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TH-3 Medium-Haul Application:

Frequency-Diplexed Auxiliary Channel

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This paper describes a means of economically adding up to fifty VF circuits to a microwave radio system in addition to the regular payload signal. One feature of this system is its ability to add or extract information at IF repeaters without either bringing the payload signal to baseband or adding additional circuitry in the payload path.

I. INTRODUCTION

Point-to-point microwave radio systems require surveillance and maintenance to insure high-quality performance and reliability. This is accomplished by having access at each of the radio stations to an order-wire facility and a surveillance and control system, as well as other various special purpose circuits. The electrical signals associated with these circuits are typically carried to and from the radio stations over 3-KHz voice-frequency circuits. Three possible ways of transmitting these signals are to carry them over voice-frequency land lines, on a separate microwave channel, or directly on the payload microwave channel.

Land lines have been widely used in the past, but have two major disadvantages. Often the land lines between radio stations may follow a long circuitous route over a wide variety of transmission facilities. Secondly, they are relatively costly, especially if construction of new lines is required to provide access at a remote radio station. The question of cost is particularly important when one talks about low- or medium-density routes where the cost of the equipment required to perform these functions is spread over a limited number of telephone circuits.

The use of a separate microwave channel (auxiliary channel) has gained popularity in recent years. It frequently provides transmission over a much more highly controlled medium than does connection through miscellaneous land lines and consequently is much more reliable and of uniformly good performance quality. In addition to the associated multiplex, this type of auxiliary channel requires separate radio transmitting and receiving equipment at each radio station, consequently it is also fairly costly.

The third alternative of using the payload microwave radio channel to carry the surveillance and control signals is reliable, has good quality transmission, and is the most modest in cost. Using the existing radio as the transmission vehicle not only permits economic advantages but also simplifies maintenance since no separate radio transmitters and receivers are required. This paper concerns itself with the development and performance of an auxiliary channel of this type (the frequency-diplexed auxiliary channel) for use with the medium-haul application of TH-3 radio.

II. SYSTEM OBJECTIVES

2.1 *Capacity*

The medium-haul radio systems require two or three VF transmission circuits (service circuits) to accomplish the necessary maintenance and control functions. The surveillance and control system requires one of the VF circuits, the radio order circuit (order wire) another VF circuit, and, if equipped with an express radio order circuit, a third.

In addition to the service circuits, another category of circuit is sometimes useful. Frequently radio repeater stations are located near small population centers which are distant from larger cities where toll switching centers would be located. If a limited number of commercial trunk circuits could be inexpensively carried over the radio from a radio station to another along the route, substantial economic savings could be had. The frequency-diplexed auxiliary channel provides this facility (up to forty-eight VF circuits) without incurring the cost and noise penalty of demodulating the overall payload signal and equipping this station with master group multiplex equipment. The only multiplex required is that necessary to accommodate the forty-eight circuits.

2.2 *Performance*

These questions of system length, noise performance, and reliability are closely related; slight sacrifices in one sometimes yield substantial added margin in another. The forty-eight circuit backhaul facility is similar in many respects to other short-haul microwave radio systems such as TL and TM microwave radio.[1] It is therefore logical to consider performance objectives similar to those set for such systems. This corresponds to a maximum length of 250 miles and a noise objective of 35 dBrnc0. The TH-3 medium-haul radio system performance model is based on a system length of 1000 miles.[2] While the backhaul may be limited to 250 miles, the circuits used to carry order-wire and alarm signals may be required to traverse the full 1000-mile length. Therefore, on a system meeting the backhaul noise objective, the worst case noise performance of the service circuits would be 41 dBrnc0. This performance is more than adequate for the order-wire and surveillance and control circuits.

2.3 *Reliability*

Another measure of auxiliary channel performance is its reliability. Since the microwave radio itself carries the auxiliary channel, an outage of the basic radio system will affect not only the payload, but the auxiliary channel as well. The need for good auxiliary channel reliability exists since the backhaul circuits are carrying commercial circuits and the service circuits are used both for maintenance and alarm reporting. The two-way end-to-end outage objective for a 250-mile short-haul system is 0.02 percent. A 0.02-percent end-to-end reliability objective therefore is not unreasonable for a 250-mile backhaul trunk. This would also be acceptable for the order-wire and alarm circuits.

Another consideration, however, which does not apply to initial medium-haul installations, but may in the near future, is the necessity of the auxiliary channel to carry control tones for the payload protection switching system. Initial medium-haul applications are protected on a one-for-one basis and do not require control tones for head end switching. Future application of some type of 1-for-n protection switching would however require the auxiliary channel to carry this type of signal. On systems of this type reliability objectives typically allocate 2.0 percent of the total radio system outage time to joint outages of the auxiliary channel. Probability studies indicate this objective can be achieved if the auxiliary channel outage is not greater than 0.02 percent for 250 miles two-way. This grade of reliability can be achieved on the auxiliary channel if it is carried simultaneously over two RF channels and the better channel selected automatically.

Assuming such a one-for-one protection switching arrangement, the fade margin of the auxiliary channel must be at least 35 dB.

2.4 *Payload Interaction*

The above system objectives all center around the auxiliary channel performance itself. The effect of the auxiliary channel on the noise performance of the payload signal must also be considered. The presence of the auxiliary channel must not cause excessive distortion to the payload signal. Since the auxiliary channel signals and the broadband payload signals are jointly carried over a common facility intermodulation effects can and do exist. To realize the benefits afforded by using a frequency-diplexed auxiliary channel, a 1-dB increase in the payload noise due to the presence of the auxiliary channel was judged to be an acceptable tradeoff. Thus for an 1800-channel, 1000-mile radio system equipped with a fully loaded auxiliary channel along the entire route, the noise in a payload circuit could increase from the nominal objective of 35.5 dBrnc0[2] to 36.5 dBrnc0. As will be seen however, the performance ultimately realized degrades the worst offended payload channel by less than 0.5 dB.

III. DESIGN CONSIDERATIONS

Several modulation techniques, such as AM, FM, or PM, might be employed to modulate the auxiliary channel information onto the payload radio channel. The use of an FM or PM modulation process makes it possible to meet the noise performance demanded by the backhaul circuits. Since the baseband signal is also FM modulated onto the radio channel, the VF auxiliary channel signals must first be shifted to an unused portion of the baseband spectrum and then mixed or diplexed with it.

