Adaptive Transversal Equalization of Multipath Propagation for 16-QAM, 90-Mb/s Digital Radio

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Adaptive transversal equalization is an effective and relatively new coun-
termeasure for dispersive multipath propagation in terrestrial digital radio
networks. In this paper we describe the design and performance of a five-tap
baseband analog equalizer developed for a family of 16-QAM, 90-Mb/s radio
systems. Laboratory measurements and field evaluation during a five-month
fading season in Palmetto, Georgia, indicate that the use of this adaptive
transversal equalizer can significantly reduce the need for costly space-diver-
sity equipment.

I. INTRODUCTION

The impairment of terrestrial digital microwave reliability due to
multipath propagation is widely recognized.[1] Unlike FM radio systems,
where system outage is predominantly determined by the thermal
noise aspect of fading, digital radio is also affected by the dispersive
character of multipath fading. This dispersion, engendered by signifi-
cant amplitude and delay distortion across the channel bandwidth,
causes considerable Intersymbol Interference (ISI) that degrades dig-
ital radio reliability well beyond that expected from the flat fade
margin alone.[2] Multipath-induced distortion thus is considered the
predominant cause of digital radio outage for frequencies under 12
GHz.
Presently, several methods are used to counter the impact of mul-

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tipath fading. These include frequency diversity,[3] space diversity,[4] and adaptive Intermediate Frequency (IF) equalization. Examples of the latter include slope equalizers[5] and notch or resonance equalizers.[6] However, frequency-selective fading corrupts both the amplitude and phase of a transmitted signal. While IF equalizers can be designed to condition a channel properly for minimum phase fading, they double the delay distortion during periods of nonminimum phase fading. (Minimum phase and nonminimum phase fading is clearly defined by Giger and Barnett[1] for a two-path statistical model of multipath propagation.) This effect naturally impacts the outage of those digital radio systems that rely solely on amplitude correction.[7]

Although adaptive transversal equalizers are a relatively new countermeasure to multipath fading in digital radio systems,[8] their prior application in mitigating the effects of linear distortion in other, lower-speed, digital communication networks is firmly established. Current practice is to use transversal equalizers in conjunction with IF equalizers. In a recent study, Foschini and Salz[9] considered the application of equalization techniques to digital data transmission over radio channels subject to frequency-selective fading. Their theoretical study of ideal transversal equalizers with an infinite number of taps clearly established the utility of linear equalization during multipath propagation. These equalizers are especially noteworthy in that they are capable of providing amplitude *and* delay equalization for minimum *and* nonminimum phase fades.

The baseband synchronous transversal equalizer briefly described here was designed for a family of 16-QAM (Quadrature Amplitude Modulation), 90-Mb/s radio systems. Designated DR 6-30 and DR 11-40, these digital systems provide 3-bit/Hz operation in the 6- and 11-GHz common carrier bands, respectively.[10] In this paper, we focus on the design and performance features of a high-speed (approximately 22.5-MHz) synchronous transversal equalizer. A theoretical development of equalization principles is specifically omitted since those points are amply discussed in the technical literature (for example, see Chapter 6 of Ref. 11).

II. GENERAL DESCRIPTION

2.1 DR 6/DR 11 radio system

Figure 1 functionally depicts the DR 6/DR 11 digital radio system. Two independent, 45-Mb/s random data streams are differentially encoded to form two rails, each with four-level amplitude states, and then modulated in quadrature to form a 16-QAM, 90-Mb/s IF signal at 70 MHz. The Radio-Frequency (RF) transmitter modulates the IF signal up to 6 or 11 GHz for transmission over a line-of-sight terrestrial path to the digital receiver. At the receiver the signal is down-converted
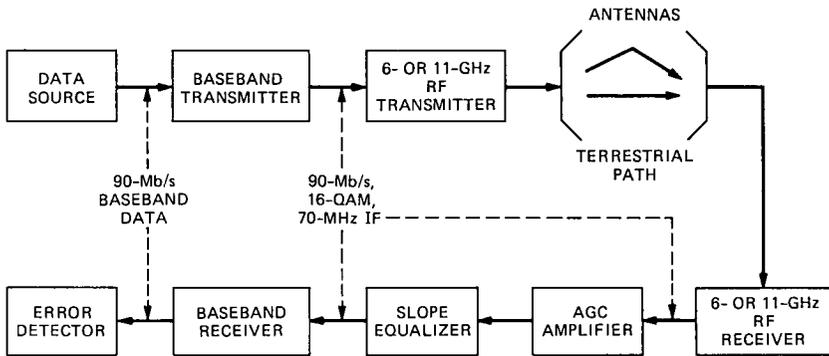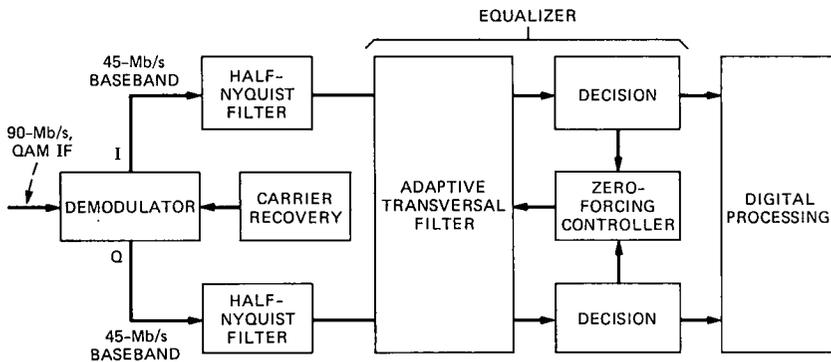
Fig. 1—DR 6/DR 11 digital radio system.

