# Performance Results of a Low-cost Alternative Equalizer Architecture for 64/256-QAM Demodulation in a CATV Receiver

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## ABSTRACT

*The viability of high order (64,256) QAM transmission techniques in a cable environment have recently been technically proven in extensive testing [1,2,3]. However, the economic goals of cable TV set-top terminal solutions for the demodulation of 64- and 256-QAM remain as the engineering challenge for modem designers. Current pricing for QAM demodulator chips will require a fairly significant reduction in cost within the next year to meet consumer demands as well as the competitive demands from market forces such as Direct Broadcast Satellite.*

*One expedient method for cost reduction exists in the demodulation algorithms. Within the demodulator architecture, it is not uncommon for the adaptive equalizer to occupy upwards of 40–50 percent of the silicon area. Traditional, T-spaced and T/2-spaced equalizers have been the cornerstone of many of the currently proposed architectures [1,4]. However, there exists a strong economic motivation in the consumer marketplace for examining alternative equalizer structures in order to decrease the silicon area. The intent of this paper is to address the technical performance capabilities of an alternative equalizer architecture that could potentially result in an equalizer die area savings of approximately 33 percent. More specifically, laboratory and field test results of a T/2-spaced prototype will be discussed and compared to simulation results of the proposed design.*

## INTRODUCTION

The advent of low-cost digital compression techniques for use in the CATV industry ushered in the search for a means of a high capacity method for digital transmission. Two likely candidates, QAM (Quadrature Amplitude Modulation) and VSB (Vestigial Side Band), have been tested in prototype equipment in both simulated and live cable systems **[1,2,3,5,6]**. Both methods are efficient transmission techniques and are equivalent in terms of the number of bits/Hz that can be transmitted in a 6 MHz channel. For the purposes of this paper, the discussion will be limited to QAM systems, although extensive literature on VSB exists **[4,5,6,7]**. QAM has become the logical transmission choice for several key set-top terminal manufacturers because of its widespread success in digital microwave radios and voiceband modems, as well as its adoption as the standard in Europe for Digital Video Broadcasting (DVB).

The generation of a QAM signal is theoretically straightforward. The information bit stream is demultiplexed into in-phase and quadrature rails. Each rail encodes its bit stream into $2^n$ levels and then bandlimits the signal with baseband filters in order to limit the resultant signal to a 6 MHz band. The filtered baseband signals are then multiplied by two quadrature tones, which are typically at TV IF (43.75 MHz). The resultants are then summed together to produce a 6 MHz-wide signal centered at TV IF. In a typical Head End, this signal is then upconverted to the destination channel frequency and transmitted via the cable. The function of QAM demodulation generally is found in the set-top terminal block diagram between the A/D Converter and Forward Error Correction as depicted in **Figure 1**. Its purpose is generally the following:

1. Extraction of the in-phase (I) and quadrature (Q) rails.*
2. Baud or symbol timing recovery.
3. Carrier recovery.
4. Automatic Gain Control (AGC).
5. Channel equalization.
6. Provide symbol decisions for the Forward Error Correction.

* Functions which are also commonly performed in analog circuitry

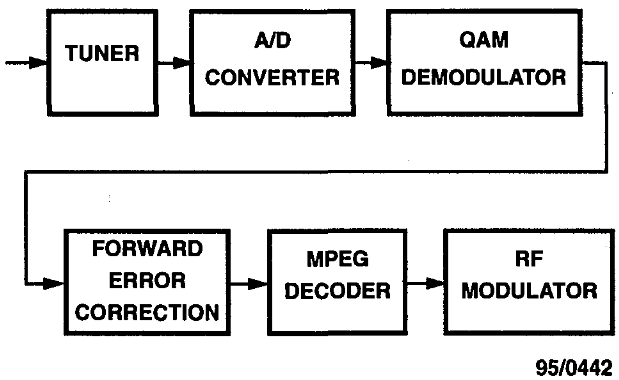
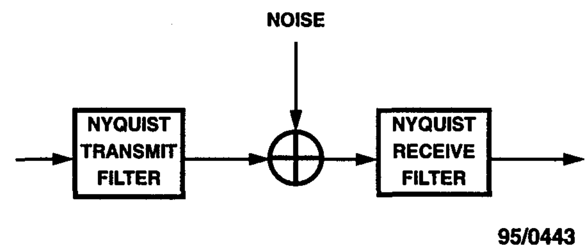



**Figure 1. Set-top Terminal Signal Processing Chain**

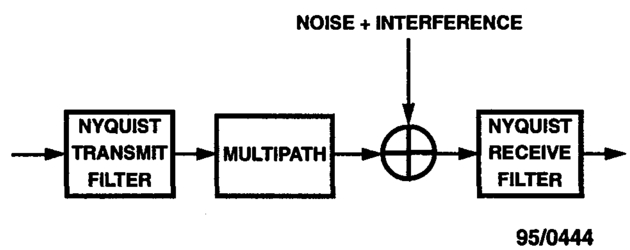
Channel equalization is necessary to mitigate the effects of echoes caused by impedance mismatches, co-channel interferers, adjacent channel interferers, and amplitude distortions caused by other set-top terminal components such as SAW filters. The function of conventional channel equalization can typically consume 40–50 percent of the silicon area in VLSI implementations of a QAM demodulator. While it is true that advances in silicon fabrication processes (i.e., 0.7 micron to 0.35 micron) and full custom layouts will eventually drive the cost of silicon down, more expedient algorithmic methods are needed in the short term in order to meet the price goals set by consumers as well as other market forces such as Direct Broadcast Satellite. Therefore, there exists significant motivation towards examining alternative equalizer architectures.

## Traditional Approaches

A simplistic view of a digital communication link is shown in **Figures 2(a) and (b)**. In **Figure 2(a)** the idealized case of a channel consisting of additive white Gaussian noise is shown. In this case a Nyquist transmit filter is employed and the requirements at the receiver are relatively straightforward. Since the goal at the receiver is to minimize the intersymbol interference (ISI), a simple matched Nyquist filter at the receive site will suffice. However, in real cable systems the link model contains additional interference phenomena such as microreflections caused by mismatches in impedances and co-channel interferers caused by NTSC carriers. Thus, a more realistic model for the link is shown in **Figure 2(b)**. The channel model for the multipath can be described as adding a pole to the overall channel response. In this case a simple Nyquist filter at the receiver will not be capable of removing the resultant ISI since the symbol nulls have been corrupted and the result is a smearing of energy from one adjacent symbol to the next, which can result in incorrect symbol decisions.