3.1 *Auxiliary Channel Spectrum*

The choice of the shift or diplexing frequency is dependent on many factors, the most important of which is the baseband frequency spectrum occupied by the 1800-circuit payload signal. For TH-3 medium-haul systems the baseband spectrum of the payload and related signals is shown in Fig. 1. The signal from mastergroup multiplex equipment typically used in conjunction with the radio system occupies a band spectrum 0.564 to 8.524 MHz. In some medium-haul applications of TH-3 such as video the baseband spectrum is occupied essentially to dc. To allow the auxiliary channel to be used with any

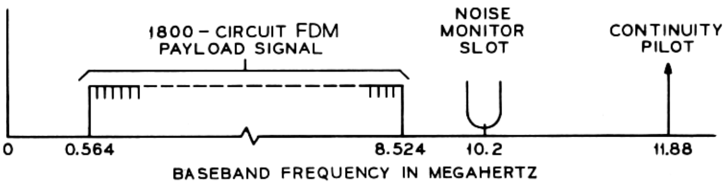

Fig. 1—TH-3 medium-haul baseband frequency assignments without auxiliary channel.

of these applications, a diplexing frequency above the payload is required. A diplexing frequency greater than 10 MHz is also desirable. Although TH-3 has a usable baseband bandwidth out to about 12 MHz, Fig. 1 shows that portions of the spectrum between 10 and 12 MHz are occupied or used for other purposes. The 1×1 protection switch for the radio system utilizes a 17-kHz noise slot at 10.2 MHz and a pilot at 11.88 MHz to control switching logic. In addition, the spectrum at 10.7 ± 0.150 MHz must be avoided since a spurious tone can arise in this region under certain combinations of radio channel frequencies. Based on these restrictions and the need for an absolute minimum bandwidth of 200 kHz for the service and backhaul circuits, the spectrum between 10.7 and 11.88 MHz must be used. Although the available bandwidth in this region is about 1 MHz, the usable portion is less than this. The bandwidth of the auxiliary channel signal should be less than 564 kHz to keep $A - B$ intermodulation products[3] due to second-order nonlinearities below the lower end (564 kHz) of the payload.

The final frequency choice depends on the modulator techniques used to diplex the signal. In this case, a two-step modulation process is used to translate the individual VF circuits to the 11-MHz region. The first step of modulation utilizes conventional SSB suppressed carrier modulators to shift the VF circuits to an intermediate frequency range. To accomplish the second step of modulation i.e., shifting the 8- to 284-kHz SSB multiplex spectrum to the 11-MHz region, a double sideband suppressed carrier* process was selected. The decision to use DSB-AM was influenced by the ability to achieve the diplexing process within the available spectrum with a minimum of circuitry and easily realized filters. With this modulation process the signal also carries its own frequency reference, ensuring end-to-end frequency stability.

* As will be discussed later, some carrier is transmitted along with the sidebands for synchronization purposes, but the modulation process retains all the characteristics of the DSBSC process.

It is necessary to select the exact carrier frequency of the DSB-AM modulator with some care. To eliminate tone interference into the normal 1800-circuit payload (0.564 to 8.524 MHz), the difference between the 11.88-MHz switching pilot and the subcarrier should be less than 0.564 MHz. Also for those applications using multiplexed 4-kHz signals in the spectrum below 564 kHz, the same (A − B) product should fall in the guard band between the 4-kHz slots. Finally, to minimize interference into a video signal, the product should be an odd multiple of the half-line rate (i.e., 15734/2 Hz).[4] Considering all these factors a subcarrier frequency of 11.384379 MHz evolves.

Figure 2 shows the DSB-AM spectrum generated by the two-step modulation process used. This is the signal which is ultimately diplexed onto the radio channel.

3.2 *Noise Performance Factors*

This section develops the relationships between the frequency deviation of the radio carrier due to the auxiliary channel signal and the auxiliary channel noise performance. This provides the basis for selecting the auxiliary channel drive. Having determined this drive, further considerations such as noise contributions of the diplexing circuits and the effects of the auxiliary channel on the 1800-circuit payload are examined.

3.2.1 *Deviation Requirement*

The noise performance of the auxiliary channel (W_{n0}) in dBrnc0 is directly related to the noise power measured at the output of the individual VF circuits. This relationship is:

$$W_{n0} = [N_0 + 88] \text{ dBrnc0}, \tag{1}$$

where N_0 is the rms noise in dbm at the output of the VF channel as measured with C-message weighting and referenced to zero transmission level. The noise, N_0, can be expressed as a function of the signal-to-noise ratio $(S_0 - N_0)$:

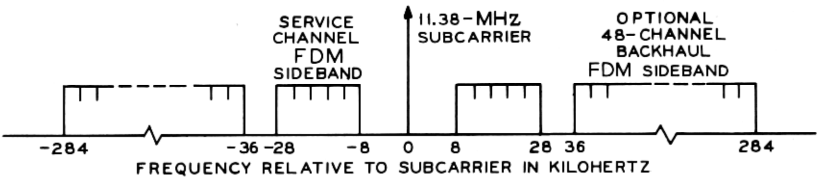

Fig. 2—Auxiliary channel 11-MHz DSB-AM spectrum.

$$N_0 = S_0 - [S_0 - N_0]. \tag{2}$$

The signal S_0 is the rms power in a single message circuit during the average busy hour as measured at the output of the VF channel relative to zero transmission level. The character of the signals carried by the auxiliary channel (i.e., primarily nondata signals) results in S_0 being equal to -17 dBm0. The noise performance can then be expressed as:

$$W_{n0} = [71 - (S_0 - N_0)] \text{ dBrnc0}. \tag{3}$$

When the auxiliary channel is carried over a ten-hop radio system, the noise performance objective is 35 dBrnc0. The signal-to-noise ratio will then be:

$$(S_0 - N_0)_{\text{VF}} \geqq 71 - 35 = 36 \text{ dB}.$$

Since a signal-to-noise ratio is being considered, the reference to zero transmission level may be disregarded. Therefore, in terms of a signal-to-noise ratio, directly at the demodulated VF output, the objective is:

$$(S - N)_{\text{VF}} \geqq 36 \text{ dB}. \tag{4}$$

The auxiliary channel is diplexed onto the radio system by a double-sideband AM process; therefore, the post-detection signal-to-noise ratio is ideally 3 dB greater than the double-sideband predetection signal-to-noise ratio.* Therefore, the per circuit signal-to-noise objective at a point ahead of the DSB demodulation process in the 11-MHz spectrum is:

$$(S - N)_{11 \text{ MHz}} \geqq 33 \text{ dB}. \tag{5}$$

The minimum signal level that will give this signal-to-noise ratio can be determined once the magnitude of the noise has been established. The auxiliary channel signal goes through two distinct tandem transmission paths: the multiplexing and diplexing part of the path which carries only the auxiliary channel signals and the basic radio transmission path which carries both the auxiliary channel signals and the 1800-circuit payload signals. The diplexing circuits were custom designed for the auxiliary channel signal and therefore it was possible to keep their noise contribution to a minimum. Consequently the noise performance of the auxiliary channel is limited primarily

* This assumes that the noise contribution by the DSB and SSB demodulating equipment is negligible.

by noise introduced by the radio system at 11 MHz. The following development of an expression for the required auxiliary channel deviation will initially neglect the effects of the circuit dedicated exclusively to the diplexing of the auxiliary channel. The secondary noise contributions by the diplexing equipment will be considered separately.

The model of the radio system being considered includes one FM terminal pair and ten radio transmitter-receiver pairs (hops). Both the FM terminals and the radio transmitter-receiver pairs are significant noise contributors. Each of these add several basic types of noise:

(*i*) *Idle noise independent of signals carried by the system.* This can be due to shot noise, front end noise, etc. Let p_1 be the noise power contributed by this mechanism from the FM terminals and p_2 be the corresponding contribution of a radio hop.

(*ii*) *Intermodulation products generated from within the 1800-circuit payload signal which fall in the auxiliary channel spectrum.* This will also appear as a contributor to the idle noise floor of the auxiliary channel. Let p_3 be the noise power contributed by this mechanism from the FM terminals and p_4 be the corresponding contributions of a radio hop.

(*iii*) *Intermodulation products generated by the presence of the auxiliary channel signal* (either by itself or interacting with the 1800-circuit signal) *which fall in the auxiliary channel spectrum.* This is conventionally called the intermodulation noise. Let p_5 and p_6 be the noise power contributed by this mechanism for the FM terminals and radio hop, respectively.

