THE BELL SYSTEM TECHNICAL JOURNAL
Vol. 62, No. 10, December 1983
Printed in U.S.A.

The AR6A Single-Sideband Microwave Radio System:

Equalization for Multipath Fading

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(Manuscript received February 25, 1983)

Multipath fading can introduce severe amplitude distortion and level changes in a radio channel. These must be dynamically equalized to meet the toll transmission requirements of AR6A. This article describes equalizer circuitry at intermediate frequencies, which continuously senses the level as a function of frequency in the transmission band and dynamically corrects the effects of multipath fading.

I. FADING CHARACTERISTICS

In line-of-sight microwave radio transmission, the broadband radio channels (20 to 30 MHz) can exhibit the phenomena of both selective and nonselective fading. During nonselective fading, the signal power across the channel remains constant with frequency and simply decreases in level. This type of fade can be caused by attenuating effects of the atmosphere or it can be the precursor of selective fading. Some atmospheric conditions can cause propagation over two or more distinct paths, resulting in the reception of multipath components.[1] This event can cause the channel to experience selective fading. During selective fading, not only does the channel show a decrease in received signal power, but the signal level measured as a function of frequency (frequency response) also contains one or more minima.[2] Reference 2

* Bell Laboratories.

contains graphs of measured field data showing typical time-varying frequency responses of a channel during selective fading.

A fade model consisting of four to six multipath components can match most observed channel characteristics.[3] However, a two-path fade model closely approximates a large number of observed channel characteristics.[4] The two-path model has the transfer function:

$$H(f) = 1 - re^{-j2\pi(f-f_0)\tau},$$

where f_0 is the frequency of maximum fade (i.e., minimum signal level) and τ is the delay difference in the two path lengths. The expression $-20 \log (1 - r)$ is the fade depth at frequency f_0.

Computer simulations were used to show that a two-path fade with a fade depth of 20 dB, a time-delay difference of 4 ns, and all possible frequencies of fade maximum (f_0) matches adequately the amplitude characteristics of the worst fades that would have to be equalized to meet system outage objectives for AR6A.*,† An equalizer that could compensate for such a fade to within ±2 dB of the nominal level for all values of the fade center frequency, f_0, will meet system specifications. Some examples of channel characteristics undergoing a two-path, 20-dB, 4-ns fade are shown in Fig. 1.

A good approximation of this selective fade characteristic can be obtained using a power series expansion truncated after the quadratic term: $H(f) = A_0 + A_1(f - f_m) + A_2(f - f_m)^2$, where f_m is the midchannel frequency. The flat term, A_0, can be compensated using an Automatic Gain Control (AGC) amplifier leaving the shaped component alone to be equalized.

From the two-path model of the fading channel, the range of the linear term, A_1, must be ±18.5 dB and the range of the quadratic term, A_2, must be 17 dB. However, large values of the quadratic and linear shaping coefficients are not required simultaneously. This allowed the use of two Bode "bump" networks[5] with center frequencies at the channel ends to jointly realize the linear and quadratic correction terms.[6] It was further determined that a ±10 dB range on each of the Bode "bump" networks is sufficient to meet system requirements on shape equalization. Figures 2 and 3 depict the approximation of linear and quadratic correction functions by Bode "bump" networks. This technique has many advantages with respect to dynamic range and control circuitry, as well as noise figure and intermodulation distortion.

The remaining system equalization objective concerns the rate of change of the channel shape as a selective fade sweeps through the channel. Field data indicate that during deep selective fading, the rate

* Amplitude Modulation Radio at 6 GHz for the initial (A) version.

† Acronyms and abbreviations used in the text and figures of this paper are defined at the back of this *Journal*.

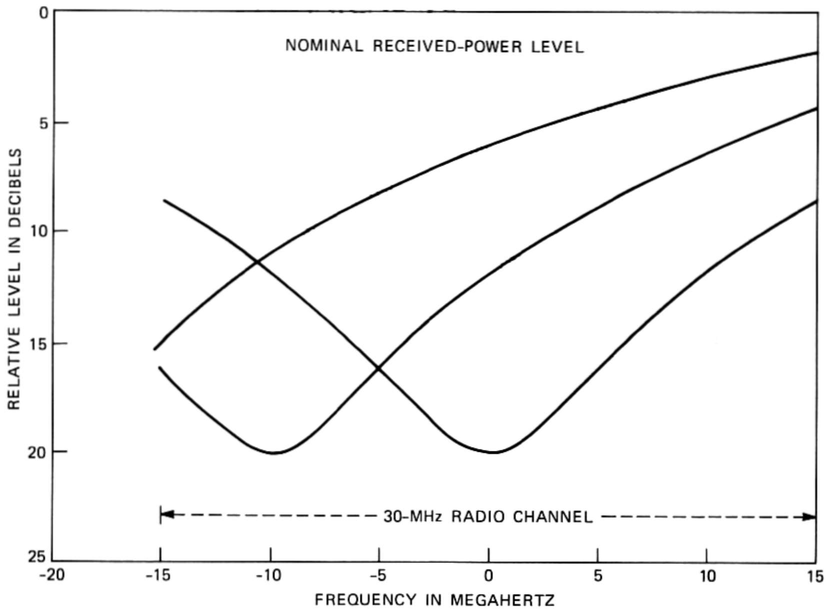

Fig. 1—Typical received-power frequency characteristic for the two-path model of a 20-dB, 4-ns fade in a 30-MHz channel.