**(a) Simplified Digital Communication Link**




**(b) Digital Communication Link with Co-channel Interferers and Multipath**

**Figure 2. Digital Communication Links**

The poles created by the microreflection model require inverse filtering, i.e., an inverse filter with a zero. Since these microreflections can occur at variable amplitudes and delays, an adaptive equalizer is typically used. **Figures 3(a) and (b)** show two common feedforward linear Finite Impulse Response (FIR) equalizer architectures. In **Figure 3(a)** a T-spaced architecture is shown. "T-spaced" refers to the spacing or delay between adjacent taps, which in this case is one baud or symbol period. **Figure 3(b)** contains a T/2-spaced architecture, which simply means that the spacing between taps is one-half of a baud period. Many of the published, proposed designs have employed T- or T/2-spaced architectures **[1,4]**.

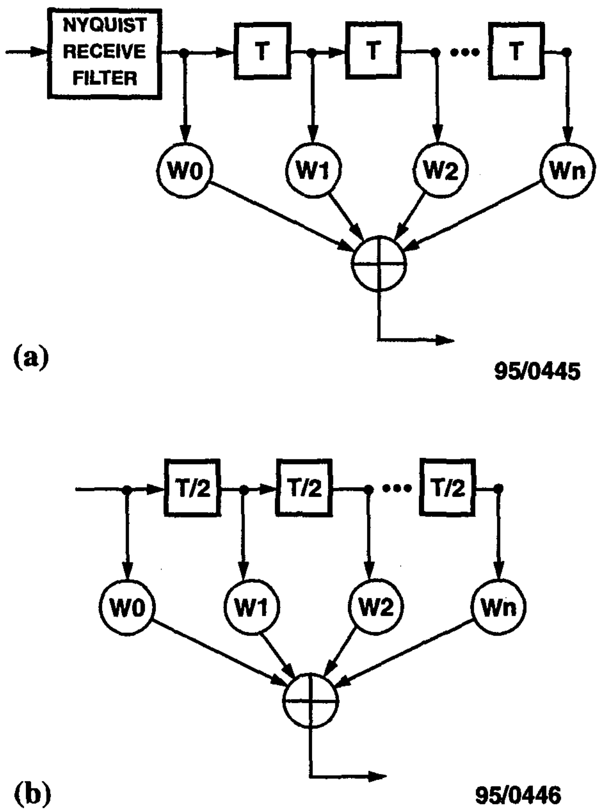



**Figure 3. (a) T-Spaced and (b) T/2-Spaced Equalizers**

There are several issues involved in choosing one spacing over another. One advantage of the T/2 architecture is that it is capable of aiding symbol timing recovery in attaining optimal baud phase. In addition, a separate Nyquist receive filter is needed before the T-spaced equalizer since this structure is not capable of synthesizing the matched receive filter. Thus, a T/2 architecture was chosen by Applied Signal Technology for the development of a prototype system for use in characterizing performance in both "live" and simulated cable environments. This prototype system would also serve as the design basis for a VLSI architecture for use in set-top terminal QAM receivers. The T/2 prototype has been through extensive testing at the Advanced Television Test Center (ATTC), in the laboratory, and in "live" cable systems using existing NTSC gear and analog set-top tuners. Results of this testing will be examined and referenced throughout this paper as a point of comparison with the proposed alternative architecture.

## PERFORMANCE RESULTS

### Performance Results of a T/2-Spaced Demodulator

*Results of the ATTC/CableLabs 64/256-QAM Test*

Two rounds of extensive testing were performed on the Applied Signal Technology T/2-spaced prototype at the Advanced Television Test Center (ATTC). The first round of tests was conducted in January by CableLabs, Inc., as part of the evaluation process for proposed HDTV transmission systems. In this round of testing the prototype was tested solely in the 256-QAM mode of operation. The second round of testing involved 64-QAM only and was conducted by CableLabs in October. For both rounds of testing impairment scenarios were developed in order to fully characterize each proponent's system and determine robustness. Thus, impairments such as microreflections, Gaussian noise, phase noise, residual FM, carrier offset, CTB and CSO, AM hum, etc. were added to the test signal for full system characterization and determination of each system's point of failure. The results are shown in **Table 1**. Results which are largely dependent upon the equalizer are shown with an asterisk (*).

The "Channel Acquisition Time" is germane to this discussion since this test consisted of switching from an unimpaired channel to a channel (12) with impairments which included microreflections. Case 1 consisted of a 300 nsec, –18 dB ghost on channel 12. Case 2 consisted of Gaussian noise at a level which is 3 dB below the threshold of visibility (TOV—defined as the coded Bit Error Rate (BER) of 3.0E–06), and a long delay ray of 2.5 µsec which was –20 dB down from the signal. Case 4 included both Gaussian noise (–3 dB below TOV) and a microreflection which was –20 dB down at 600 nsec delay. Note that the T/2-prototype was capable of acquiring within 0.5 seconds for both 64- and 256-QAM, which is satisfactory for the majority of consumers. Since the 256-QAM testing in January, the acquisition times for the Applied Signal Technology prototype were improved to be on the order of 250 msec, which is extremely quick even by today's NTSC standards. Note that the 64-QAM acquisition times reflect this improvement, cutting down the acquisition times by a factor of two. This currently holds true for 256-QAM as well.