The bandwidth and total power of the auxiliary channel signal is sufficiently limited that noise due to contributions from within the third category (p_5 and p_6) are of secondary importance. Therefore only contributions from the first two types of noise will be considered. The measured results reported later in the paper will show this to be a valid approximation.

Since the noise contributions being considered are generated independently, it is reasonable to assume they add to each other on a power basis. Further, the noise p_2, contributed by individual radio hops in a multihop system, will accumulate on a power basis since no correlation exists between hops. The noise contribution p_4, however, may exhibit some correlation between hops. Based on these factors the overall auxiliary channel noise p_N is:

$$p_N = p_1 + np_2 + p_3 + n^k p_4 , \qquad (6)$$

where n is the number of radio hops, k is a correlation coefficient with a range from 1.0 (power addition) to 2.0 (voltage addition).

In order to appreciate the full significance of the term n in equation (6) one must realize that the noise performance of the auxiliary channel is almost completely dependent on the noise performance of the basic radio system. The noise as shown will result from the collective number of hops between the transmitting terminal in the switching section and the station being measured. If one is not in the center of a switching section this number will differ depending on the direction of transmission.

The absolute magnitude of each of the noise powers in equation (6) is dependent upon where they are measured in the system. In an FM radio system a convenient way to express noise levels for comparison purposes is to use the equivalent rms frequency deviation of the radio carrier produced by each noise contributor. Since power is proportional to the square of the frequency deviation, equation (6) may be rewritten as:

$$\bar{f}_N^2 = \bar{f}_1^2 + n\bar{f}_2^2 + \bar{f}_3^2 + n^k\bar{f}_4^2 , \qquad (7)$$

where $\bar{f}^2$ is the rms frequency deviation corresponding to p. Similarly the signal power is proportional to a frequency deviation, $\bar{f}_S^2$. Therefore the signal-to-noise ratio at a point such as the output of the FM receiver can be expressed as:

$$(S - N)_{11\text{ MHz}} = 10 \log [\bar{f}_S^2/\bar{f}_N^2], \qquad (8)$$

where $\bar{f}_S$ and $\bar{f}_N$ are the rms frequency deviations produced by equal bands of signal and noise in the auxiliary channel 11-MHz DSB-AM spectrum. Substituting this into equation (5) yields:

$$10 \log [\bar{f}_S^2/\bar{f}_N^2] \geqq 33 \text{ dB}$$

or

$$\bar{f}_S \geqq 44.6\, \bar{f}_N . \qquad (9)$$

Equation (9) is the desired result. The auxiliary channel per circuit rms deviation of the radio carrier ($\bar{f}_S$) required to meet the 35-dBrnc0 objective may be determined using equation (7) once the corresponding value of $\bar{f}_N$ is determined.

To obtain the data necessary to calculate $\bar{f}_N$ a series of noise measurements were made. The noise in a 3-kHz slot at 11 MHz at the FM receiver output was measured with and without an 1800-circuit noise load signal applied. The contributions for the FM terminals were found to be:

$$\bar{f}_1 = 123.5 \text{ Hz (for 3-kHz band centered at 11 MHz)}$$

$$\bar{f}_3 = 67.0 \text{ Hz.}$$

The measurements also indicated the idle noise contributed by a radio hop ($\bar{f}_2$) to be 47.5 Hz. Since these measurements were made on a radio system having 1 dB higher idle noise than the objective,[5] a correspondingly lower value for $\bar{f}_2$ is used here, i.e.,

$$\bar{f}_2 = 42.3 \text{ Hz.}$$

To determine $\bar{f}_4$ and the law of addition (k), the noise measurements were repeated with the number of hops a variable. Two possible radio system configurations were considered. The 1044A IF bandpass filter is normally used at each repeater. For this case:

$$\bar{f}_4 = 44.9 \text{ Hz}$$

$$k = 1.0.$$

For certain possible radio interference conditions a narrower IF bandpass filter (1009A) may be required. For systems using this filter:

$$\bar{f}_4 = 60.5 \text{ Hz}$$

$$k = 1.25.$$

Since the use of the 1044A filter is the normal case, the corresponding values for $\bar{f}_4$ and k will be used in this analysis. Therefore, with the following values inserted in equation (7):

$$\bar{f}_1 = 123.5 \text{ Hz}$$

$$\bar{f}_2 = 42.3 \text{ Hz}$$

$$\bar{f}_3 = 67.0 \text{ Hz}$$

$$\bar{f}_4 = 44.9 \text{ Hz}$$

$$n = 10$$

$$k = 1.0,$$

$$\bar{f}_N = 239.5 \text{ Hz in a 3-kHz band at 11 MHz, and}$$

$$\bar{f}_S = 10{,}700 \text{ Hz* per 3-kHz sideband at 11 MHz.}$$

* For comparison purposes the deviation level of the top (8.5 MHz) circuit in the 1800-circuit payload on a medium-haul system is 20,000 Hz. At this deviation level a ten-hop noise performance, including a 3A FM transmitter and a 4A FM receiver, of about 30 dBrnc0 is achievable.

Thus, based on the idle noise floor at 11 MHz due to the radio system alone, each 11-MHz VF sideband must be impressed on the radio carrier with at least 10,700 Hz rms frequency deviation. If no other noise sources were present this is the deviation required to just meet the 35-dBrnc0, ten-hop objective. Two additional factors must be taken into consideration to determine the actual frequency deviation. The first of these involves the secondary noise sources previously mentioned. The total noise from the auxiliary channel diplexing and multiplexing circuits may be quantatively expressed as follows:

SSB-AM Multiplex Equipment	23 dBrnc0
11-MHz DSB-AM Diplexing Equipment	16 dBrnc0
	Total—23.8 dBrnc0

The composite of these noise contributions must be considered a part of the overall 35-dBrnc0, ten-hop auxiliary channel noise objective. Increasing the auxiliary channel drive 2 dB (i.e., to a frequency deviation of 13,350 Hz per sideband) will allow sufficient margin to insure meeting the overall 35-dBrnc0 objective.

3.2.2 *Noise Introduced into 1800-Circuit Payload*

As indicated in Section 2.4, the objective for noise introduced into the 1800-circuit payload signal by the presence of the auxiliary channel signal is 1 dB or less. This interaction noise is primarily due to intermodulation effects. Intermodulation products between the 1800-circuit payload and the 11-MHz auxiliary channel signals, and products generated from within the auxiliary channel signal itself, may fall back into the payload spectrum. Of these contributors only the first type involving product formation between the auxiliary channel and payload signals are of importance. The spectral width and location of the 11-MHz DSB-AM signal were carefully chosen to keep intermodulation products generated from within the auxiliary channel signal out of the payload spectrum. However intermodulation between the two signals can result in products (A − B and A + B for example) which fall into the payload occupied spectral region between 2.576 and 8.524 MHz. The noise produced by these products, which are generated as a result of radio system nonlinearities, will be uncorrelated with the intrinsic payload channel noise. Therefore power addition between the intrinsic and auxiliary channel induced noise may be assumed. With a nominal ten-hop FM-terminal-to-FM-terminal payload performance of about 30 dBrnc0, the noise introduced into the payload by a fully loaded auxiliary channel signal

(48 backhaul circuits and 3 service circuits) traversing the same hops may be as much as 24 dBrnc0 without exceeding the 1.0-dB degradation objective. Analysis of the results of the measurements mentioned earlier indicated that this would not be a difficult requirement to meet at the 13,350 Hz per circuit deviation level. A worst case ten-hop terminal-to-terminal value of 13.5 dBrnc0 was indicated by the measurements. Thus the degradation can be expected to be about 0.1 dB.