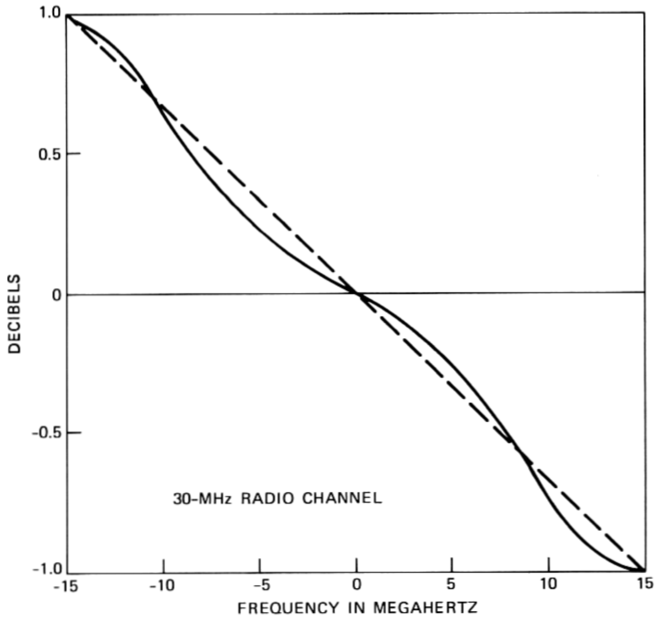

Fig. 2—Summation of two Bode "bump" networks to approximate a linear shape.

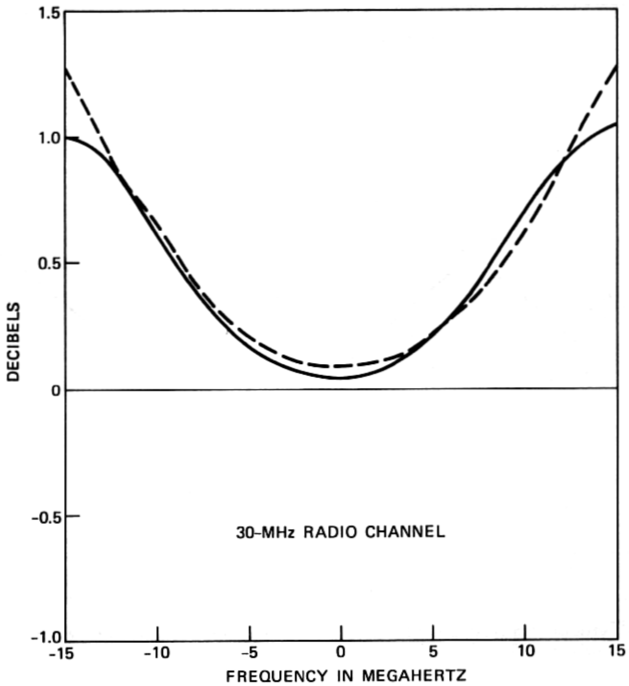

Fig. 3—Summation of two Bode "bump" networks to approximate a quadratic shape.

of change of signal level can be as high as 90 dB per second. Since the most severe fades will be eliminated by space-diversity switching, an objective of adapting to a rate of change of 50 dB per second was established.

II. FUNCTIONAL DESCRIPTION

An error-detecting, zero-forcing technique was chosen to dynamically control the variation of the AGC and shape units. Three pilot tones are transmitted in the radio channel, one near each edge and one near the center. The pilot errors are determined by analog processing of the detected pilot levels. The errors thus determined are fed back to an analog circuit that varies the AGC and equalizer shape coefficients to force the detected errors to zero at the pilot frequencies. The control loop also detects when a space-diversity switch or pilot resupply should be initiated.

Figure 4 is a functional block diagram of the units comprising the dynamic equalizer.

2.1 Gain and equalization control

Gain in the intermediate frequency (IF) channel is controlled by an AGC amplifier that is present at both repeater and main stations. The

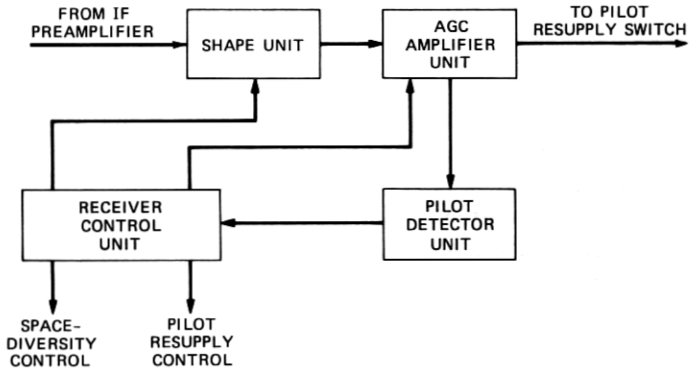

Fig. 4—Block diagram of the AR6A dynamic equalizer.

frequency characteristics of the IF channel are controlled by a shape unit that consists of electronically controlled Bode "bump" networks peaked at the high and low ends of the band. The shape unit is provided only at main stations.

The detector unit senses the levels of the three equalization control pilots and the pilot resupply enable pilot. Processing of the detected pilot levels is done within the receiver control unit. An error voltage for the low (high) bump is derived by subtracting a reference from the difference of the low (high) pilot level and the center pilot. An error voltage for the AGC is formed by subtracting a reference from the average of the three equalization pilot levels. These error voltages will all be zero when the three equalization pilots are at their nominal level. The error voltages are amplified, low-pass filtered, and used as the electronic control for the AGC amplifier and bump shapes.

Nonlinear shaping is provided in the control characteristics of the AGC gain and bump networks such that the gain (in dB) introduced is proportional to the drive voltages. A closed-loop gain of 100 is provided. A 1-Hz cutoff in the loop filter results in a closed loop response time of 10 ms.

The dynamic equalizer has been designed to regulate the pilot levels to within 0.5 dB of their nominal value under conditions of nominal input. For a 20-dB step change in input, the equalizer will settle to within 2 dB of its final value in under 10 ms. Also, a maximum dynamic tracking error of 2 percent of the fade depth in decibels is achieved for fade rates of less than 50 dB per second.

The dynamic equalizer has been designed to achieve a gain flatness of ±0.15 dB at nominal temperatures and ±0.5 dB over the temperature range of 40 to 120 degrees F.

The dynamic equalizer achieves a maximum noise figure of 20.7 dB and third-order intermodulation coefficient for $A + B - C$ products of −72.9 dB for main-station applications.

2.2 Space-diversity and pilot resupply control

The regulation accuracy requirements dictate that the pilot detector realize a precise measure of the nominal pilot level. A low-precision realization of the control loop would suffice were it not for a requirement to precisely determine the crossing of thresholds used to initiate a space-diversity switch.