## Table 1: 64/256-QAM Test Results, Cable Labs

| | 64-QAM | 256-QAM |
|---|---|---|
| **C/N (dB)** [(1)] * | 21.2 | 29 |
| **CSO (dBc)** [(1)] * | –27.95 | –38 |
| **CTB (dBc)** [(1)] * | –41 | –48 |
| **Phase Noise (dBc/Hz)** [(1,2)] | –78.22 | –85 |
| **Residual FM (kHz)** [(1,3)] | >99 | 66 |
| **Hum (% Modulation)** [(1,4)] | 13.8 | 5.7 |
| **Tuner Pull-in Range (kHz)** [(5)] | –165/+300 | ±300 |
| **Channel Acquisition Time (Sec.) *** | | |
| No impairments | 0.234 | 0.48 |
| 300 nsec, –18 dB ghost on test channel | 0.291 | 0.52 |
| 2.5 µsec, –20 dB ghost plus noise at –3 dB from TOV on test channel | 0.284 | 0.54 |
| Noise at –3 dB from TOV plus phase noise at –3 dB from TOV on test channel | 0.263 | 0.64 |
| 600 nsec, –20 dB ghost plus noise at –3 dB from TOV on test channel | 0.404 | 0.55 |
| Average | 0.309 | 0.55 |
| **Isolation Between Receivers *** | | |
| Echo (dB) at 0 BER | –20.9 | –24 |
| Data loss/hit at +6 dB Echo (sec.) | 0.22 | 0.046 |
| **CW Interference *** | | |
| C/I (dB) Continuous (208 MHz) | 23.65 | |
| C/I (dB) gated (205.25 MHz) | 21.65 | |
| **Adjacent Channel Interference *** | | |
| Degradation in threshold C/N caused by equal power adjacent QAM signal (dB) | 0.25 | |
| Degradation in threshold C/N caused by adjacent NTSC @ +7.64 dB (dB) | 0.25 | |
| **Grand Alliance Test *** | | |
| BER | Not Tested | Passed |
| Acquisition | Not Tested | Passed |

(1) TOV <3.0E–06 after error correction.
(2) Measured at 20 kHz offset
(3) Peak values. Carrier modulated with quasi-rectangular 120 Hz signal.
(4) Carrier Am modulated at 120 Hz.
(5) Threshold in <5 sec for acquisition. No impairments.

Another test based on a real life cable impairment scenario requiring robust equalization is the "Isolation Between Receivers" test. This test simulates a remote viewer channel surfing on another receiver connected to the same splitter as the demodulator under test. The test varies the level of a 150 nsec echo which is being pulsed off by virtue of a switch for 40 msec at a 5-second repetition rate. The amplitude of the echo is increased until errors occur ("Echo at 0 BER"). Note that the prototype was error free for an isolation of 24 dB, which can be achievable in a consumer grade splitter for reasonably low cost.

Finally, a multiple impairment test was devised by the Grand Alliance for which the BER was checked to ensure it was below TOV and the acquisition time was less than or equal to 0.5 seconds. The impairments consisted of 33.5 dB C/N, 3% AM hum, and an echo –13 dB down at a delay of 600 nsec. The T/2 prototype performed well and exceeded the specification for 256-QAM.

Additional testing was done on the 64-QAM system relative to microreflections as single impairments (see **Table 2**). Acquisition threshold and TOV tests were run with echo delays ranging from 0.5 to 5 microseconds. Performance proved to be sufficiently robust for real cable systems. It has been shown in one particular study involving measurements taken at approximately three hundred subscriber homes in twenty cable systems that 99 percent of all microreflections measured had echo amplitudes less than –19 dB below the desired signal and delay times less than 1.28 microseconds **[8]**. After the testing at CableLabs was completed, an independent test was performed on the demodulator only (without the tuner) at Applied Signal Technology in order to determine 256-QAM performance in the presence of microreflections as single impairments. The results are shown in **Table 2**. Results are within 1.5 dB of the 64-QAM performance for the shorter echo at 0.5 microseconds, but start to diverge slightly as the echoes get longer. This makes sense since the equalizer need only synthesize a single notch for the shorter echoes in order

**Table 2: 64-QAM Echo Test Results**

| | 64-QAM Tested by CableLabs (1) | | 256-QAM Tested by Applied Signal Technology (2) |
|---|---|---|---|
| **Delay (μs)** | **Acquisition (dB relative to signal** | **Threshold (TOV) (dB relative to signal)** | **Threshold (TOV) (dB relative to signal)** |
| 0.5 | –5 | –3 | –4.5 |
| 1 | –6 | –4 | |
| 1.5 | –6 | –5 | –11.5 |
| 2 | –7 | –7 | –12.5 |
| 2.5 | –10 | –10 | |
| 3 | –11 | –10.5 | |
| 3.5 | –11 | –11 | |
| 4 | –11 | –10.5 | |
| 4.5 | –10.5 | –10.5 | |
| 5 | –20 | –20 | |

(1) 64 taps, initialized at tap 16

(2) 32 taps, initialized at tap 8

to mitigate the distortion. When the echoes get longer, the amplitude ripple or "scalloping" in the frequency domain occurs with increasing frequency. The equalizer has a harder time synthesizing an increasing number of notches for a given number of taps and this, combined with the additional sensitivity inherent in 256-QAM, causes the aforementioned diversion of performance for the longer echoes. As can be seen from **Table 2**, 256-QAM performance for TOV (29 dB C/N) is approximately 6.5 dB from 64-QAM performance for a ~1.5 microsecond echo. However, this performance is also sufficient for the majority of cable systems.

### *Results of the 256-QAM New York City Field Test*

Between February 24 and March 3, 1994, a three-phase test was conducted by OmniBox, Inc., a developer of interactive television networks, over the New York City cable system of Time Warner Cable. All hardware used during the testing was standard NTSC equipment normally employed in the system, except that which provided the 256-QAM input signal to the upconverter, and the QAM demodulator. The test equipment did not provide any Forward Error Correction (FEC) or interleaving, and all BER numbers were raw, uncoded numbers. The test was set up in three phases, with each phase designed to examine different aspects of television transmission and reception through a typical cable system, thereby identifying degradation associated with different system elements. Phase One consisted of sending the 256-QAM signal across a 22-kilometer fiber optic link on channel 41 between the Head Ends at Brooklyn Queens Division (Flushing, Queens) and Manhattan Cable (23rd Street). Phase Two consisted of transmitting the QAM signal over standard coax cable and through the second longest cascade of trunk amplifiers in New York City with performance being measured at the end of the distribution chain at the southern tip of Manhattan. Phase Three was set up to receive the 256-QAM signal at a subscriber site (within Manhattan Cable's building) through approximately four trunk amplifiers and one bridge amplifier plus numerous splits and taps. These three phases of testing were selected as the best way to characterize the transmission and reception of 256-QAM over a typical cable system.