3.3 *Repeater Deviation Process and Modulator Requirements*

3.3.1 *Deviation Process*

The 11-MHz DSB-AM auxiliary channel signals must be diplexed onto the radio channel at each radio site. At a terminal station, where access to the baseband signal exists, the diplexing process is relatively simple, requiring only a direct addition of the 1800-circuit payload and 11-MHz auxiliary channel signals ahead of the FM terminals. At an IF radio repeater where access to the baseband signal is not available, the diplexing process is more involved. The desired end result is the same, however. The local 11-MHz auxiliary channel signal must be applied in such a manner that the resulting FM on the outgoing radio carrier is the same as if the baseband signal causing the existing FM on the incoming IF signal were added linearly with the new 11-MHz signal and the composite then used to frequency modulate the outgoing radio carrier. What is desired in this case is a process obeying the following equations:

Given the radio signal coming into a repeater station:

$$v_i(t) = A_i \cos [\omega_c t + \phi_i(t)],$$

where ω_c = carrier radian frequency (RF or IF), $\phi_i(t)$ = instantaneous phase argument due to existing payload frequency modulation. The desired output radio signal after adding the new auxiliary channel information is:

$$v_0(t) = A_0 \cos [\omega_c t + \phi_a(t) + \phi_i(t)],$$

where ω_c and $\phi_i(t)$ are as previously described and $\phi_a(t)$ = instantaneous phase argument due to the auxiliary channel. Since both frequency and phase modulation produce complex spectrums, it is difficult to realize the desired output signal without introducing excessive distortion into both modulation arguments as well as interaction between them. One technique however which has been used to accomplish this without these pitfalls involves modulating the converter beat oscillator signal before combining it with the through path signal.

Figure 3 shows how this process is used at a TH-3 repeater to modulate the 11-MHz auxiliary channel signal onto the outgoing radio carrier. The locally generated DSB-AM 11-MHz auxiliary channel signal, $v_a(t)$, is applied as phase modulation on the transmitter microwave carrier, ω_{BO}, via a varactor type phase modulator (16A modulator). Therefore, at the output of the 16A, the microwave carrier signal is of the form:

$$v_{BO}(t) = \cos [\omega_{BO}t + \phi_a(t)],$$

where $\phi_a(t) = kv_a(t)$.

This phase-modulated signal and the already frequency-modulated IF signal,

$$v_{IF}(t) = \cos [\omega_{IF}t + \phi_i(t)],$$

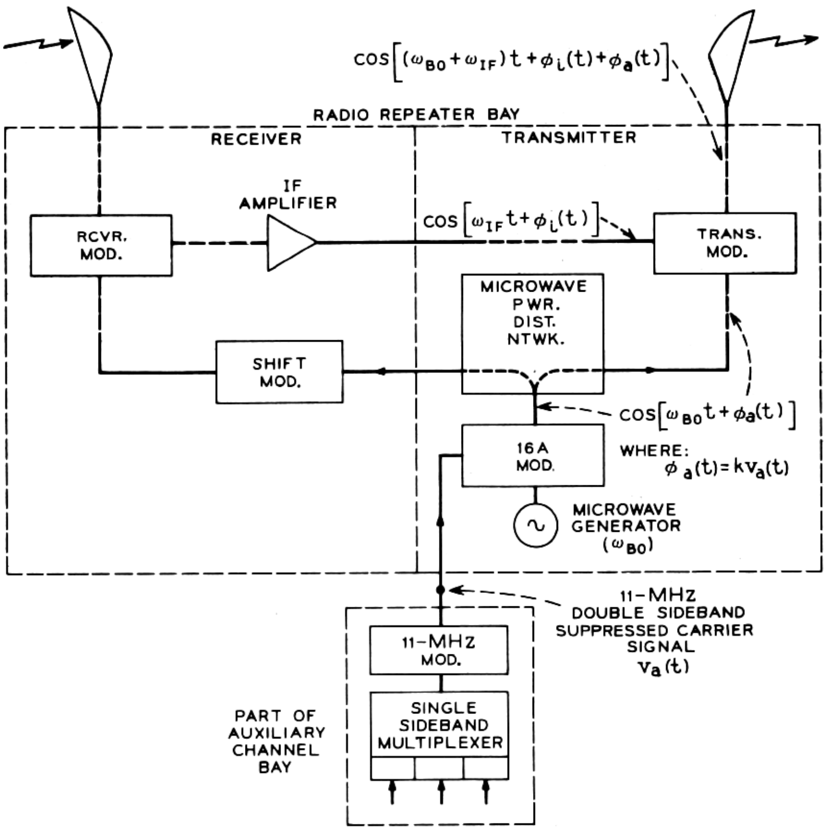

Fig. 3—Auxiliary channel transmitter.

are applied as inputs to the transmitter upconverter. The upconverter forms the product of these inputs, thus generating sum and difference frequencies. RF filtering is used to select the sum frequency:

$$v_0(t) = \cos [\omega_c t + \phi_i(t) + \phi_a(t)],$$

where $\omega_c = \omega_{IF} + \omega_{BO}$,
which is the desired result.

Note that Fig. 3 also shows that a shifted version of modulated microwave carrier is used in the receiver downconverter. The 11-MHz modulation is stripped off the receiver microwave carrier before it reaches the downconverter by the normal selectivity included in this path. This avoids the problem of double modulation.

It should also be noted that phase modulation is used to modulate the 11-MHz auxiliary channel signal onto the transmitted carrier even though a frequency demodulator is used at subsequent points to recover this information. Because of the relatively narrow band involved with the 11-MHz modulating signal, the difference between PM and FM is negligible. No shaping is used to account for the fact that the modulation is ultimately recovered with an FM demodulator. An advantage of this type of modulator is that it is in tandem with the microwave generator. This preserves the inherent frequency stability of the microwave carrier.

3.3.2 *Phase Modulator Requirements*

Figure 4 shows a simplified schematic of the 16A phase modulator. The unmodulated 6-GHz signal appearing at the coaxial input port (RF IN) is routed by a circulator to port 2 and into the reflecting coaxial side arm containing a reverse-biased varactor diode. The 11-MHz modulating signal is superposed on the dc reverse bias and causes the junction capacitance and therefore the equivalent electrical length

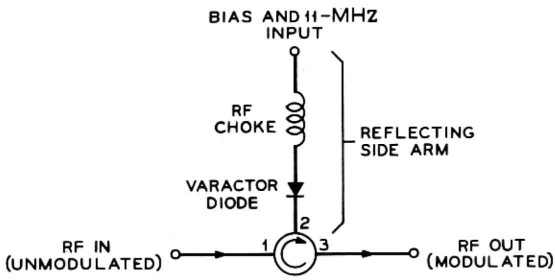

Fig. 4—Simplified schematic of 16A phase modulator.

of the reflecting side arm to vary. The reflected 6-GHz signal which ultimately leaves port 3 of the circulator (RF OUT) is thus phase modulated by this process.