Fig. 2—Baseband receiver with adaptive transversal equalizer.

to IF, where it is processed by an Automatic Gain Control (AGC) amplifier and adaptive slope equalizer. The baseband receiver demodulates the IF signal into in-phase (I) and quadrature (Q) rails, where the baseband data states are detected and estimates of the original transmitted data are made. An error detector provides for system performance monitoring.

Figure 2 functionally illustrates the baseband receiver. As described above, the 90-Mb/s, QAM IF signal is demodulated into I and Q rails, each 45 Mb/s. After conventional half-Nyquist spectral shaping (using delay-equalized analog filters with raised-cosine shaping and 45-percent roll-off), the four-level signals enter the transversal equalizer for removal of the linear intersymbol interference previously generated by multipath propagation, imperfect Nyquist filtering, etc. After

baseband equalization, the transmitted symbol states are estimated at the decision point, and the decoded binary signals are used in subsequent digital processing.

2.2 Adaptive transversal equalizer

To remove in-rail and cross-rail intersymbol distortion, two adaptive transversal filters (each with five complex-valued tap weights) are configured for baseband equalization of QAM signals. The selection of five taps is based on theoretical studies of equalizer performance as a function of equalizer length. For example, Amitay and Greenstein[12] have investigated the multipath outage performance of digital radio receivers using finite-length adaptive equalizers. Using Rummler's statistical description of multipath channels,[13] equalizer performance for a broad ensemble of fading scenarios was simulated. Their study indicated that five synchronous taps considerably reduce ISI relative to performance attained with three taps and that equalizers with seven or more taps, while obviously further reducing ISI, exhibit a rapidly diminishing relative reduction in linear distortion. (Independently, Murase et al.,[14] and Takenaka et al.[15] have also selected five-tap filters for their transversal equalizer designs.)

The equalizer tapped-delay lines are fabricated using lumped-delay elements isolated with buffer amplifiers. The buffer amplifiers are Hybrid Integrated Circuits (HICs) and provide high isolation between the delay line and coefficient-weighting taps. Tap weighting is accomplished with variable gain amplifiers. These, too, are hybrid integrated circuits fabricated in single in-line packages, thereby permitting high-density electronics on each circuit board. Summing amplifiers (also HICs) then add the individual tap-weighted signals to form the filter output.

The coefficient control portion of the equalizer uses zero-forcing adaptation and is implemented with high-speed Emitter-Coupled Logic (ECL). The control circuit accepts error polarity and estimated-symbol polarity from the in-phase and quadrature decision circuits. Appropriately delayed versions of these bits are then correlated during each symbol period using exclusive OR gates. The time-averaged values of these correlations determine the weight of each tap in the two transversal filters. Time averaging is achieved using operational amplifier filters optimized for the trade-off between coefficient noise and dynamic multipath tracking ability.