The Phase One test setup is shown in **Figure 4**. In this phase, the QAM signal was carried on channel 41 and the entire fiber optic line was terminated at the Manhattan Cable Head End site (i.e., it did not go to any subscribers). The laser being used to drive the fiber line was not specified to drive the entire length of 22 kilometers; it would normally be set up to drive a maximum of 12 kilometers and thus a reduction of Carrier-to-Noise ratio due to the longer fiber length incurred. Reasonably good BER numbers (4.7E–05) were obtained with the 256-QAM signal. The signal was set to be –5 dB lower in overall power compared to the adjacent NTSC signals and was bandlimited to be confined to the 6 MHz channel spacing by filtering the input to the upconverter with a standard Vestigial SAW filter centered at 43.7 MHz. **Figures 5** and **6** show the receive signal spectrum and constellation, respectively.

In Phase Two, a 256-QAM signal was transmitted through a "live" (i.e., on-the-air) cable system. The signal was transmitted through 23 trunk amplifiers, plus a high gain bridge amplifier (**Figure 7**). The BER of the 256-QAM signal was recorded at 4.3E–05 and 64-QAM was nearly error free at 8.2E–10. Both results were better than those obtained over the fiber link. The CNR of the channel was measured to be approximately 48 dB (~41 dB SNR). A spectral plot of the received digital signal, along with the adjacent aural and video carriers, can be seen in **Figure 8** with a photograph of the real-time 256-QAM constellation shown in **Figure 9**.

The Phase Three test consisted of demodulating the 256-QAM signal at a test subscriber site (within Manhattan Cable's building) followed by splitting to the various subscribers. The received BER was 1.2E–05.

The results of the tests are summarized in **Table 3** including the approximate link margins in parentheses (assuming an uncoded BER ~1.0E–03 is required with a coded system). Note that the tested channels were <u>not</u> SNR limited but rather phase-noise and filter distortion limited.

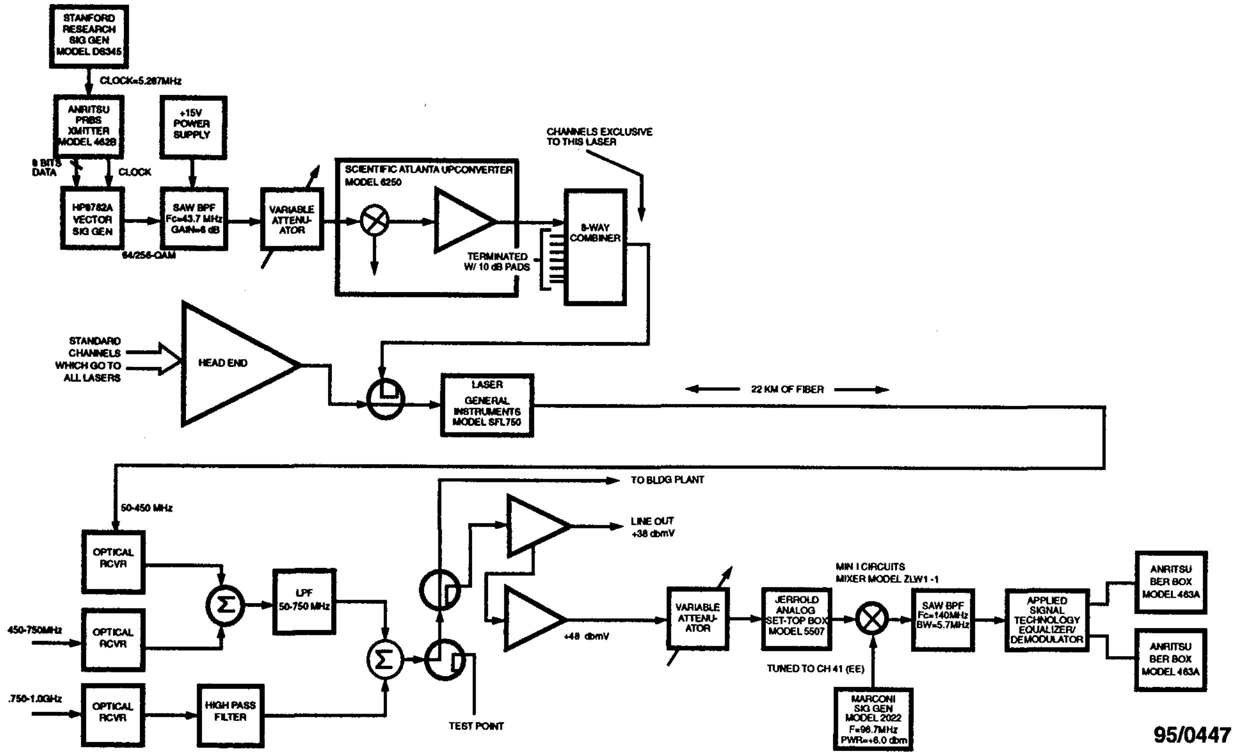



**Figure 4. Phase One Test: 22 km of Fiber**

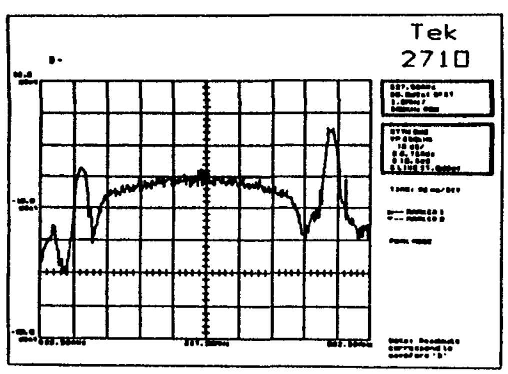



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**Figure 5. Phase One Test: Signal Spectrum**