This type of phase modulator is extremely reliable and economical but is limited to relatively low modulation indices due to the inherent nonlinear relationship between junction capacitance and applied voltage. However, careful design and choice of operating parameters coupled with a low modulation index permitted a modulator design meeting linearity constraints.

With a full complement of service and backhaul circuits, the deviation required to meet noise performance requirements dictate that the 16A must be capable of producing a 10-degree peak deviation (index = 0.174) without appreciable modulation distortion products due to overload.[6] With a modulating spectrum of 568 kHz centered at 11.38 MHz, the main products of concern are the second-order (2A), (A − B), and third-order (A + B − C) types.[3] With approximately 30-MHz RF channel spacing, excessive (2A) products (22.76 MHz modulation) could result in interference in an adjacent TH radio channel or another system using the same frequency plan. The (A − B) products, on the other hand, will generate interference which generally falls below the lower end of the normal 1800-circuit payload spectrum (564 kHz). For those applications using this lower portion of the baseband however, this interference must be kept to tolerable levels. Finally, the third-order (A + B − C) products fall back into the auxiliary channel itself and these must also be controlled if noise objectives are to be met. Analysis and testing showed that to meet the noise objectives dictated by the above considerations, a modulator meeting the following linearity requirements was required.

For ± 10-degree peak deviation by a single sine wave at 11.38 MHz:

$$20 \log [v_{1f}/v_{2f}] = 20 \text{ dB},$$

$$20 \log [v_{1f}/v_{3f}] = 25 \text{ dB},$$

where v_f = voltage at frequency f at the output of an FM receiver detecting modulation and

$$v_{2f}, v_{3f} = \text{2nd, 3rd harmonics of } v_f .$$

After considerable design effort and optimization of modulator parameters such as diode type, diode location, and operating bias, a modulator meeting the above objectives was achieved. Other important constraints such as a nominal deviation sensitivity of 2.6 degrees/volt and an RF insertion loss less than 1 dB were also met. Further, only a single modulator configuration was required for all the possible TH-3 microwave carrier frequencies. (5.875–6.335 GHz)

Figure 5 is a photograph of a TH-3 repeater bay equipped with a 16A modulator.

IV. SYSTEM DESCRIPTION

The first step of the two-step modulation process utilizes conventional SSB suppressed carrier modulators to shift the VF circuits to an intermediate frequency range. The service circuits are shifted to a band of 4-kHz slots between 8 and 28 kHz. Similar multiplex equipment is available to provide the optional backhaul feature. The spectrum between 36 and 284 kHz is allocated for this purpose.

In most multiplex systems, the oscillators used for demodulation at the receiving end of a multiplex link are synchronized to those used at the transmitting end. This is the technique used with the backhaul circuits; however, its use with the three service circuits would result in a relatively high cost per circuit. To eliminate the need for synchronization in this case, the service channel transmit and receive units are each equipped with independent crystal controlled oscillators. The stability of these oscillators is adequate to hold the end-to-end VF error due to this source to ± 2 Hz. This stability is more than adequate for all service channel uses.

Unlike the first step of modulation, where existing equipment was used, the shift to 11 MHz required the development of new equipment. Except for the synchronization technique the modulators and demodulators involved are quite conventional. Both use standard balanced ring modulators and filter configurations to generate and demodulate the DSB signal. A local crystal oscillator is used in each case to produce the diode switching necessary for product formation. For synchronization purposes the modulator at a terminal radio station is deliberately unbalanced to allow a small amount of properly phased local carrier to leak out with the sidebands. At subsequent demodulators this carrier is picked off and a local voltage-controlled crystal oscillator is locked to it by a phase lock loop circuit.* The free-running stability of the 11-MHz crystal oscillators used and the gain of the phase loop is such that under worst case "pull-in" the

* If as is used here a product demodulator is used to demodulate the DSBSC signal, the local carrier used at the demodulator must be of the same phase that the original carrier used for modulation would be at the point of demodulation; otherwise quadrature distortion results and the amplitude of the detected signals roll off as the cosine of the phase error.

maximum phase error of the regenerated carrier is less than 5 degrees. When the oscillator is locked the frequency is exactly that of the leaked carrier and therefore the frequency error introduced by the shift to 11 MHz and back is zero. To insure the proper phasing of auxiliary channel information launched at a repeater, the 11-MHz modulators are also phase and frequency synchronized to the leaked

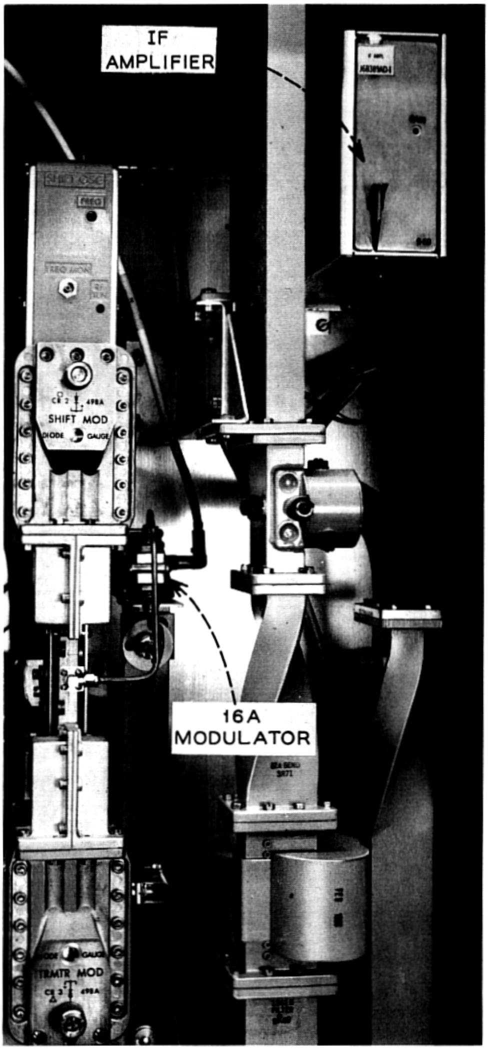

Fig. 5—TH-3 equipped for auxiliary channel.

carrier by utilizing a similar scheme. Figure 6 is a photograph of the DSB-AM modulator/demodulator panel.

4.1 *Terminal Station*

After being DSB-AM modulated to the 11-MHz region, the auxiliary channel information must be impressed on the radio signal as FM. Figure 7 shows an auxiliary channel terminal station. At a terminal radio station where there is access to the baseband signal, the existing baseband and the locally generated DSB 11-MHz auxiliary channel signal are added linearly in a resistive combining network. The composite is then used to deviate the 70-MHz IF signal via the FM terminal. Note also that it is at this point that the 11.38-MHz subcarrier required for synchronizing subsequent 11-MHz modulators and demodulators is launched.

Recovery and demodulation of the 11-MHz auxiliary channel signal from other stations is also a simple matter at a terminal station. At the output of the terminal FM receiver, the desired 11-MHz band along with the synchronizing 11.38-MHz carrier launched at the other end of the system is separated from the composite signal by a resistive splitting network and the appropriate filter. The filter in this case is built into the 11-MHz demodulator which synchronously demodulates the DSB-AM signal to recover the 8- to 284-kHz SSB multiplexed spectrum of the service and backhaul information.

4.2 *Repeater Station*

At a radio repeater access to the baseband signal is not available since IF repeaters are employed. Therefore the process of adding new and recovering existing auxiliary channel information is more difficult.