The entire equalizer consists of three 1-inch plug-in circuit packs in a format compatible with the DR 6/DR 11 terminal or regenerative equipment. A photograph of these circuit packs appears in Fig. 3. Two of these packs are identical analog transversal equalizers, one for in-phase and cross-rail equalization of the I rail, the other for similar
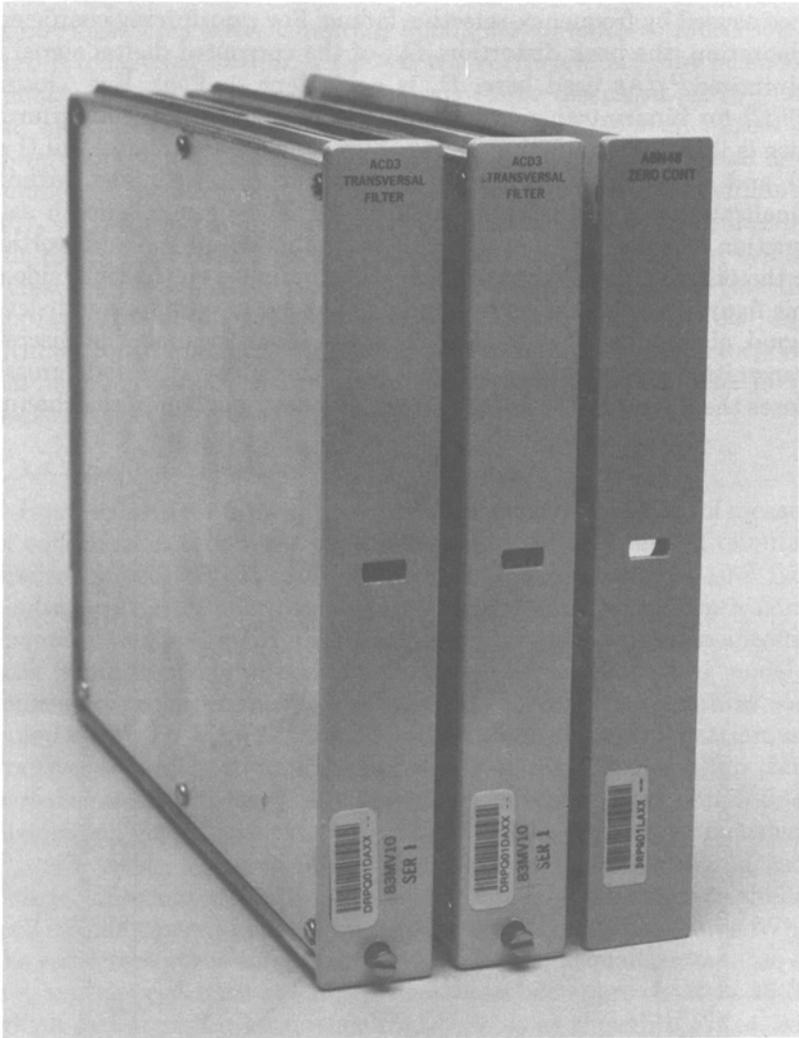
Fig. 3—Adaptive transversal equalizer consisting of two transversal filter circuit packs and one zero-forcing control circuit pack.

equalization of the Q rail. Equalizer coefficient control is generated in the third circuit package.

III. EQUALIZER PERFORMANCE

3.1 Theoretical performance

3.1.1 Reduction of peak distortion

As we noted above, five-tap synchronous transversal equalizers are theoretically capable of substantially reducing intersymbol interfer-

ence caused by frequency-selective fading. For zero-forcing coefficient adaptation, the peak distortion, D_p, of the corrupted digital signal is minimized.[11] (As used here, D_p is equivalent to Peak Eye Closure (PEC) for binary transmission.) Representative theoretical performance is illustrated in Fig. 4. In Fig. 4 we consider one digital rail (I or Q) and show the variation of peak distortion—with and without equalization—of a digital signal for a 20-dB fade notch depth as a function of notch position in a ±18-MHz channel. (Ideally, distortion in the other rail would be identical.) The ordinate on the right side of this figure provides the corresponding peak eye closure for a four-level signal, given by $PEC = D_p(L - 1)$, where L is the number of discrete transmitted symbol states on each rail. This illustrative fade grossly closes the digital eye with $D_p > 1$ over at least a portion of the channel
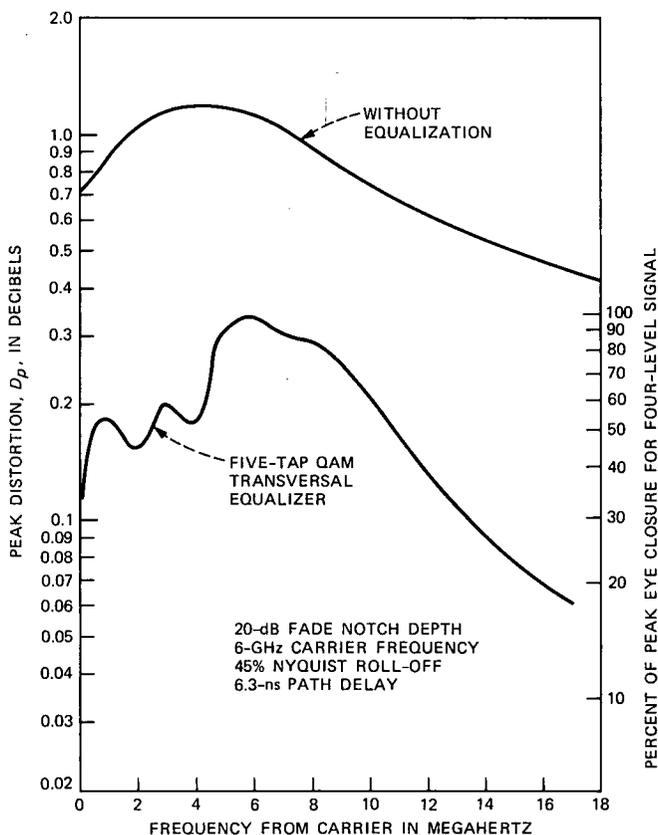

