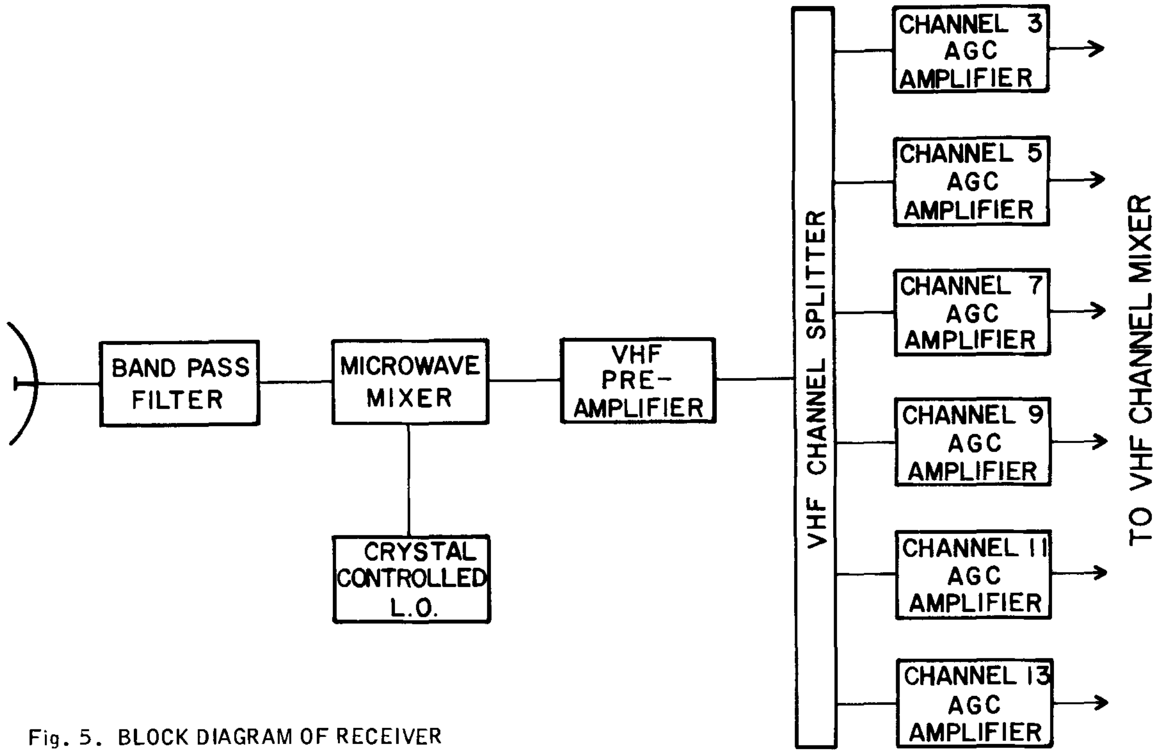
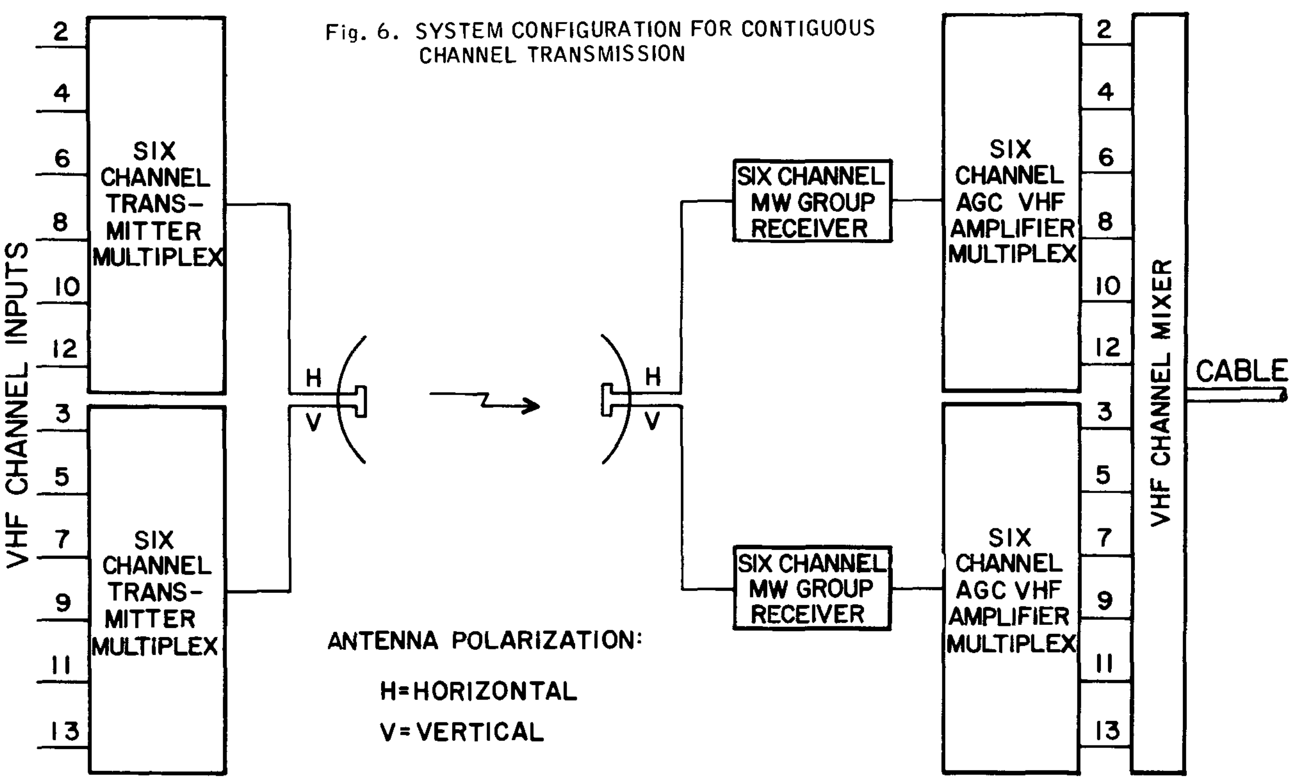