A space-diversity switch will be initiated if any pilot at the *input* to the dynamic equalizer is more than 36 dB below its nominal level. To avoid the need for separate detectors to monitor this condition, the space-diversity control is derived within the dynamic equalizer circuitry. It turned out that this requirement limited the control circuitry design.

The detector output is an indication of the output pilot value relative to its nominal value. The control voltages to the AGC and bump networks are an indication of the amount of gain supplied between the equalizer input and output. Nonlinear shaping of the detector, AGC, and bump-network control characteristics yields a linear relationship in units of dB per volt; a weighted sum of the detector outputs and the control voltages yields a measure of the input pilot levels. These characteristics must be precisely controlled to provide accurate threshold comparisons.

In addition to the space-diversity control, the equalizer circuitry realizes the control signal that initiates a pilot resupply. This circuitry utilizes a fourth pilot detector, which senses the level of the resupply enable pilot.

III. DETECTOR AND CONTROL CIRCUITS

3.1 Detector

The detector circuit contains four separate pilot detectors interconnected by a tree of hybrid transformers (see Fig. 5). Each pilot detector consists of a hybrid transformer, an IF bandpass filter, an IF amplifier detector, and an operational amplifier gain circuit.

The IF bandpass filter is a two-section, monolithic crystal filter with a 3-dB bandwidth of approximately ±6 kHz and a 60-dB bandwidth of approximately ±50 kHz. The midband loss is approximately 3 dB. Figure 6 shows a typical characteristic of these filters.

The IF amplifier (see Fig. 7) consists of two stages of a series-shunt feedback pair.[7]

The detector portion of the circuit consists of a Schottky diode. An R-C circuit serves as a filter for the detected signal. This circuit acts essentially as a peak detector that derives a dc voltage proportional to the peak of the input IF signal.

The operational amplifier circuit is used as a buffer between the

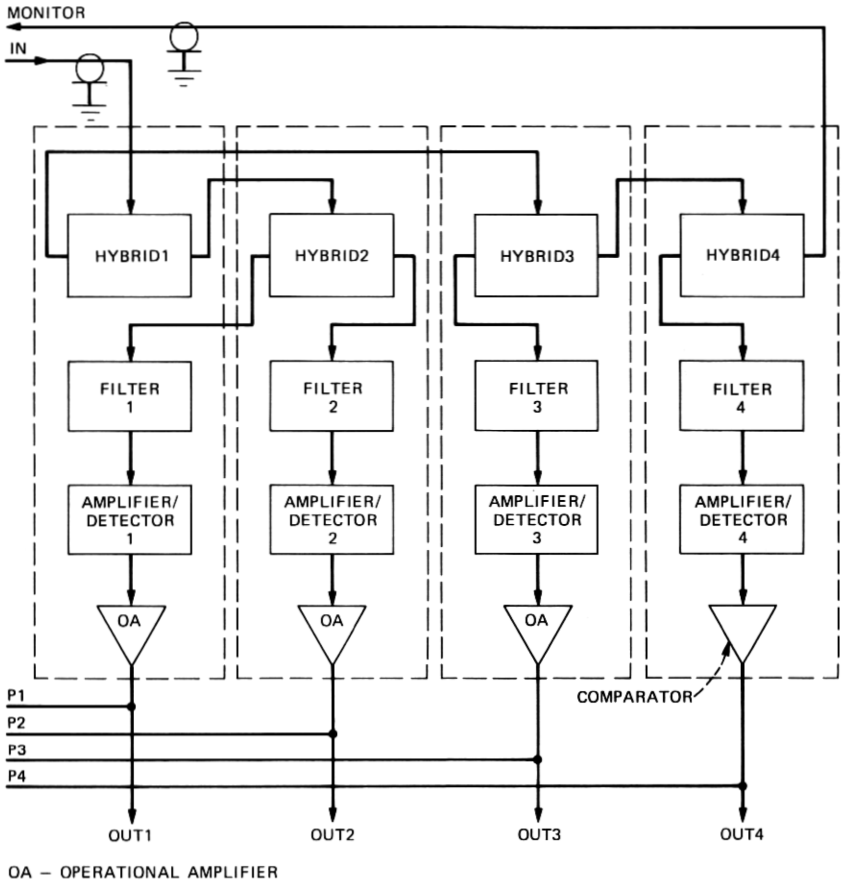

Fig. 5—Pilot detector circuit.

detector and the output of the circuit. This circuit has two adjustments. One is an offset adjustment used to adjust for zero output voltage with a nominal input signal level. The other is a gain adjustment that is set for a given dc output when the input level is 10 dB below nominal. This adjustment is required to compensate for variations in gain at the three pilot frequencies and also for variations in the Schottky diode.

The resupply-enable pilot detector is similar to the three other detectors except that the operational amplifier gain circuit is replaced by a comparator circuit, and the only adjustment is the comparator threshold voltage. A single adjustment is sufficient because only the detection of the presence of the resupply pilot above a certain level is required.