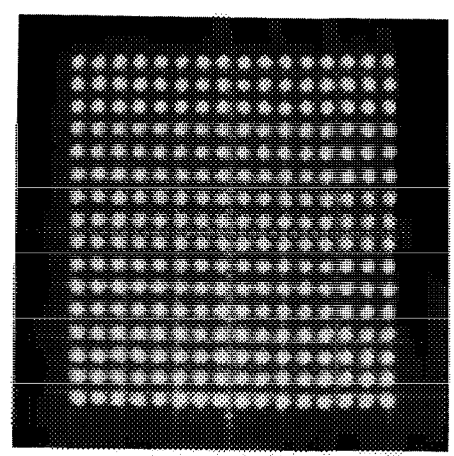

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**Figure 6. Phase One Test: Signal Constellation**

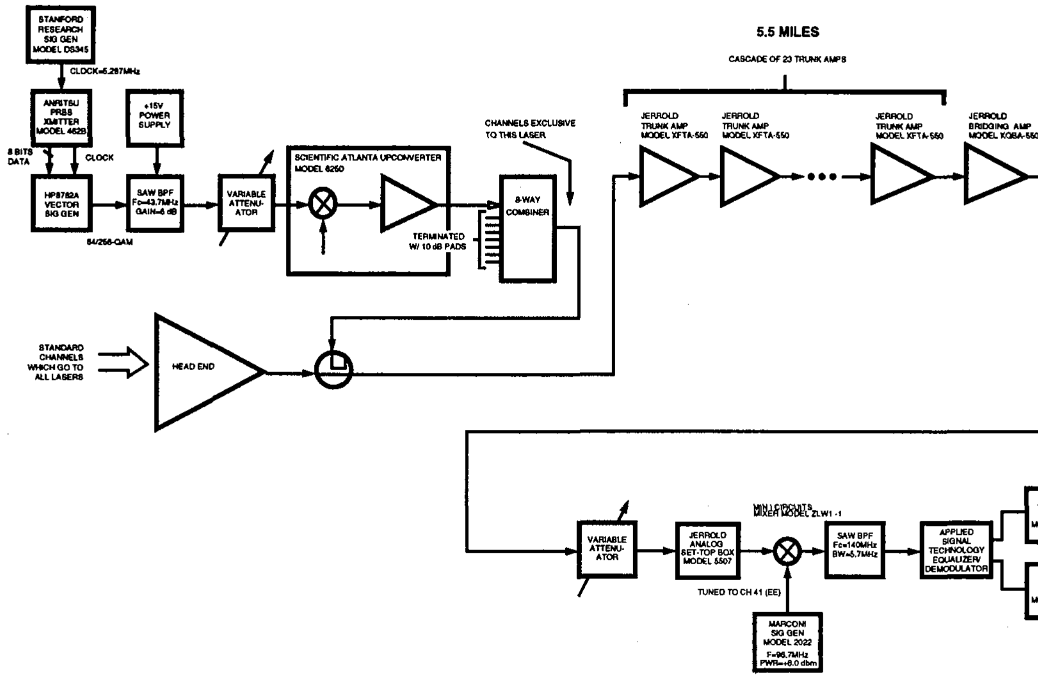


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**Figure 7. Phase Two Test: 23-Trunk Amp Channel**

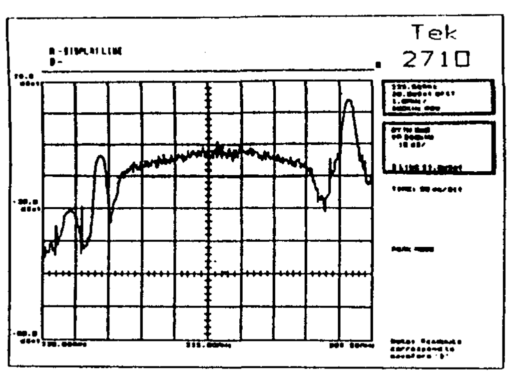


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**Figure 8. Phase Two Test: Signal Spectrum**

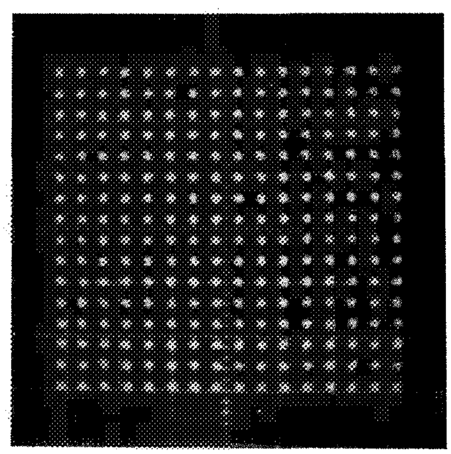

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**Figure 9. Phase Two Test: Signal Constellation**

**Table 3: Summary of Bit Error Rate Results (Uncoded)**

| Test Condition | 256-QAM BER | 64-QAM BER |
|---|---|---|
| Fiber Link | 4.70E–05 | 1.85E–08 |
| | (2 dB) | (5.5 dB) |
| Coax Run | 4.30E–05 | 1.85E–08 |
| | (2 dB) | (6.5 dB) |
| Subscriber | 1.20E–05 | Not Measured |
| | (3 dB) | |

The next phase of the test will include broadcasting four channels of NTSC quality compressed digital video over one 6 MHz cable channel. Transmission will utilize OmniBox's proprietary compression technology, DVC™ (Digital Vector Compression), with 256-QAM and Forward Error Correction.

## An Alternative Architectural Approach

As consumer price pressures assert their power on modem designers, the functional blocks which occupy the largest amount of real estate will come under increasingly close scrutiny. As mentioned previously, the equalizer functional block represents the top candidate for re-examination, occupying up to 40–50 percent of the demodulator die area. To this end, alternative equalizer structures were explored and a new architecture was chosen based upon signal processing considerations associated with the other functional blocks in the system and their relationship to video data rates and TV IF sampling methodologies. This architecture was arrived at as a result of an engineering trade-off between sufficient performance and the economic utilization of silicon. It is not the intent of this paper to examine the precise implementation aspects of the proposed design, but rather to state its existence, associated economy with respect to computational complexity and die area, and performance merits relative to the T/2-spaced prototype.