Fig. 5. BLOCK DIAGRAM OF RECEIVER

Fig. 6. SYSTEM CONFIGURATION FOR CONTIGUOUS CHANNEL TRANSMISSION



be seen, all the unwanted up-conversion products fall either within the transmitted channel itself or in the two adjacent channels. The FCC requires that the out of band products be attenuated by at least 50 dB below the peak power of emission [9]. It thus becomes clear that the isolation between the orthogonal polarizations of commercially available parabolic antennas for CARS band applications, whose order of magnitude is 20 dB, can significantly contribute to the suppression of adjacent channel interference when the transmitter multiplexing scheme of Fig. 6 is used.

The configuration of the receiving end is straightforward. Separate RF heads are used for each polarization and the VHF channels are multiplexed into the cable using conventional CATV techniques.

4. TRANSMISSION PERFORMANCE

4.1 Objectives

The described SSB-AM CARS-band system is conceived as a wireless substitute for cable trunklines. The transmission objectives depend, therefore, on the length of the cable trunkline the system is supposed to replace. The thermal noise and non-linear distortion allowance will be proportional to the length of the link in accordance with established cable system planning procedures [10].

The approach taken at Fairchild with regard to transmission performance objectives is twofold:

- Use the most effective system and component design for high transmission performance, consistent with reliable operation and competitive pricing.

- Closely cooperate with potential users of the SSB-AM CARS-band system in order to determine realistic transmission performance objectives for some immediate applications.

This approach turns out to be most beneficial to all the parties involved, which is understandable since a new class of systems is concerned.

It has been determined in this way that one of the most immediate needs is for multichannel radio transmission to replace the trunkline cable between the head-end and the distribution center. The described SSB-AM CARS-band system has been found to satisfy the requirements of such an application with a comfortable margin for link lengths up to 10 miles approximately, except in locations with extremely heavy rainfall which are limited to a few regions of the United States.

4.2 Signal-to-Noise Ratio

The following data are given for a 12-channel link in such a form as to facilitate their use in quick estimates of obtainable S/N values for link lengths of practical interest.

Transmitter output power at antenna terminal, per channel*	10 mW
Receiver noise figure	10 dB
Filter and isolator losses in receiver	2 dB
Feeder looses (transmitter and receiver)	2 dB

A 7 mile 12-channel link equipped with 10 ft. parabolic antennas will be assumed as illustrative example. The net transmission loss between the transmitter and receiver antenna terminals would amount to 45 dB for the case of ideal propagation conditions; i.e., no fading. A 4 MHz receiver bandwidth is used to calculate the ideal noise level, -108 dBm. Performing the straightforward arithmetic operation with these data gives

$$S/N = 65 \text{ dB}$$

which leaves a fading margin of approximately 20 dB for excellent reception (TASO Grade 1). The exact amount of the fading margin depends on whose system design criteria are used.