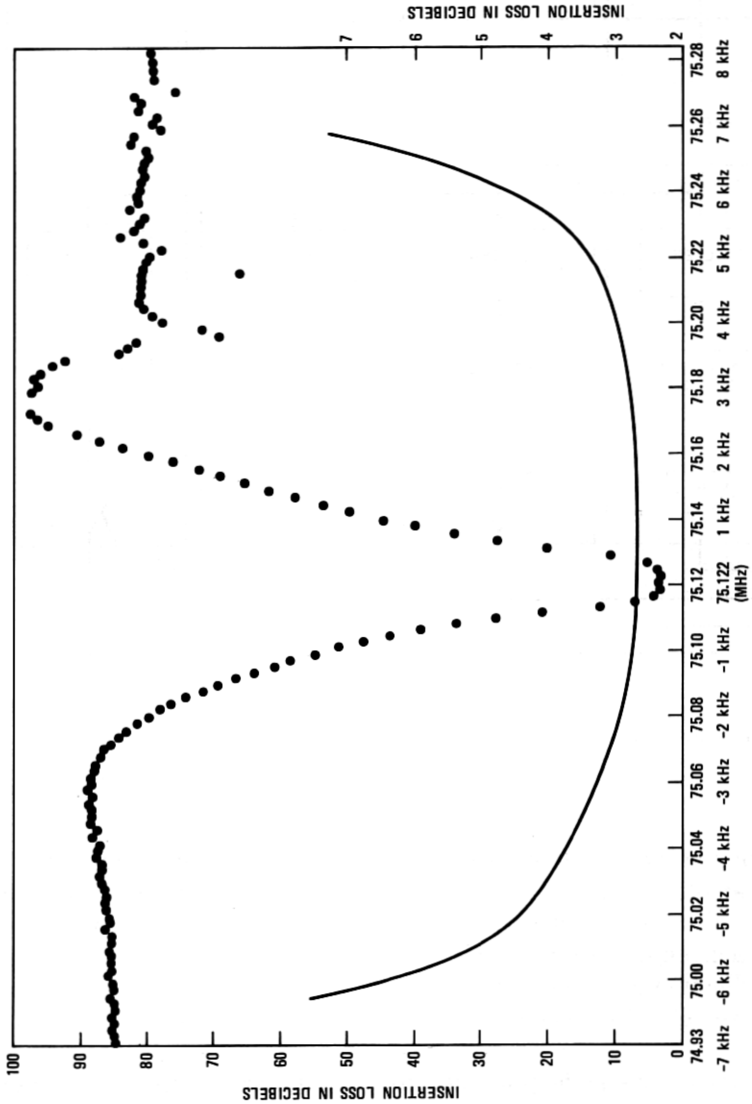

Fig. 6—Typical IF bandpass filter characteristic.

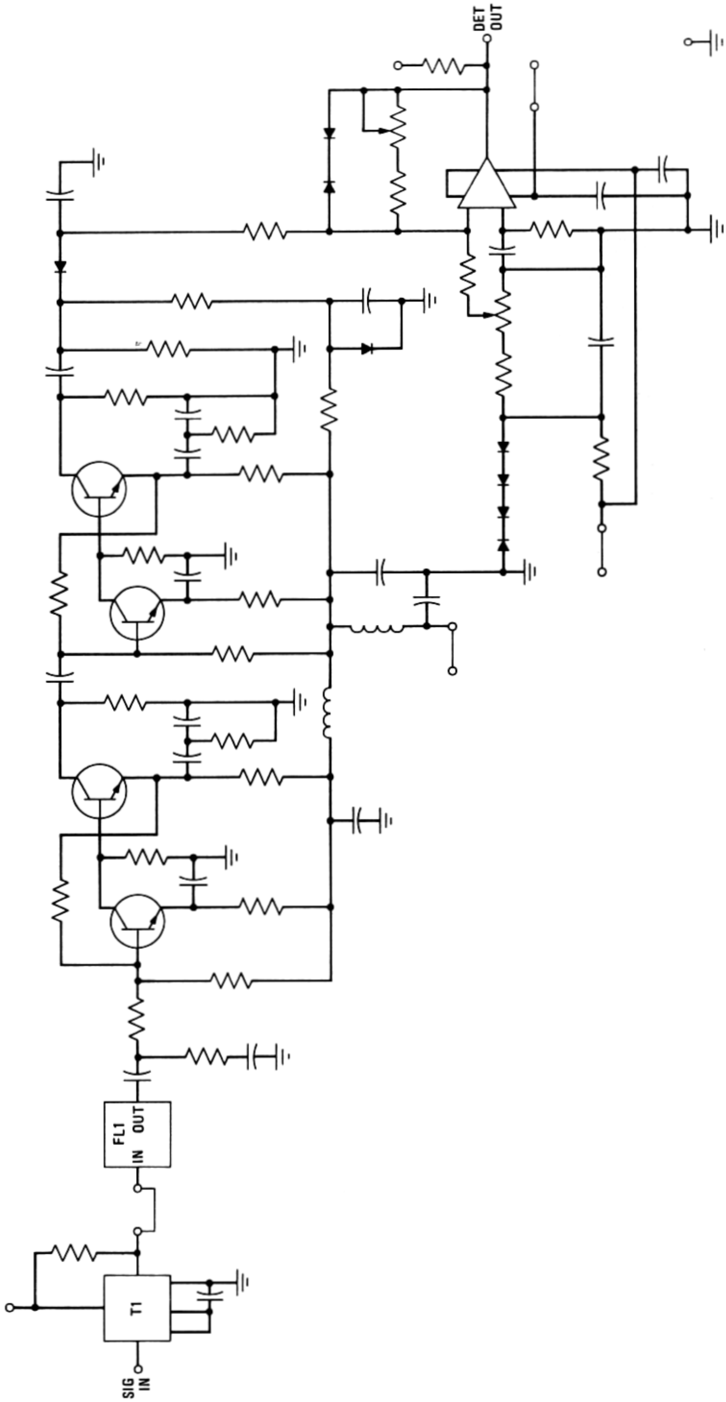

Fig. 7—Pilot detector circuit.

3.2 Receiver control circuit

There are two types of receiver control units. The type that only controls the gain of the AGC amplifier is used at repeater stations. The type used only at main stations controls the gain of a shape unit as well as an AGC amplifier.

The receiver control circuit also generates the following initiation signals: (1) a signal to initiate a pilot resupply switch when the receiver is either underpowered or overpowered, and (2) a signal to initiate a space-diversity switch when the level of any one of the three line pilots drops below a certain threshold.

The circuit controls manual and remote receiver gain and remote pilot resupply, and also controls alarm initiating signals when the receiver is in other than its normal mode of operation.

Figure 8 is a block diagram of a main-station receiver control unit. The operation of the circuit is as follows.