Fig. 4—Theoretical reduction in peak distortion, D_p, with a five-tap QAM transversal equalizer arrangement. Peak eye closure is noted for four-level transmission, that is, one rail of a 16-QAM system.

bandwidth. This latter condition highlights an analytic limitation of zero-forcing equalization: if $D_p > 1$, the coefficient set may be suboptimal.[11] In spite of this, other analysis (to be discussed shortly) and our own measured data show that adaptive transversal equalizers do, in fact, notably reduce intersymbol interference in just such an environment. Moreover, zero-forcing is known to assure a global minimum if $D_p < 1$, affords comparative ease of circuit realization, and minimizes Bit Error Rate (BER) in the high signal-to-noise ratio that typifies quiescent digital radio operation. The other dominant adaptation approach for automatic equalizers, Least-Mean-Square (LMS) algorithmic control, is more difficult to realize in high-speed circuits and has a proclivity for unsatisfactory local minima when used in the decision-directed mode.[16]

3.1.2 Equipment signatures

Equipment signatures[17,18] provide a particularly meaningful measure of equalization capability since they can be directly related to outage predictions for digital radio systems. The signatures are 10^{-3} BER contours: at each point on the contour, the fade notch depth corresponding to a 10^{-3} BER (defined as a digital radio outage) is specified as a function of notch position for a fixed-delay statistical model of multipath propagation. Figure 5 presents theoretical signatures computed by M. H. Meyers[19] for no equalization, slope equalization, and transversal equalization. Figures 4 and 5 confirm that five-tap transversal equalizers theoretically provide a significant reduction in linear distortion. Indeed, even the use of zero-forcing control for fades with $D_p > 1$ yields a degree of equalization that mitigates digital radio outage. The data of Fig. 5 indicate that a fade notch depth as shallow as 7 dB can cause an outage in the absence of countermeasures. When the radio receiver is equipped with a transversal equalizer, outages are not experienced until the notch depth reaches approximately 23 dB, which can occur for an unequalized $D_p > 1$, as shown in Fig. 4. Also observe from Fig. 5 that slope equalizer performance is influenced by the minimum or nonminimum phase character of the fade, as we mentioned earlier. This is not a limitation of transversal equalization.

3.2 Measured laboratory performance

3.2.1 Equipment signatures

The definition and significance of equipment signatures were previously mentioned. The laboratory measurement of these signatures is facilitated through the use of a new computer-controlled multipath fade simulator that continuously varies notch depth and notch frequency to achieve a 10^{-3} BER. The simulator is inserted in the IF path of the receiver just before the AGC amplifier (see Fig. 1).
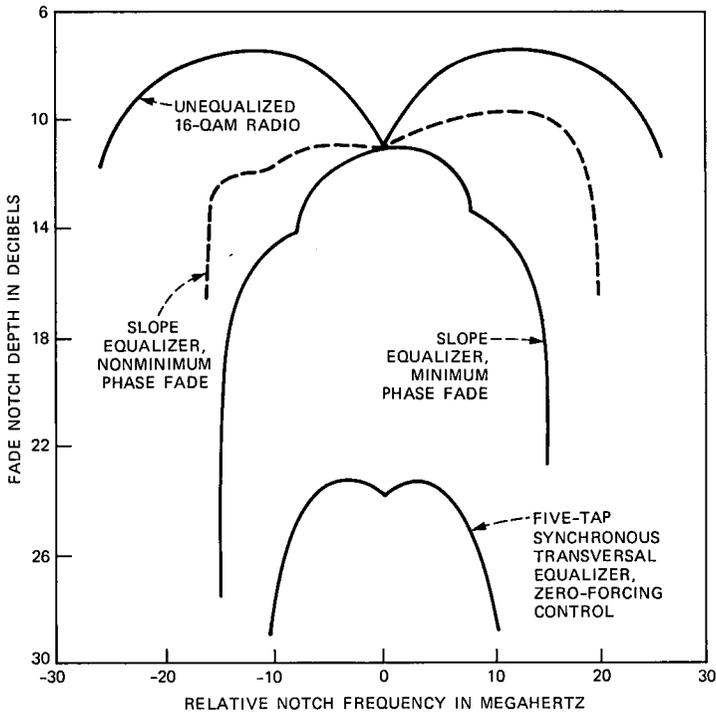
Fig. 5—DR 6 theoretical equipment signatures for 16-QAM digital radio. Performance for radio without equalization, with an adaptive slope equalizer, and with a five-tap synchronous transversal equalizer using zero-forcing control.