As a first order basis of comparison, consider a 32-tap, linear, T/2-spaced equalizer. It has been shown **[2,8]** that this is a reasonable length to span for most cable environments that might be encountered. In order to compute one output, there are 32 taps x 4 FIR structures (complex equalizer)=128 multiply accumulates (MACs) per output. Assuming a data rate of 5 Mbaud, this corresponds to 5Mx128=640M (MAC ops/sec). For an equalizer span which is equivalent to 32 T/2-spaced taps, the proposed design is capable of reducing the computational complexity by a factor of roughly one-third. In addition, die size comparisons with an existing T/2-spaced design have revealed an equalizer real estate savings of greater than 30 percent. Assuming that this architecture performed well in simulated cable environments with associated multiple impairment scenarios involving phase noise, microreflections, and Gaussian noise, a strong motivation to move toward a VLSI implementation would be warranted. Two computer models of the proposed architecture were created. The first model consisted of a floating point VAX simulation with reasonable first order quantization effects included. The second model consisted of a hardware specific fixed point COMDISCO simulation. In both models performance was characterized over single and multiple impairments for both 64- and 256-QAM. Throughout the design and simulation process, results were consistently being reviewed and compared to the T/2 prototype results in order to gauge the efficiency of the trade-off between performance and economy. The question continually posed to the design team was: "How did the T/2-spaced prototype perform in this scenario?"

## Simulation Results

A computer model of the advanced architecture was generated in floating point and simulated on a VAX with reasonable first order quantization on critical parameters such as the data and equalizer tap weights. The functions modeled include: digital downconversion from TV IF to baseband, baud timing recovery, carrier recovery, equalization, and symbol decisions. The block diagram of the simulated environment is shown in **Figure 10.** A 20 percent Square Root Raised Cosine (SRRC) transmit filter was assumed throughout. The impairments modeled included microreflections, additive Gaussian noise, phase noise, and carrier offsets. These impairments were first added individually, and the equalized SNR was measured. Finally, the impairments were applied to the channel as a group. The results for 64-QAM are shown in **Table 4**. Laboratory tests involving these same impairments were then conducted for purposes of comparison using

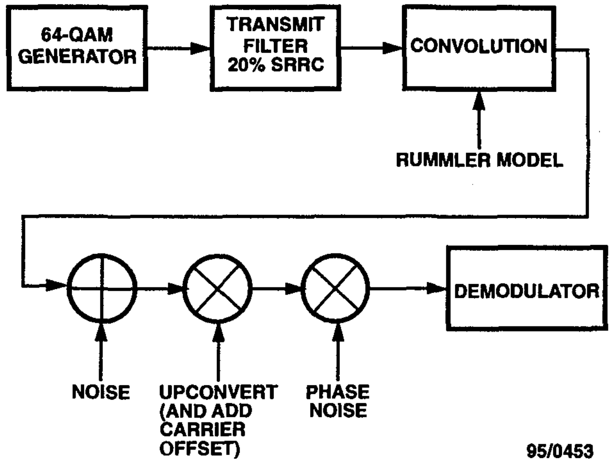


**Figure 10. System Simulation Block Diagram**

the Applied Signal Technology Model 242 (T/2-spaced) prototype. The results of these T/2 hardware tests are also shown in **Table 4**. Similar results for 256-QAM are shown in **Table 5**.

**Figure 11** shows the spectrum of the 64-QAM signal just before equalization for the multiple impairment scenario shown at the bottom of **Table 4. Figure 12** shows the constellation prior to demodulation. This scenario includes a microreflection with a relatively short delay of 500 nsec and a ray amplitude which is –10 dB down from the signal of interest. Note the deep notch in the center of the frequency response in **Figure 11** caused by the echo.This notch is due to the reflected ray summing 180 degrees out of phase with the signal of interest. The equalizer must build the inverse of this response in order to equalize the channel, as it does in **Figure 13**. A magnitude plot of the converged equalizer weights is included in **Figure 14.** The highest peak on the left represents the tap location where the impulse response of the equalizer was initialized. The second highest peak to the right signifies the location of the zero which the equalizer created to equalize out the effects of the pole caused by the echo. This second peak is –10 dB down from the first peak, which is precisely what one would expect since the echo is –10 dB down from the transmitted signal. Finally, **Figure 15** shows the demodulated 64-QAM constellation.

**Table 4: 64-QAM Performance Comparison of Simulated Architecture with Prototype T/2 Architecture**

| | Multipath | CNR (dB) | Phase Noise (dBc/Hz @ 10 kHz Offset) | Carrier Offset (kHz) | Equalized SNR (dB) |
|---|---|---|---|---|---|
| Simulation Model | None | No Noise | None | 0 | 38 |
| Model 242 (T/2) | None | No Noise | None | 0 | 37.1 |
| Simulation Model | –10 dB @ 500 nsec | No Noise | None | 0 | 36.8 |
| Model 242 (T/2) | –10 dB @ 500 nsec | No Noise | None | 0 | 36.8 |
| Simulation Model | None | 28 | None | 0 | 26.5 |
| Model 242 (T/2) | None | 28 | None | 0 | 26.8 |
| Simulation Model | None | No Noise | –72 | 0 | Not Tested |
| Model 242 (T/2) | None | No Noise | –72 | 0 | Not Tested |
| Simulation Model | –10 dB @ 500 nsec | 28 | None | 0 | 25.8 |
| Model 242 (T/2) | –10 dB @ 500 nsec | 28 | None | 0 | 26.7 |
| Simulation Model | –10 dB @ 500 nsec | 28 | –72 | 100 | 24.8 |
| Model 242 (T/2) | –10 dB @ 500 nsec | 28 | –72 | 100 | Not Tested |