To generate the space-diversity switch initiating signal, the inputs

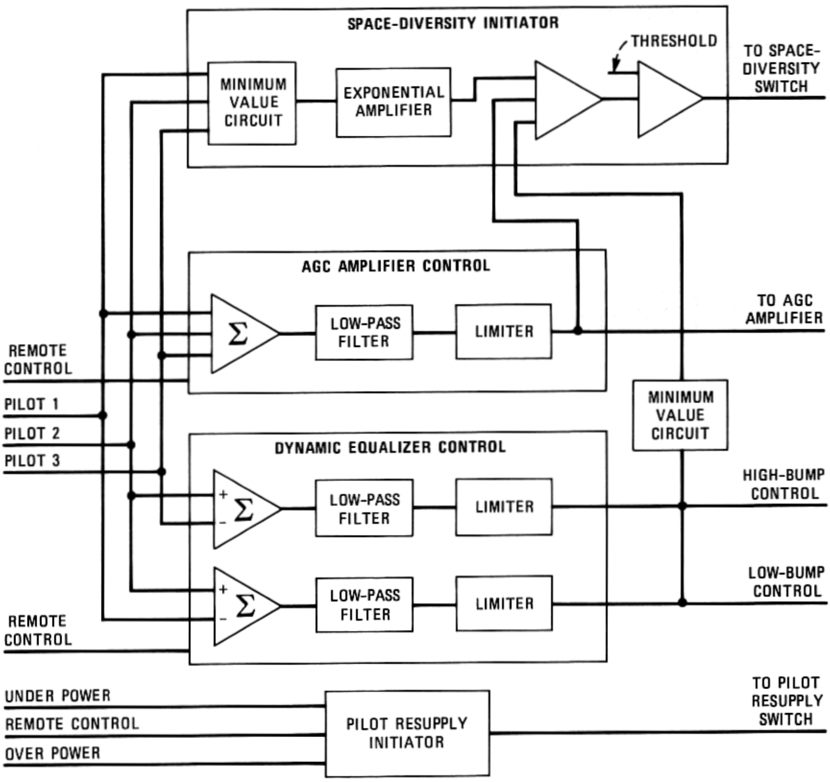

Fig. 8—Main-station receiver control circuit.

from the pilot detector circuits (PLT1–PLT3) are applied to a minimum value circuit. This circuit takes the level representing the lowest level pilot and applies it to an exponential amplifier. The output of this amplifier is a voltage that is linearly proportional to the decibel pilot level. The other input that determines the space-diversity threshold point is the AGC amplifier control voltage. The AGC amplifier is designed so that the gain in decibels is a linear function of the control voltage. The AGC control voltage is determined by the average of the three pilots. The comparator threshold is set to trip when the input voltages are such that the AGC control voltage and the voltage representing the level of the minimum-level pilot indicates that one of the pilots is 36 dB below nominal. The only difference between the repeater-station and the main-station receiver control circuits is that in the main-station circuit the control voltages for the shape unit are also used to determine the space-diversity initiation circuit trip point.

The pilot resupply is initiated in any one of three ways. It will be initiated when the power at the receiver output remains approximately 12 dB above nominal for 100 milliseconds. In this case, the functional input to the receiver control unit is from the resupply switch unit, which senses the total power and produces a control voltage proportional to the average power at the output of the AGC amplifier. The pilot resupply circuit will also be initiated if the average level of the three pilots drops 5 dB below nominal. It releases when the average level returns to less than 4 dB below nominal. This condition is derived from inputs from the detector unit. The pilot resupply can also be initiated remotely via the command and control system.

The AGC amplifier control section takes the voltage proportional to the level of the three pilots, averages them, and low-pass filters the resulting voltage to set the bandwidth of the loop. The output of the low-pass filter is applied to a limiter to limit the maximum gain of the AGC amplifier.

The shape unit control section of the receiver control unit takes the difference between the level of the center pilot and the upper or lower end pilots to control the appropriate bump equalizer in the shape unit. These voltages are also low-pass filtered and limited.

The repeater station receiver control unit does not contain a shape unit control section because a repeater station does not use a shape unit.

The receiver control unit also allows for the AGC amplifier to be set to nominal gain or manually adjusted over its entire gain range. Light-emitting diodes (LEDs) on the faceplate of the unit indicate when the dynamic equalizer is in other than its normal mode of operation.

IV. THE SHAPE UNIT

The shape unit is composed of four Bode-type adjustable "bump" networks separated by amplifiers and controlled by four driver circuits as shown in Fig. 9. Two identical networks provide a bump-type characteristic at 59.8 MHz. The remaining two networks are also identical and peak at 88.5 MHz. Each network section is separated by amplifiers to provide both impedance buffering and gain to offset the flat loss introduced by the networks. High-frequency network sections are alternated with low-frequency sections to minimize interaction between like sections.

Each network section has an associated drive circuit. This provision allows for the independent operation of each network section so that varying p-i-n diode characteristics may be compensated in the driver element of the network section.

4.1 The bump equalizer sections

Each "bump" network section is composed of a series-type, adjustable Bode network as shown in Fig. 10. The adjustable element is a p-i-n diode. The p-i-n diode acts as a resistor that varies in accordance with a bias voltage supplied by the drive circuit. As the resistance value of the p-i-n diode varies, the network shapes the amplitude of the transmission above and below the flat loss level. Measured amplitude shapes are shown in Fig. 11.

4.2 The buffer amplifiers

As shown in Fig. 12, all of the amplifiers provide hybrid-type inputs and outputs. All amplifiers are designed to present 75-ohm input and output impedances. The amplifiers are, however, tuned to operate against the 301-ohm impedance presented by each "bump" network section. Each amplifier provides 7 dB of gain to compensate for the loss introduced by the bump sections.

4.3 The drive circuits

The drive circuits receive the drive voltages from the receiver control unit. As shown in Fig. 9, two voltage follower circuits isolate the drive circuits from the receiver control unit. A schematic description of the drive circuits is shown in Fig. 13.

Each drive circuit is a unity gain dc amplifier. Potentiometer R26 allows for the adjustment of the offset voltage to the input of the amplifier. It is adjusted to provide flat transmission over the 59- to 89-MHz band with a drive voltage of 0V.