Signatures were measured using two DR 6 receivers, the first equipped with an adaptive slope equalizer (the standard arrangement) and the second equipped with both the adaptive slope equalizer and a five-tap adaptive transversal equalizer. The 10^{-3} BER minimum phase and nonminimum phase equipment signatures appear in Fig. 6. As the data reveal, the adaptive slope equalizer performs best when used for minimum phase fades, with a performance deterioration experienced for nonminimum phase fades. We commented earlier that IF equalizers typically double delay distortion during nonminimum phase fading, and this effect can degrade equipment signature performance. The same effect naturally occurs when the adaptive slope and synchronous transversal equalizers are used together. Comparing both sets of curves, however, we also observe the significant improvement in equipment signature performance that can be ascribed to the transversal equalizer alone.

The relative reduction in digital radio outage time is estimated using a prescription described by Meyers,[21] wherein the areas under equipment signature contours, with and without transversal equalization,
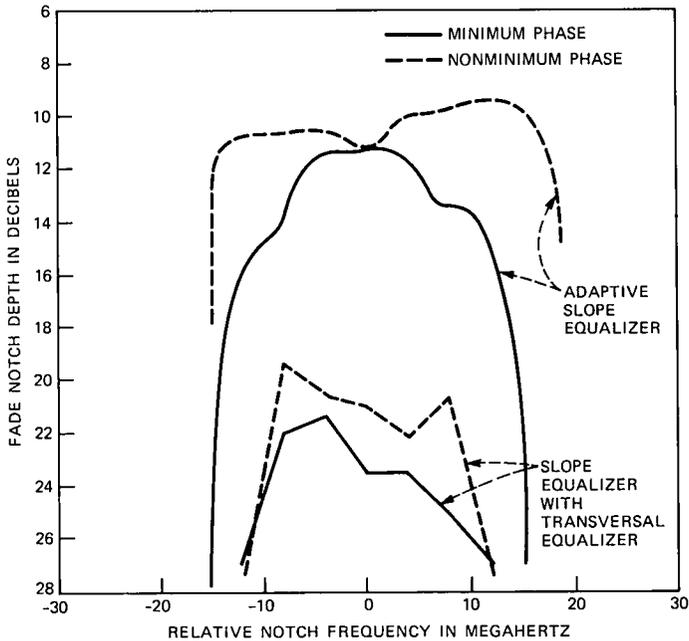
Fig. 6—DR 6 measured equipment signatures for 16-QAM digital radio. Performance for radio with adaptive slope equalization and adaptive slope and transversal equalization for 6.3-ns path delay. (Adapted from Ref. 20.)

are compared. The predicted relative outage reduction factor, derived from theoretical equipment signatures for combined ideal slope and transversal equalization (see Fig. 5) is 5. This assumes equally probable minimum and nonminimum phase fading. The predicted relative outage reduction factor for the measured equipment signatures (see Fig. 6) is 4.5, again assuming equally probable minimum and non-minimum phase fading. The relative reduction factors for other ratios of minimum to nonminimum phase fading range from 4 to 5. The measurements in Fig. 6 attest to the quality of the transversal equalizer circuit design itself. Regarding this point, baseband implementation of the equalizer permits integration of substantial portions of the circuitry, thus simplifying design and manufacture. The development of new carrier and timing recovery circuits also helps place laboratory performance close to the theoretical limit shown in Fig. 5.

3.2.2 Simulation of dynamic fading

An important aspect of multipath propagation is its rapid temporal variation. To assure optimal equipment performance in the field, dynamic (time-varying) tests were performed during the development phase. Dynamic multipath fading is produced in the laboratory by

controlling the continuously variable fade simulator with a microcom-
puter. Realistic time sequences of multipath behavior were pro-
grammed into the simulator. Equalizer performance was monitored
during the simulation of these dynamic fades, thereby permitting
optimization of the equalizer timing-recovery, carrier-recovery, and
coefficient-updating loop parameters.

Several aspects of an equalizer's response to dynamic multipath
propagation are exercised with the following test sequence (schemat-
ically depicted in Fig. 7): starting with a shallow fade notch depth d_1
at a particular notch frequency f_1, the notch depth increases at a rate
s_1 until a notch depth d_2 is reached. The notch then sweeps across a
band of frequencies from f_1 to f_2 at a rate s_2. At the notch frequency
f_2, the notch depth decreases from d_2 back to d_1 at a rate s_3. This
fading trajectory retraces itself and is repeated several times for
statistical averaging of the receiver's error performance. A test se-
quence like this tests the receiver's ability to track notch depth and
notch frequency dynamics. For trajectory parameters of $d_1 = 6$ db, d_2
$= 15$ dB, $s_1 = s_3 = 9$ dB/s, $f_1 = -12$ MHz (12 MHz below the IF
frequency), $f_2 = +12$ MHz, and $s_2 = 24$ MHz/s, the transversal equalizer
consistently operates error free. Those test velocities are also faster
than 90 percent of all observed notch depth and notch position rates
of change reported by Sakagami et al.[22]