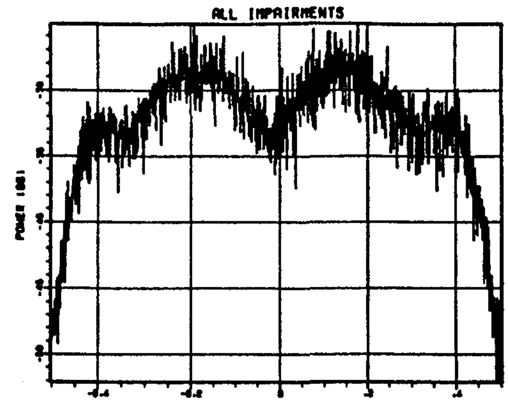


Figure 11. 64-QAM Input Signal Spectrum: Multiple Impairment Scenario, Table 4

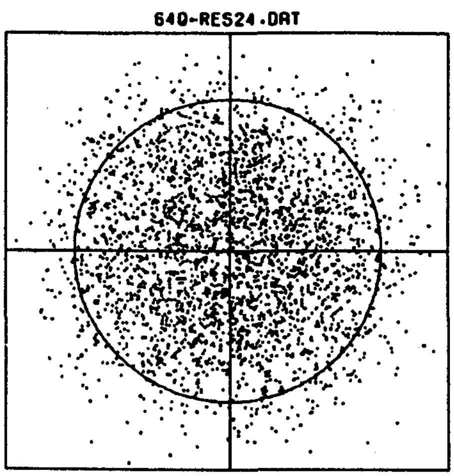


Figure 12. 64-QAM Input Signal Constellation: Multiple Impairment Scenario, Table 4

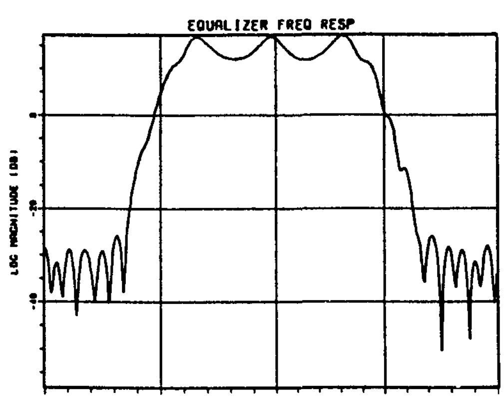


Figure 13. Resultant Equalizer Frequency Response: Multiple Impairment Scenario, Table 4

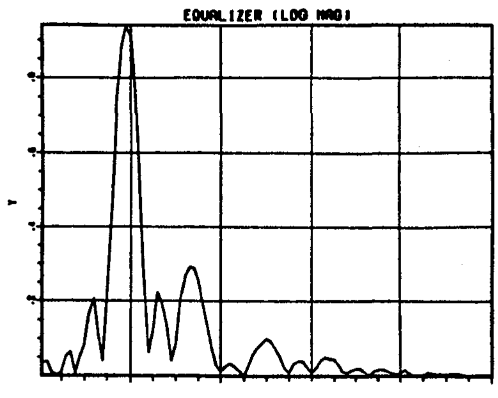


Figure 14. Resultant Magnitude of Equalizer Weights: Multiple Impairment Scenario, Table 4

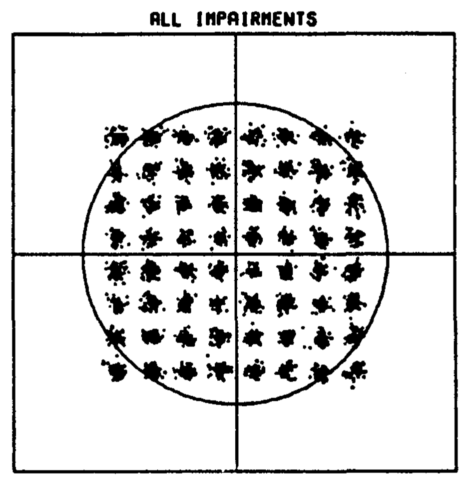


Figure 15. Equalized and Demodulated 64-QAM Constellation: Multiple Impairment Scenario, Table 4

Similar simulations were run with weaker reflected rays (–18 dB) and much longer delays on the order of 2 μsec. **Table 5** shows the results of a longer delay echo on 256-QAM. **Figures 16–18** correspond to this case. **Figure 16** shows the frequency response of the received signal prior to equalization. Note the "scalloping" that results in the amplitude of the signal spectrum. Larger notches such as those simulated in **Table 4** do occur, but are extremely improbable on real cable systems for a delay range of 1–2 μsec as has been shown in **[8]**. **Figure 17** shows the final equalized constellation. **Figure 18** shows the frequency response built by the equalizer after convergence. Comparison of this frequency response to that of **Figure 16** reveals that the equalizer response "enhanced" or amplified the notch energy in order to equalize the channel

**Table 5: 256-QAM Performance Comparison of Simulated Architecture with Prototype T/2 Architecture**

| | Multipath | CNR (dB) | Phase Noise (dBc/Hz @ 10 kHz Offset) | Carrier Offset (kHz) | Equalized SNR (dB) |
|---|---|---|---|---|---|
| Simulation Model | None | No Noise | None | 0 | 36 |
| Model 242 (T/2) | None | No Noise | None | 0 | 35.8 |
| Simulation Model | –18 dB @ 2 μsec | No Noise | None | 0 | 33 |
| Model 242 (T/2) | –18 dB @ 2 μsec | No Noise | None | 0 | 33.8 |
| Simulation Model | None | 33 | None | 0 | 31.5 |
| Model 242 (T/2) | None | 33 | None | 0 | 31.2 |
| Simulation Model | None | No Noise | –78 | 0 | 33 |
| Model 242 (T/2) | None | No Noise | –78 | 0 | Not Tested |
| Simulation Model | –18 dB @ 2 μsec | 33 | –78 | 100 | 28.7 |
| Model 242 (T/2) | –18 dB @ 2 μsec | 33 | –78 | 100 | Not Tested |

response. In both of the aforementioned cases the equalized constellations (**Figures 15** and **17**) exhibit the residual effects of Gaussian noise ("fuzziness" of the constellation points) and phase noise, i.e., "arcing" of constellation points in a direction perpendicular to the imaginary line between the point and the constellation origin. Note that the simulated results are within 1 dB of the T/2 prototype performance over all individual impairments and within 1 dB for the ensemble of impairments.