Elements R13 through R20, CR2, and CR3 function to make the insertion loss in decibels at the 62.448- and 85.856-MHz pilot frequencies proportional to the drive voltages. The circuit is adjusted so that

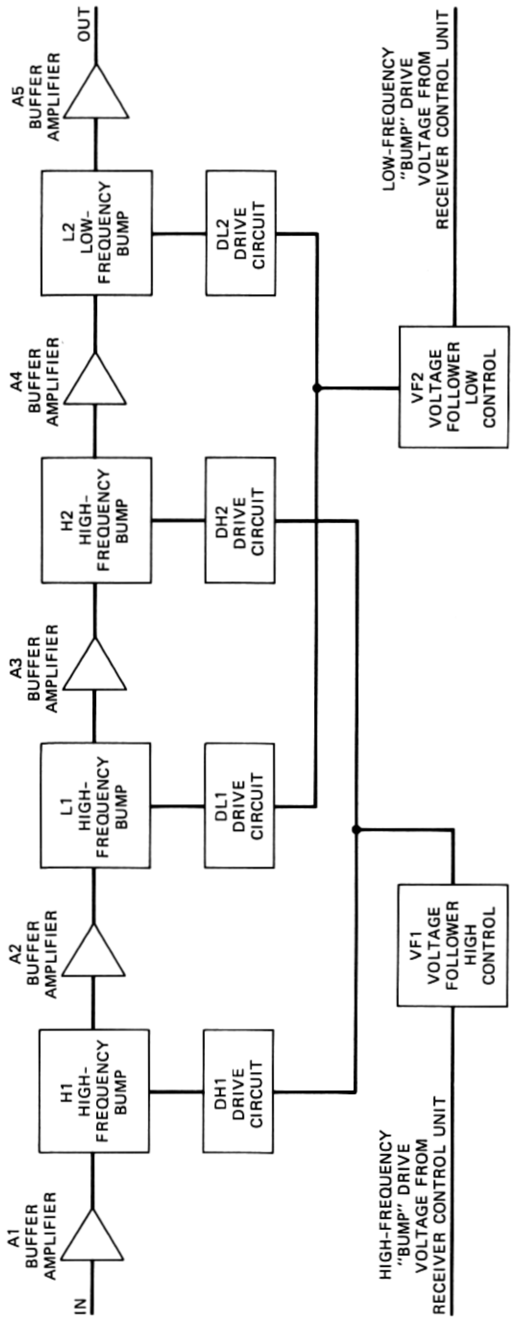

Fig. 9—Block diagram of the dynamic equalizer.

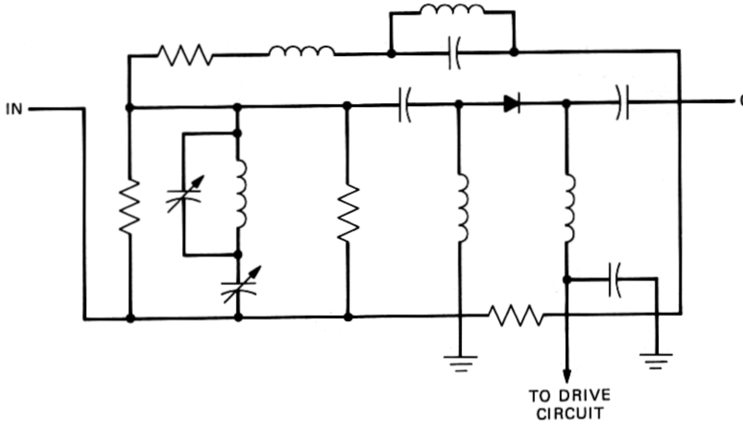

Fig. 10—Bode-type adjustable equalizer.

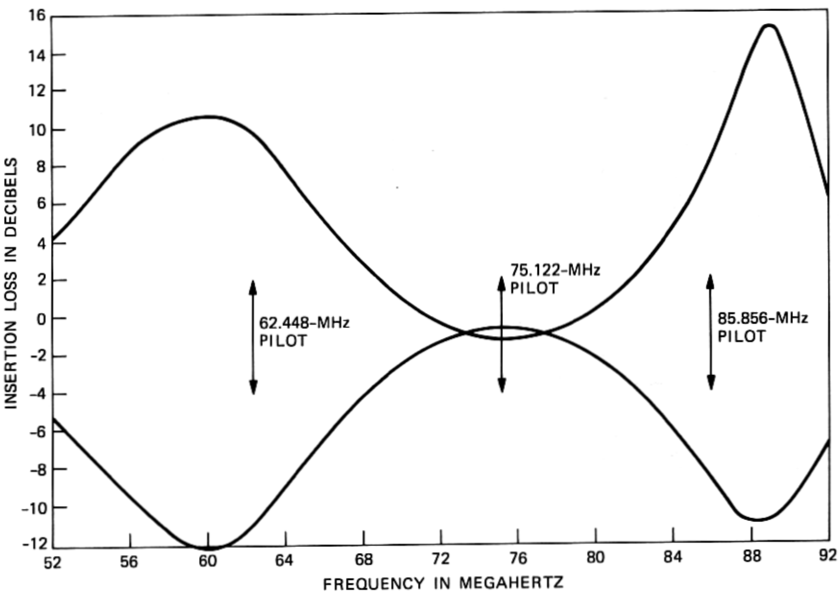

Fig. 11—Typical amplitude shapes generated by the dynamic equalizer for the AR6A System.

a change of 1V in drive voltage results in a 1-dB change in transmission for each network section. This linear relationship is the criterion upon which the space-diversity switching is based.

Diodes CR4 through CR6 act as temperature-sensing elements. Their purpose is to compensate for the temperature versus resistance characteristic of the p-i-n diode. Over the 40- to 140-degrees F temperature range, amplitude distortions in the transmission amount to

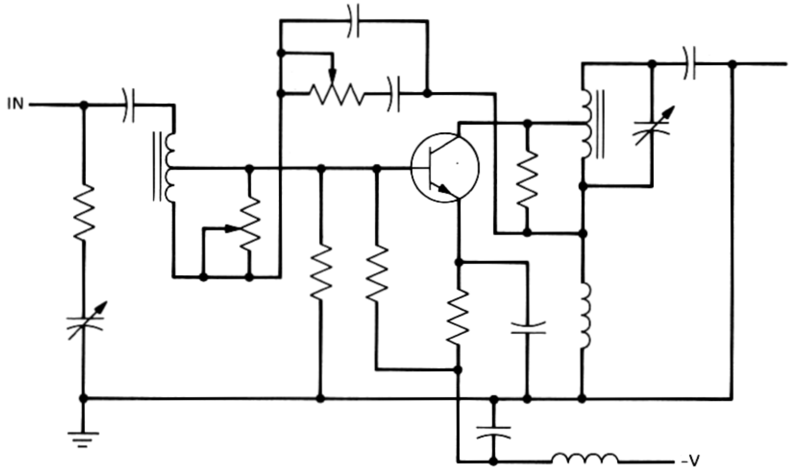

Fig. 12—Buffer amplifier.