3.3 Field evaluation

The adaptive transversal equalizer was installed in a DR 6-30 field
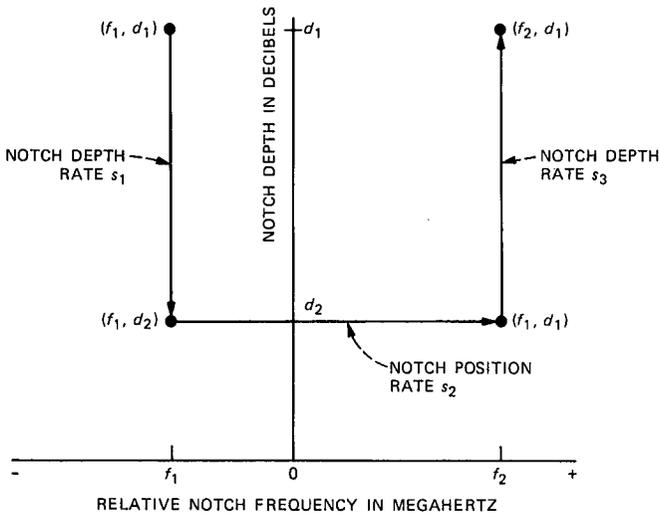test facility at Palmetto, Georgia, on June 4, 1982. This modified

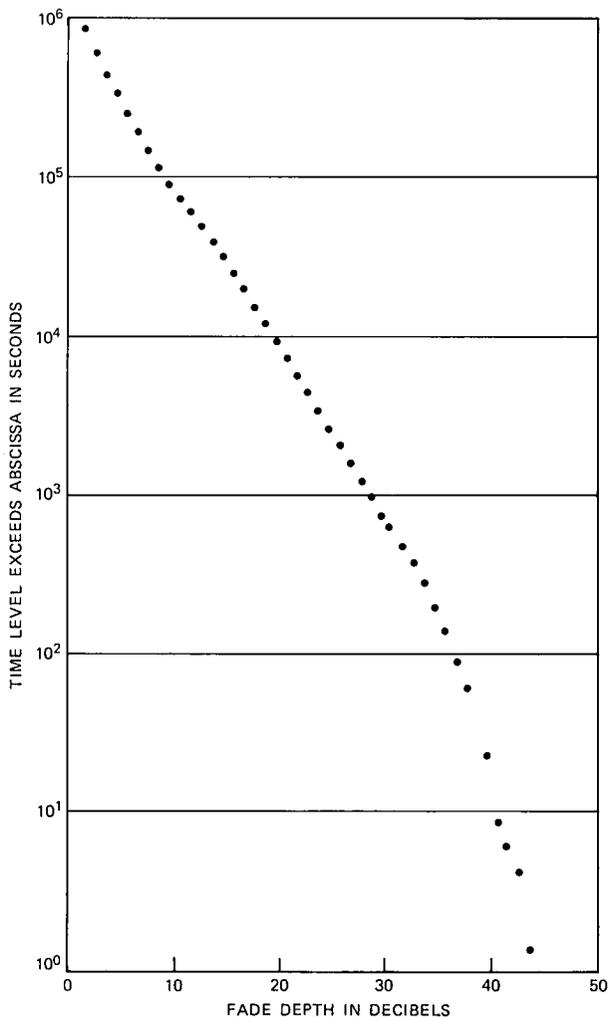Fig. 7—Test sequence for dynamic simulation of multipath propagation.

Fig. 8—Time-below-level propagation data for Palmetto, Georgia, in 1982.

baseband receiver was compared with a standard DR 6 receiver (equipped with an adaptive slope equalizer) during a multipath season from June 6 to November 6, 1982. Propagation data collected during the field evaluation period are shown in Fig. 8.[23] The abscissa of this figure reports fade notch depth; the ordinate indicates time faded below the respective abscissa value. A considerable amount of fading exhibits notch depths in excess of 10 dB, which, from Fig. 5, could correspond to an outage in the absence of suitable countermeasures. The two baseband receivers shared the same RF and IF front ends. Field measurements, monitored by AT&T Bell Laboratories personnel

from Merrimack Valley, were grouped into 11 two-week intervals. In Fig. 9, the number of seconds for which BER $> 10^{-6}$ is presented for both receivers for each of the two-week intervals. Also presented is the ratio of these two time measurements, representing a composite improvement factor attributable to the transversal equalizer, alone. Figure 10 presents similar data for a BER $> 10^{-4}$. In Fig. 11 we show the incidence of frame loss with and without the equalizer, as well as the corresponding reduction in loss of frame.