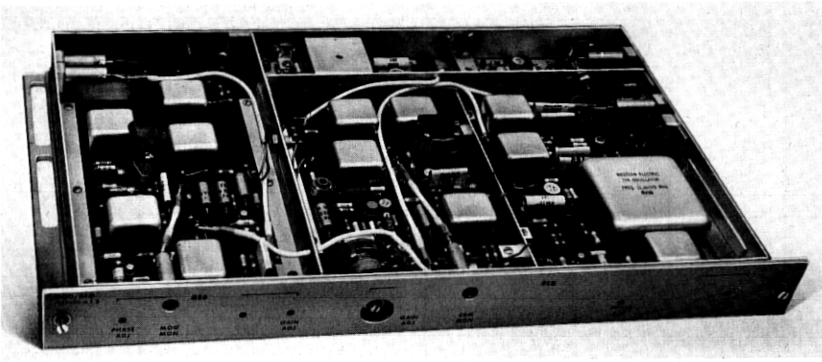

Fig. 6—DSB-AM repeater modulator/demodulator panel.

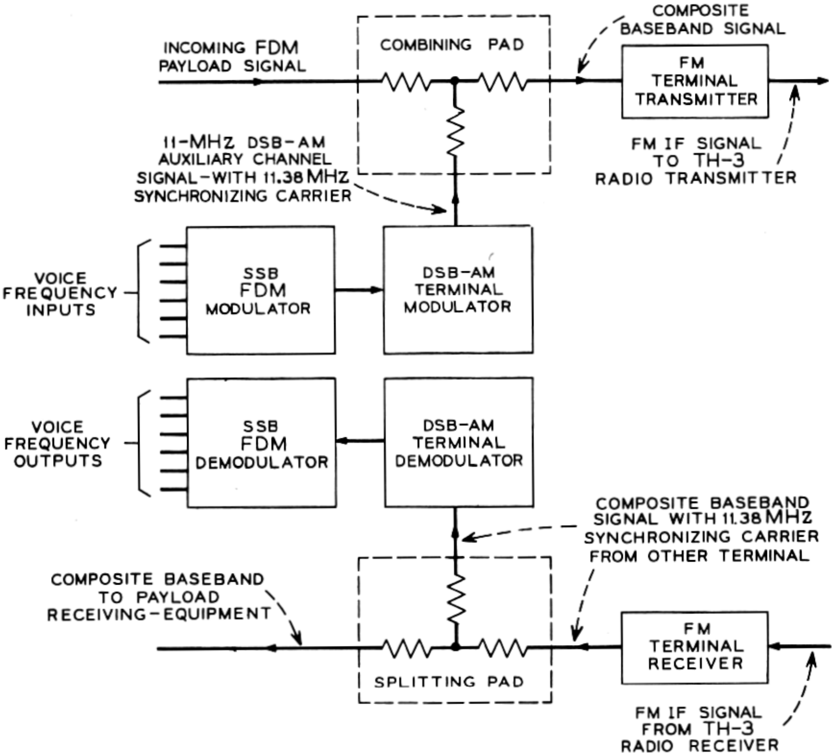

Fig. 7—Auxiliary channel diplexing process at a terminal radio station.

4.2.1 *Receiver*

Figure 8 shows how the recovery process is achieved at a repeater. A portion of the frequency-modulated 70-MHz IF signal is picked off the thru path at point "A," amplified, and FM demodulated to gain access to the composite baseband. At this point the auxiliary channel signal is synchronously demodulated by a circuit identical to the terminal receiver. Since this process adds no active circuitry to the transmission path, it is possible for the existing IF signal to continue through the repeater undistorted.

4.2.2 *Transmitter*

Modulating the 11-MHz auxiliary channel information onto the FM radio signal at a repeater is more involved. For subsequent 11-MHz DSB demodulators to properly demodulate the 11-MHz sidebands launched at a repeater, the sidebands added at a repeater must have the correct phase relationship to the existing 11.38-MHz synchronizing subcarrier. If this phase relationship is not achieved, quadrature distortion will result. The 11-MHz sidebands added at a repeater must have the same phase relationship to the 11.38-MHz carrier as if they were launched via the terminal modulator. Just

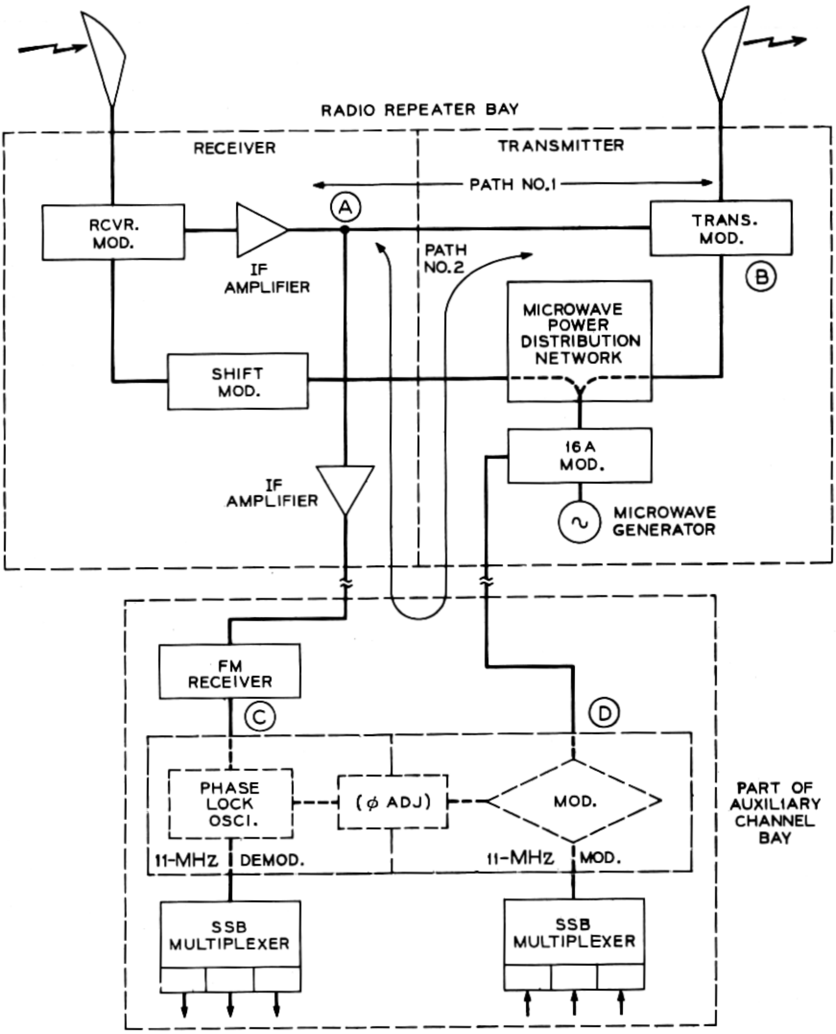

Fig. 8—Repeater auxiliary channel modulator synchronization.

as with the demodulator, this requires that the local 11.38-MHz carrier used to generate the 11-MHz DSBSC signal at a repeater also be phase synchronized to the existing 11.38-MHz subcarrier. Figure 8 shows how the required synchronization and absolute phase angle of the modulator carrier is achieved by using a portion of the demodulator phase-locked carrier.