The quoted S/N performance has been verified in the laboratory using a transmitter-receiver pair whose electrical characteristics conform with the above data. Small horn antennas were used and up to 40 dB of fading was simulated with a variable attenuator.

4.3 Intermodulation

As pointed out before, intermodulation in the single-channel up-converter is the dominant form of 3rd order product interference in the SSB-AM system under consideration. Advice obtained from the Jerrold Electronics Corporation on how to carry out laboratory

*Higher output powers per channel are available for most transmitter configurations with less than 12-channels because of simpler microwave channel multiplexing.

tests of this particular transmission characteristic was invaluable in the absence of a standard test procedure. Three CW signals are used to simulate the color TV signal and sound. The amplitudes of the signals simulating the sound carrier and color subcarrier are -10 dB and -16 dB relative to the signal simulating the vision carrier. The most troublesome in-band 3rd order intermodulation product, V+S-C (refer to Fig. 7), must not be higher than -50 dB relative to the amplitude of the CW signal simulating the vision carrier.

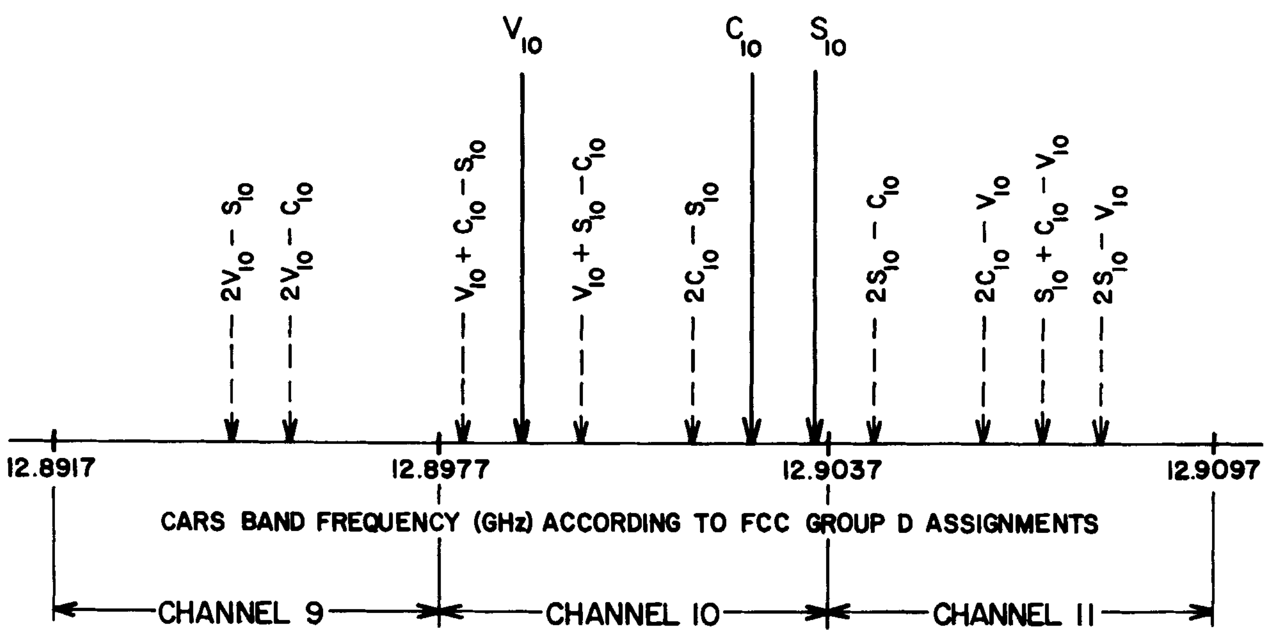
Figure 8 shows the result of this test for channel 10 up-converted into CARS band in accordance with the FCC Group D frequency assignments [9]. As can be seen, all the in-channel 3rd order intermodulation product amplitudes are more than 50 dB below the amplitude of the CW signal simulating the vision carrier. It should be mentioned, at this point, that the suppression of the out-of-band intermodulation products (refer to Fig. 7) which are not seen in Fig. 8 was satisfactory, as well.