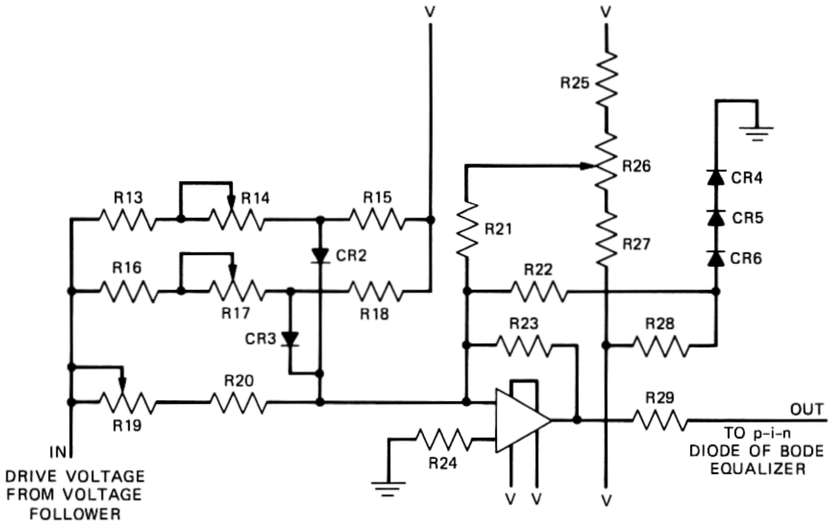

Fig. 13—Drive circuit.

as much as ±1.5 dB between pilot frequencies without compensation circuitry. With compensation these distortions are held to within ±0.25 dB.

V. AUTOMATIC GAIN CONTROL AMPLIFIER

The AGC amplifier normally operates at a nominal gain of 15.7 dB and has a gain range of 61 dB. It is made up of a series of fixed-gain amplifier blocks alternating with variolossers (see Fig. 14). Each

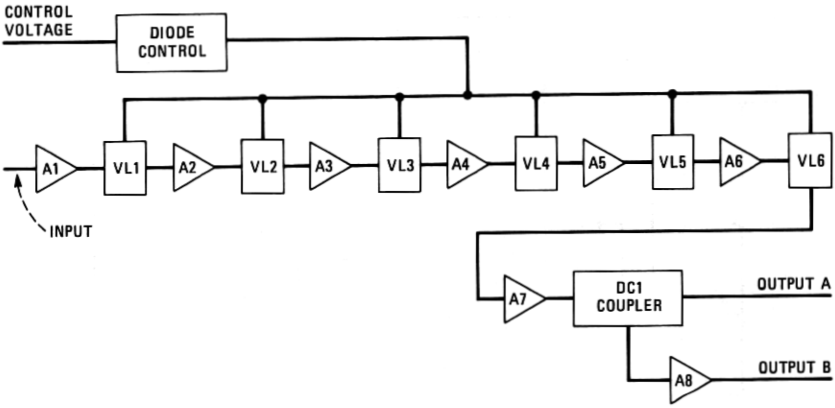

Fig. 14—Block diagram of an AGC amplifier.

variolosser has a dynamic range of approximately 10 dB, so six are necessary to provide the required 61-dB overall control range.

A control circuit is provided to convert the AGC input control voltage to a form that can be used to control the loss of the variolossers. This circuit is basically a voltage-controlled current source that linearizes the input control voltage versus overall AGC gain transfer curve. Another function of the control circuit is to stabilize the temperature of the AGC amplifier.

5.1 Amplifier blocks

Eight fixed-gain amplifiers of the same basic design are required in the AGC amplifier.

Amplifiers A1 through A6 (see Fig. 14) are two-stage feedback amplifiers with a gain of 10.5 dB each. Amplifier A7 has a gain of 16 dB. This gain distribution was chosen to optimize the noise figure and intermodulation performance of the AGC amplifier. Very careful attention had to be paid to the physical design and layout since there is a total distributed gain of almost 80 dB.

The buffer amplifiers in the AGC saturate at a rather high power level due to the heavy biasing required to achieve low intermodulation distortion. Interstage clamping circuitry was added to the AGC to limit the output power to a safe level without affecting normal operation.

Directional coupler DC1 samples a portion of the main path signal and directs this signal to the amplifer A8. Amplifier A8 is a single-stage feedback amplifier with a gain of 8.5 dB. This output provides the signal to the pilot detector unit.

All eight of the amplifier blocks utilize a hybrid transformer impedance-matching configuration (see Fig. 15). This circuit can easily

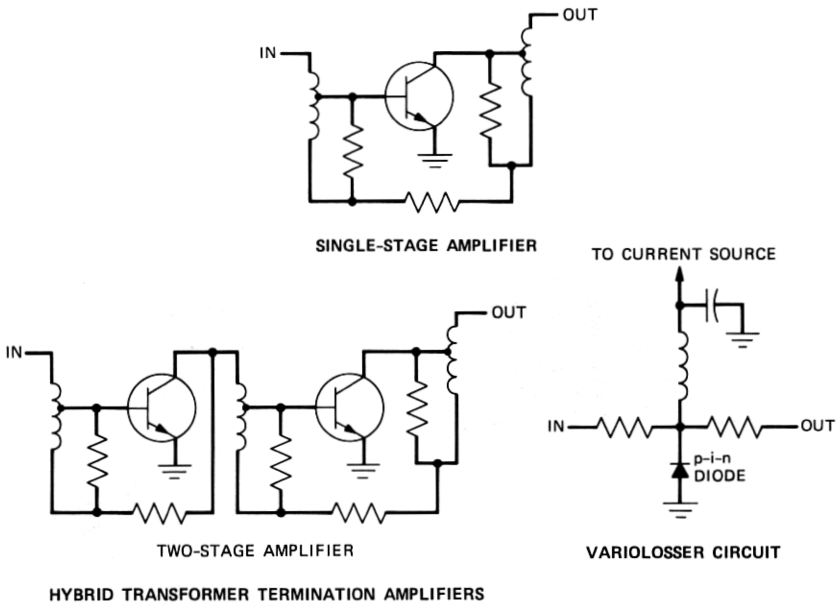

Fig. 15—Functional diagram of the AGC amplifier.

provide better than 30-dB return loss, which is important for the input and output ports of the AGC amplifier and for providing good buffering characteristics to mask the variolosser impedance variation.