Relative to the phasing problem, the points in the radio thru path marked "A" and "B" are of critical concern. Point "A" is the point at which the IF signal for the auxiliary channel receiving equipment is bridged from the main thru path signal. Point "B" is the point in the upconverter where the newly added 11-MHz DSBSC information, now existing as FM on the microwave carrier, finally mixes with the existing 11-MHz DSB-AM information from the preceeding station. Point "C" is another important point relative to this discussion. This is the point at which the local phase-locked oscillator is synchronized to the existing 11.38-MHz subcarrier.

As the thru signal travels from "A" to "B" over path 1, the 11.38-MHz carrier, existing as FM sidebands on the IF signal, undergoes a phase shift. The phase of the local 11.38-MHz phase-locked oscillator, on the other hand, is synchronized to the detected 11.38-MHz carrier existing at point "C" in path 2. The phase shift in the carrier from "A" to "C" also depends on the delay and absolute phase shift associated with the equipment and variable length cabling in this path. Similarly there is a variable amount of delay or phase shift associated with the circuits and cabling between the output of the 11-MHz DSBSC modulator, point "D", and the mixing point "B" over the remaining part of path 2. This latter phase shift affects the modulated sidebands only since the carrier is fully suppressed in this case. The phase of the 11.38-MHz carrier is contained in the sidebands however and it is this equivalent phase that is important when the new sidebands ultimately join the thru path signal (at point "B"). To avoid quadrature distortion when the signal is demodulated, the phase angle of the equivalent 11.38-MHz carrier relative to the existing carrier should be zero or 180 degrees (polarity of signals added at a repeater relative to other auxiliary channel signals is not important for the type information being carried). To compensate for the variable phase shift over path 2 relative to that over path 1, an adjustable phase shifter (ϕ ADJ in Fig. 8) is used in the carrier path between the output of the 11.38-MHz phase-locked oscillator and the ring modulator used to generate the repeater 11-MHz DSBSC signal. Once set, the delays and phase shifts associated with the various circuit elements involved in the two paths are stable enough to hold the phase error within a few degrees. This is more than adequate for the applications involved.

4.3 *Auxiliary Channel Switching*

Auxiliary channel transmission outages may be the result of either equipment failures or propagation disturbances. Since the auxiliary channel is carried over the basic radio, when a radio channel on a particular hop experiences a transmission outage, so will the auxiliary channel on that radio channel. This could represent somewhat of a problem since alarms and order wire are always most needed during outage periods. The outgrowth is the need for a protection switching arrangement for the auxiliary channel. Conceptually this is straightforward. The auxiliary channel signals are simultaneously carried over two separate RF channels and the better performing is automatically selected for use. The outage time of the auxiliary channel can then be reduced to a matter of only minutes per year.

The reasons why information introduced at a repeater must be phase synchronized with the information coming from the preceding stations has already been discussed. This requirement has a strong influence on the design of the auxiliary channel protection switching system. It means that the terminal station and all the repeater stations must have their auxiliary channel switch on the same RF channel. This in turn suggests that the quality of auxiliary channel transmission be established at the receiving terminal station and a choice made. The repeater switches can then be slaved to the switch at the receiving terminal station. Figure 9 shows this relationship. The switch at the receiving terminal station includes a control oscillator panel which generates one of two VF tones depending on the status of that switch. The tone is sent back over the system, in the opposite direction, to the repeater stations where it causes the repeater switches to operate to the same RF channel.

This figure shows transmission in only one direction. There exists a mirror image (not shown in Fig. 9) for transmission in the opposite direction. The photograph in Fig. 10 shows an overall repeater auxiliary channel bay.

V. SYSTEM PERFORMANCE

The overall performance objective for the auxiliary channel is that it be capable of carrying the required service circuits and up to forty-eight backhaul circuits. While extensive laboratory testing and analyt-

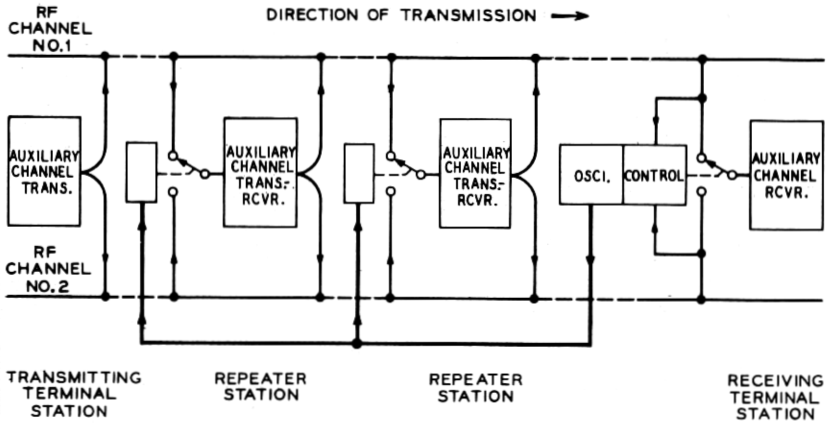

Fig. 9—Slaved protection switching.

ical work was done during all phases of development to insure meeting objectives, final evaluation ultimately requires statistical data from the field. Field testing of the initial installation, a four-hop TH-3 medium-haul route between Great Falls and Shelby, Montana, indicates that noise and reliability objectives are being met.

5.1 *Backhaul Noise Performance*

The technique of noise loading is typically used to evaluate the noise performance of broadband systems. As mentioned earlier the noise performance of the auxiliary channel is dominated by the radio system which carries the composite 1800-circuit payload plus the auxiliary channel (3 service and 48 backhaul circuits). The noise contribution of the auxiliary channel equipment carrying only the 51-circuit FDM signal is small enough to be neglected. Therefore it is possible to ignore the statistical considerations associated with the narrowband 51-circuit signal itself. This permits the use of conventional noise loading for evaluating overall auxiliary channel noise performance.

Figure 11 shows some typical noise loading results under the above loading conditions over the Great Falls to Shelby route. Curve A shows the noise load result thru a typical 11-MHz DSB-AM modulator and demodulator connected back-to-back. Curve B shows the results with the same units thru a 3A FM terminal transmitter and 4A FM terminal receiver connected back-to-back at IF. In this case a noise-simulated 1800-circuit payload is also present at the input to