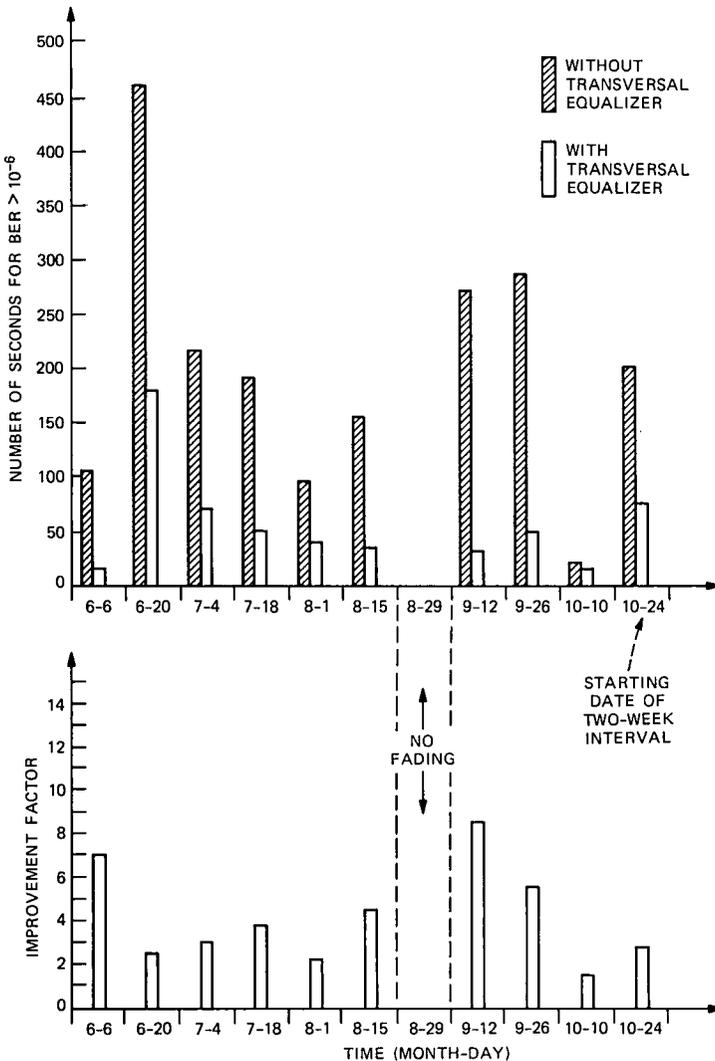For the 22 weeks represented in Figs. 9 through 11, the adaptive

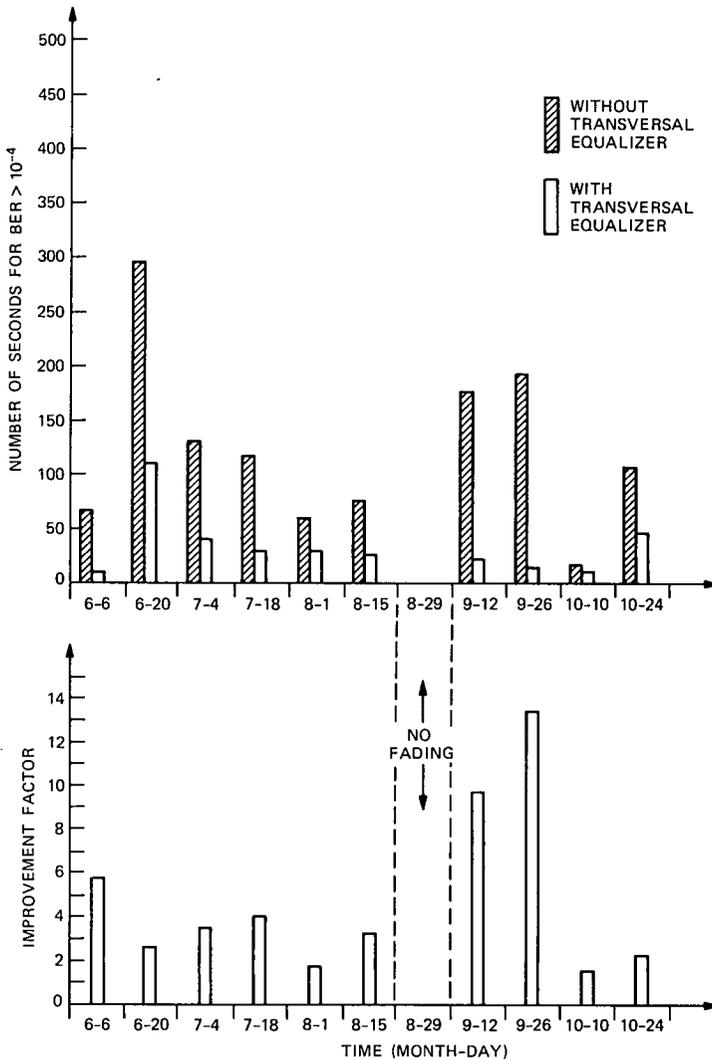Fig. 9—Field performance for BER $> 10^{-6}$.