The amplifiers in the AGC have been designed for optimum linearity performance to minimize intermodulation distortion. All eight amplifiers use a transistor that has been designed for optimum linearity. To utilize this transistor properly it must be operated at a collector voltage of 13V and an emitter current of 120 mA. Since 15 transistors are required for the AGC amplifier, the result is a relatively high total dc power consumption of 2 amps at −14.7V, or 30W. Consequently, a rather elaborate heat sink and ventilation scheme was required (see Fig. 16). The heat removal problem[8] was complicated by a very tight radio frequency interference requirement on the AGC amplifier.

5.2 Variolossers

The variolosser is essentially a T-pad attenuator with a p-i-n diode as the shunt arm to ground (see Fig. 15). The impedance of the p-i-n diode is varied by changing the bias current through the diode. The p-i-n diode is a type that was developed specifically for this application.

The input AGC control voltage is common to all variolossers (see Fig. 14), but each p-i-n diode has its own voltage-controlled current source. The loss of each variolosser is variable from approximately 3 to 13 dB.

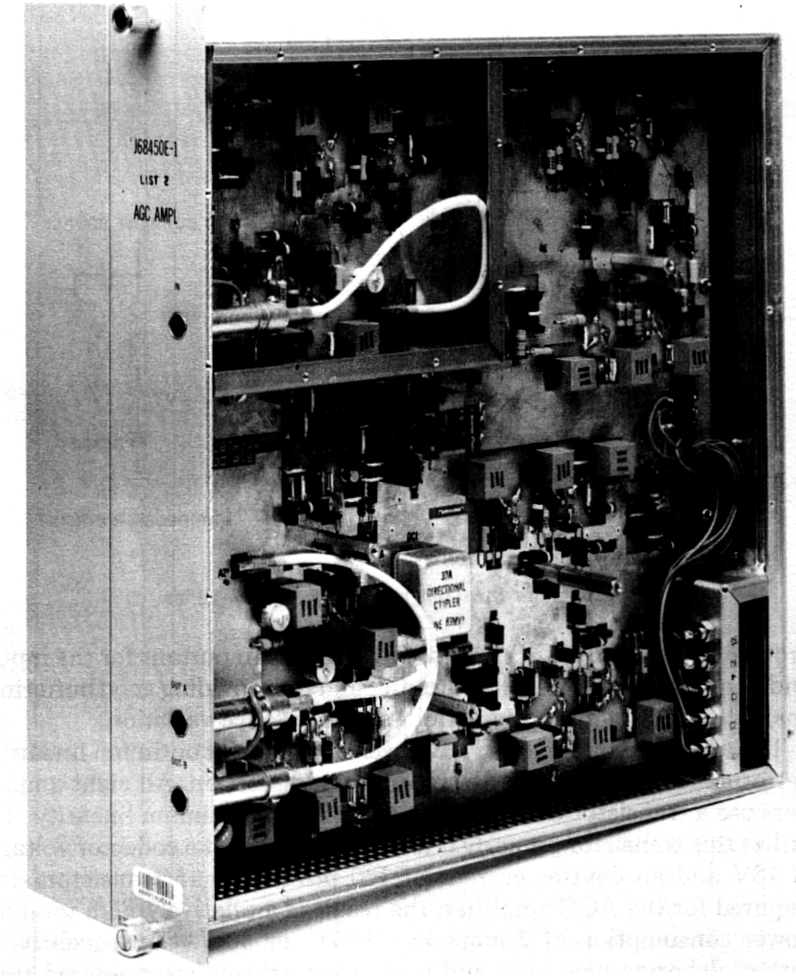

Fig. 16—AGC amplifier.

5.3 Control circuit

The control circuit linearizes the control voltage versus decibel AGC gain curve and compensates for the temperature in the AGC amplifier.

It was necessary to linearize the control function since the p-i-n diode variolosser characteristics are very nonlinear. The AGC control section introduces a compensating distortion in the control function so that the overall transfer function is linear.

The p-i-n diodes in the variolossers are temperature sensitive so the ambient temperature variations must be compensated for. The expected ambient variation is from 40 to 140 degrees F. The voltage across a forward-biased silicon diode is used as a temperature-sensing element. This temperature-dependent voltage is used to modify the variolosser drive voltage in the proper way so that the AGC gain remains constant as the ambient temperature varies.

The decision was made to utilize a two-point "switched" temperature compensation concept rather than attempting the formidable task of tracking the constantly changing p-i-n diodes. With this method two points on the AGC gain curve are perfectly temperature compensated with an acceptable smooth transition in between.

VI. CONCLUSION AND ACKNOWLEDGMENTS

A dynamic equalizer consisting of an AGC amplifier, a shape unit made up of Bode "bump" networks, and control circuitry has been designed to correct for the effects of selective fading in an AR6A channel. The use of Bode "bump" networks is key to the realization of a dynamic equalizer that is low in complexity and yet adequately meets system requirements.

Credit is due to many individuals associated with phases of this development. The authors specifically wish to acknowledge J. M. Kiker, Jr., for his guidance of the AGC amplifier development and P. D. Patel for the physical design of the dynamic equalizer units and IF shelf. The support and encouragement of F. J. Witt throughout the project is also gratefully acknowledged.

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