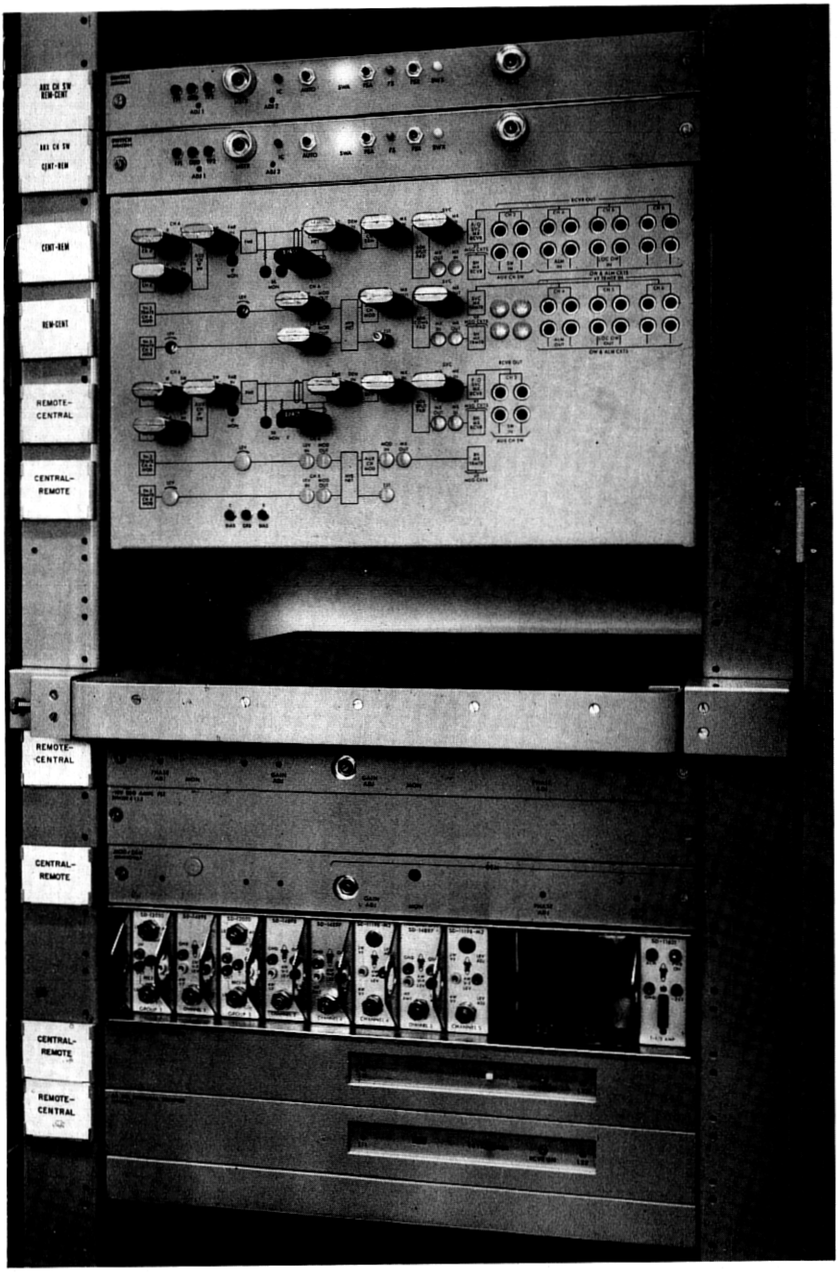

Fig. 10—Repeater auxiliary channel bay.

the 3A FMT at the average busy hour reference drive level. The 11.88-MHz switching pilot was also present to create essentially normal operating conditions. Curve C shows the results, under the same conditions, over the four-hop Great Falls to Shelby route. For comparison purposes, curve D shows the results at the end of the same four hops with the auxiliary channel signal applied via a 16A modulator at a repeater station (three hops away from the measuring end). The simulated 1800-circuit payload signal remained on the system during this measurement.

A four-hop noise performance of 33 dBrnC0 at reference drive was determined from the measurements. It should be noted that when these measurements were made, the radio system was equipped with 1009A IF bandpass filters. Using the appropriate rms noise deviations given in Section 3.2, equation (7) predicts a four-hop performance which agrees within 0.2 dB of this measured result.

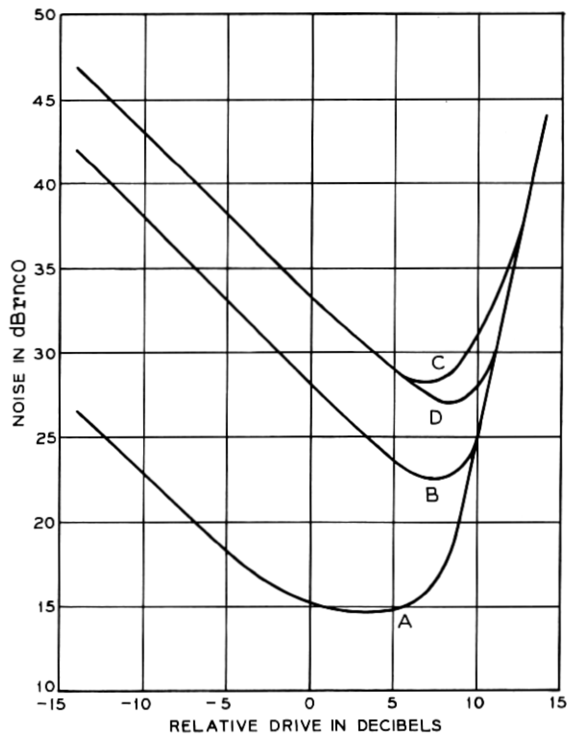

Fig. 11—Forty-eight channel noise loading results (70 KHz).

Note also from curve D that the noise contribution of the 16A modulator to the auxiliary channel noise performance is negligible compared to the rest of the system.

5.2 *Fade Margin*

To meet reliability objectives, the auxiliary channel performance should insure that in the presence of a 35-dB RF fade, the noise will not exceed 55 dBrnc0. For a hop with a nominal received RF signal of −23 dBm at the radio bay, this requirement was met at the 13,350 Hz per 3-kHz sideband deviation level. Analysis indicates nominal hops will have about 37 dB fade margin.

5.3 *Measurement of Payload Interaction*

Since the primary interference into the 1800-circuit payload is due to intermodulation products between the 11-MHz auxiliary channel signal and the payload, the noise performance of the payload signal was also studied by noise loading techniques. Several slots within the normal 0.564- to 8.524-MHz payload spectrum were carefully measured with and without 48-circuit noise load applied. This was done with the auxiliary channel signal applied via the 3A FMT as well as via the 16A modulator at a repeater. The measurements showed that the top payload circuit experienced the greatest noise increase. The degradation easily met the 1-dB objective (typically 0.1 to 0.2 dB).

Measurements in a slot below the normal payload spectrum were also made to evaluate the (A − B) noise from the auxiliary channel spectrum itself. Again this was done with the noise loaded auxiliary channel signal launched via the 3A FMT as well as the 16A modulator. For a slot at 70 kHz the increase in noise due to the auxiliary channel on the Montanna four-hop system was 2 dB. This was for the case where the auxiliary channel was applied via the 3A FMT. With the auxiliary channel signal applied via each of several 16As at repeaters, the increase was less than 0.5 dB. The predominant source of the direct interfering (A − B) products was the 3A FMT. Therefore, for a ten-hop system, the increased noise should be even less than 2 dB. The lower payload channels are generally less noisy than those at higher frequencies, therefore this interference level should be acceptable even for those special applications using the spectrum below 564 kHz.

An improved FM terminal (4A FMT) further reduces the noise due this source.

5.4 *Operational Performance*

Many other facets of system performance besides noise performance were studied. Such factors as system operation and stability during switching activity were also studied. In all cases the system functioned properly without loss of synchronization or communication between stations. In addition, stability measurements over a period of several months indicate that the system and propagation characteristics are stable enough to achieve the desired reliability. Thus, considering all factors, the frequency-diplexed auxiliary channel system should prove to be a useful and economical means of providing the surveillance, control, and other functions required for the maintenance of the radio system. The established noise performance should also make the backhaul feature an attractive option.

VI. ACKNOWLEDGMENTS

The frequency-diplexed auxiliary channel has been developed as the result of efforts by many members of Bell Telephone Laboratories. The cooperation of the American Telephone and Telegraph Company, Western Electric Company, and Mountain Bell Telephone Company was also important to the success of this undertaking.

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