Fig. 10—Field performance for BER $> 10^{-4}$.

transversal equalizer provided composite improvement factors of 3.6 for BER $> 10^{-6}$, 3.7 for BER $> 10^{-4}$, and 2.9 for frame loss. The 10^{-4} BER improvement factor of 3.7 is only 20 percent below the predicted improvement factor of 4.5, based on laboratory-measured equipment signatures.

IV. CONCLUSIONS

Because of their ability to adaptively equalize multipath-induced amplitude and delay distortion for minimum and nonminimum phase
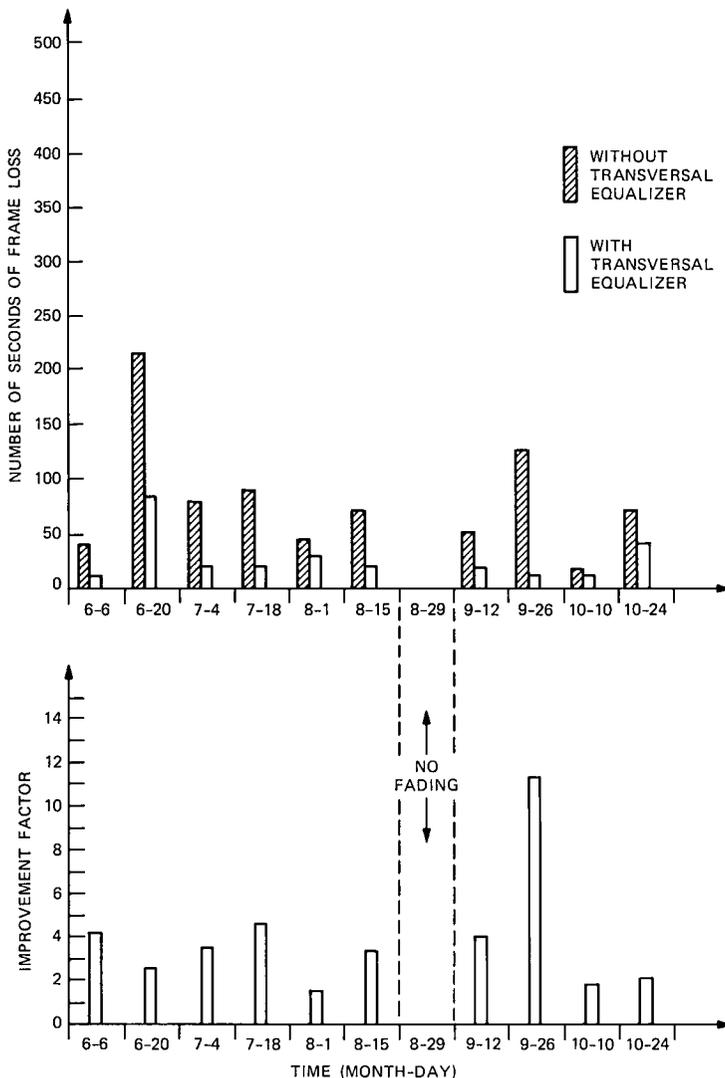
Fig. 11—Field performance for frame loss.

fading, synchronous transversal equalizers promise to play an impor-
tant role as a multipath countermeasure for terrestrial digital micro-
wave networks.

In this paper we summarize the major design and performance
features of a five-tap analog transversal equalizer for the baseband
receivers of two 16-QAM, 90-Mb/s digital radio systems. The equal-
izers heavily rely on HIC technology for their tapped-delay line buffer
amplifiers, tap-weighting coefficients, and summing circuitry. The

zero-forcing adaptation portion of the equalizer is realized with high-speed ECL logic. The entire equalizer is packaged in three 1-inch plug-in circuit packs.

During design, the equalizer was tested for its static equipment signature performance and dynamic tracking capability. The latter evaluation was facilitated with a special-purpose, computer-controlled multipath fade simulator. During a 22-week field trial evaluation in Palmetto, Georgia, the equalizer reduced the overall incidence of DR 6-30 radio outage by more than a factor of 3. System estimates indicate that this improvement factor could eliminate the need for space-diversity reception on more than 50 percent of the short-haul digital radio hops that currently use it. Use of the baseband adaptive transversal equalizer thus can provide considerable cost savings.

V. ACKNOWLEDGMENTS

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