Finally, the advanced architecture was simulated against 64-QAM echo scenarios which were similar to those encountered in the CableLabs testing of October of 1994 (see **Table 3**). Note that these tests were run with the demodulator employing an equalizer with 64 taps initialized at tap 16. The goals of the simulations were twofold. First, we sought to determine the performance hit incurred by utilizing an equalizer which spanned the equivalent of 32 taps. Secondly, the desired performance degradation should include any effects associated with the advanced architecture. The results of these simulations are shown in **Table 6**. Three microreflection delays were simulated: 0.5, 1.0 and 2.0 microseconds. In each case the power of the echo relative to the desired signal was increased until acquisition was not longer achievable. Note that the advanced architecture matches the performance of the T/2-prototype to within 1 dB for echoes with time delays which are less than 1 microsecond. The performance hit becomes more noticeable at the longer delay of 2 microseconds. In this case the equalizer acquired an echo which was –11.5 dB from the desired signal. Note the resultant constellation in **Figure 19**. This represents a performance hit of approximately 4.5 dB relative to the 64-tap T/2-spaced hardware prototype. However, the results are still quite promising when one compares this 2 microsecond, –11.5 dB ray with the statistical results of measurements taken over a wide variety of cable systems **[8]**. To reiterate, 99 percent of all subscriber sites measured delay times less than 1.28 microseconds and echo amplitudes less than –19 dB below the desired signal.

## SUMMARY

The results of extensive testing performed on a 64/256-QAM demodulator prototype employing a T/2-spaced equalizer were presented. Testing covered a multitude of cable impairments in both a laboratory and "real world" environments. The majority of the laboratory testing was done at the Advanced Television Test Center (ATTC). Testing involving a "live" cable system was performed in the New York City field trial over Time Warner's

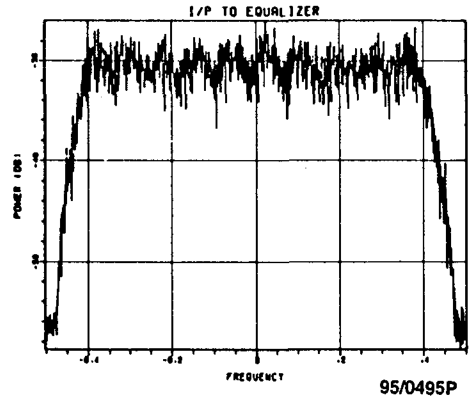


Figure 16. 256-QAM Input Signal Spectrum: Multiple Impairment Scenario, Table 5

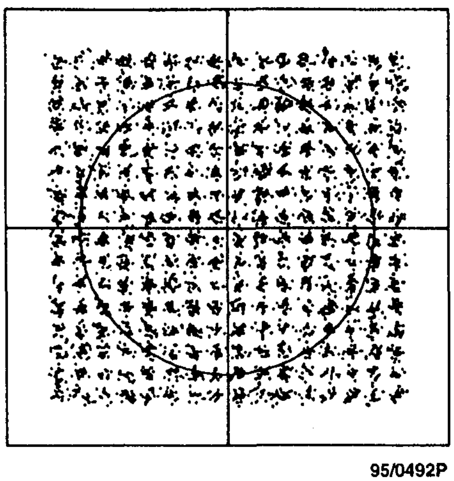


Figure 17. Equalized and Demodulated 256-QAM Constellation: Multiple Impairment Scenario, Table 5

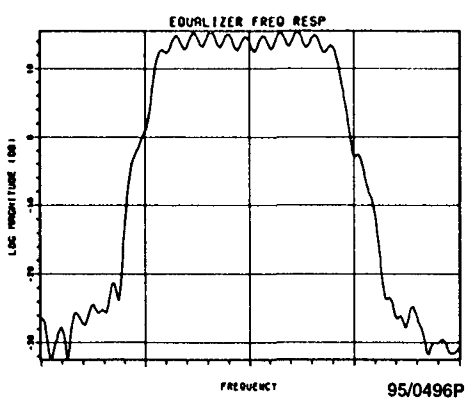


Figure 18. Resultant Equalizer Frequency Response: Multiple Impairment Scenario, Table 5

**Table 6: 64-QAM Echo Simulations vs. Prototype Performance**

| | Simulation (1) | T/2 Prototype (2) Tested by CableLabs |
|---|---|---|
| Delay (μs) | Acquisition (dB relative to signal) | Acquisition (dB relative to signal) |
| 0.5 | –5 | –5 |
| 1 | –7 | –6 |
| 1.5 | | –6 |
| 2 | –11.5 | –7 |
| 2.5 | | –10 |
| 3 | | –11 |
| 3.5 | | –11 |
| 4 | | –11 |
| 4.5 | | –10.5 |
| 5 | | –20 |

(1) Time span of equalizer equivalent to 32 T/2-spaced taps, initialized at approximately tap 8

(2) 64 taps, initialized at tap 16

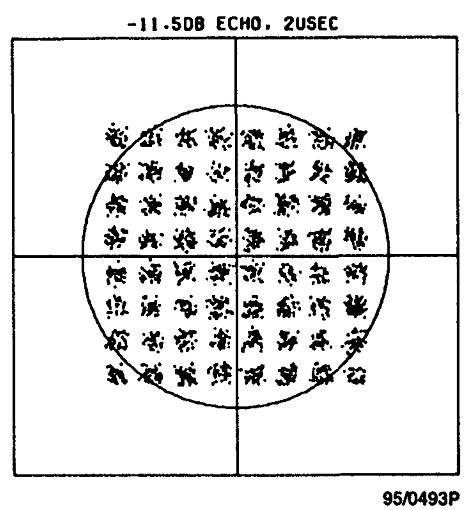


Figure 19. Equalized and Demodulated 64-QAM Constellation: –11.5 dB Echo at a Delay of 2 μsec

system. All performance testing indicates that QAM is an operationally effective means of high speed data transmission for digital CATV and that a QAM receiver employing blind equalization and carrier recovery as embodied in the T/2-spaced prototype architecture is sufficiently robust for a wide range of realistic impairment scenarios.

An alternative to the T/2-spaced architecture was suggested as a means of decreasing the equalizer computational complexity, and therefore die real estate, by a factor of roughly one-third. A computer model of the advanced architecture was created and performance was simulated against both single and multiple impairment scenarios.The results of the simulations for the advanced architecture were very close (typically within 1 dB) to that of the T/2-spaced prototype for equivalent equalizer time spans. The results were very encouraging based upon the success of the T/2 prototype at the Advanced Television Test Center and in live cable systems. The positive impact of these simulations led to a second phase of simulation modeling for the proposed architecture. In this second phase, a model was created in COMDISCO which incorporated a hardware-specific approach and included detail down to the flip-flop level.

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