V_{10} = CHANNEL 10 VISION CARRIER

C_{10} = CHANNEL 10 COLOR SUBCARRIER

S_{10} = CHANNEL 10 SOUND CARRIER

Fig. 7. THIRD-ORDER INTERMODULATION PRODUCT FREQUENCIES FOR UP-CONVERTED CHANNEL 10



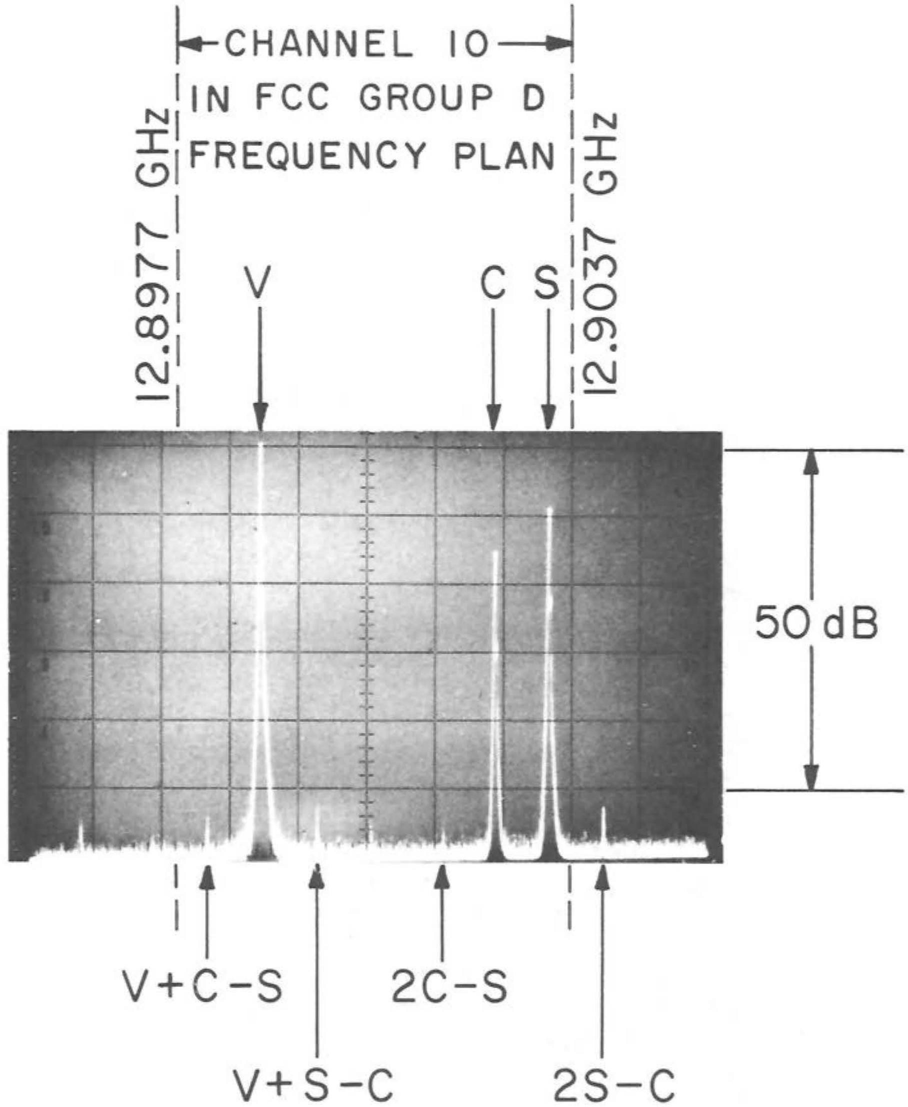


Fig. 8. MEASURED IN-BAND THIRD-ORDER INTERMODULATION PRODUCT AMPLITUDES OF CHANNEL 10 CARS-BAND TRANSMITTER

Of-the-air color TV signals were also used for subjective tests of the transmission performance. No difference could be observed between the quality of the of-the-air signal and the signal passed through the above described experimental link.

5. CONCLUSIONS AND COMMENTS

The main advantages of the described SSB-AM system are in the following design features:

- Channel multiplexing at microwave frequencies,
- simplest possible transmitter configuration, and
- all solid-state design.

These reflect on the operational characteristics of the system in the following way:

- Transmission quality is enhanced by using a separate up-converter for each channel and by avoiding subsequent microwave signal amplification.
- All three aforementioned design features enhance reliability.
- The modular transmitter design offers attractive flexibility and economy in system build-up whenever initial needs are below full transmission capacity. Plug-in transmitter modules can be easily added as needs grow.
- All solid-state system implementation became feasible only through adoption of the modular transmitter design without output power amplification. Avoiding the use of microwave tubes results in substantially lower power supply voltages (one order of magnitude) and in higher DC- to -RF conversion efficiencies which translate into lower power consumption.

ACKNOWLEDGEMENT

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