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RATE 3/4 CODED 16-QAM FOR UPLINK APPLICATIONS

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ABSTRACT

First phase development of an advanced modulation technology which synergistically combines coding and modulation to achieve 2 bits per second per Hertz bandwidth efficiency in satellite demodulators is nearing completion. A proof-of-concept model is being developed to demonstrate technology feasibility, establish practical bandwidth efficiency limitations, and provide a data base for the design and development of engineering model satellite demodulators. The basic considerations leading to the choice of 4x4 Quadrature Amplitude Modulation (16-QAM) and its associated coding format are discussed, along with the basic implementation of the carrier and clock recovery, automatic gain control, and decoding process. Preliminary performance results are presented. Spectra for the modulated signal and its interferers show the effect of the nonlinear channel. The envelope of the modulated signal shows the effects of the square root Nyquist filters in the modulator. BER results for the Encoder/Decoder subsystem show near ideal results, although power consumption is high and baseband BER performance of the Nyquist filter set is poor. Recommendations regarding the present system to improve BER performance and acquisition speed are given.

SYSTEM DESIGN

Objective (Statement of Work 0.1)

- Develop POC model of a satellite demodulator with associated special test equipment
- Significantly increase BW efficiency
- Maintain present system performance levels
- Exhibit potential for low weight and power consumption

Modulation System Requirements (SOW 3.1)

- FDM/TDMA uplink
- Single modulator & transmitter per channel
- Channel nonlinearity = TWTA (provided by NASA)
- Fixed burst rate = 200 Mbps
- Variable length of data portion of burst (range = same as preamble length to length for 1 ms burst)
- IF demodulation at 3.373 GHz. (assumes linear low noise receiver)
- 2 adjacent channels identical to desired channel but 20 dB higher in level
- 1 co-channel interferer identical to desired signal but uncorrelated and 20 dB lower in level

Performance Requirements (SOW 3.2.2)

Parameter	Specification	Performance/Operation
Bandwidth Efficiency	$\geq$ 2 bits/s/Hz	1.998 bits/s/Hz
E_S/N_O degradation at 5×10^{-7} BER	$\leq$ 2 dB	TBM
Dynamic Range for BER Spec.	20 dB (maximum)	20 dB
Time to Acquire Synchronization	$\leq$ 100 information bit times	192 info bits times
Probability of Acquisition Failure	$\leq 10^{-8}$	TBM
Unique Word Length	$\leq$ 20 bit times	12 bit times
BER Degradation for ACI	$\leq$ 1 dB	TBM
BER Degradation for CCI	$\leq$ 1 dB	TBM
Guard Time	10 nsec (minimum)	30 nsec
Burst Rate Instability	$\pm 5 \times 10^{-7}$ (maximum)	$\pm 5 \times 10^{-7}$
Mean Time to Cycle Slip (at E_S/N_O = 3 dB less than for BER Spec)	$\geq$Preamble Length x 10^4	TBM

Modulation/Coding Scheme Tradeoffs

A given information rate can be communicated in a smaller bandwidth by using a higher order modulation format (larger M, where M = the number of modulation states), but at the expense of bit error rate (BER) performance. To meet the bandwidth efficiency given in the system requirements and provide for protection against adjacent channel interference (ACI), an M = 16 modulation is desirable. The other formats investigated couldn't meet the bandwidth efficiency requirements or performed poorly. 16-PSK could theoretically yield excellent performance, but the phase accuracy required for efficient coherent detection is unrealistic. The uplink also does not have as strong of a requirement as the downlink to use the high power amplifier (HPA) optimally by continuously running it in saturation. 4,12 circular quadrature/amplitude modulation (QAM) has the advantage of only two power levels which could allow easier compensation of the high power amplifier (HPA) nonlinearity by the use of predistortion, but 4x4 -QAM is simpler in that each quadrant has independently selected, equally spaced quadrature levels. The ideal performance of coded 4x4 -QAM is also slightly better than coded 4,12 circular QAM. Of the 16-ary modulations, the 4x4 rectangular constellation is the most practical choice for both performance and implementation.

Forward error correction (FEC) coding of rate p = 3/4 yields 3 information bits per 16-QAM symbol, so that an information bit rate of R_b = 201 Mbit/s is obtained from a modulation speed of only R_s = 67 Msymbol/s. Consequently, Nyquist filtering with 30 - percent rolloff can be employed so that the coded 16-QAM power spectrum occupies only about 87 MHz of a 100-MHz channel. This provides frequency guard space for protection against ACI. A simple FEC code of only 8 states provides an asymptotic gain of 5.3 dB for coded 4x4 -QAM relative to uncoded 8-PSK.

CANDIDATE NUMBER	CODE RATE	MODULATION TECHNIQUE	SYMBOL RATE (MSymbol/s)	B/R_s for B = 100 MHZ	ASYMPTOTIC CODING GAIN RELATIVE TO 8-PSK. AVERAGE	PEAK	NUMBER OF STATES IN DECODER
1	5/6	8-PSK	80	1.25	5.0	5.0	8
2	5/6	8-PSK	80	1.25	6.3	6.3	16
3	8/9	8-PSK	75	1.33	4.3	4.3	8
4	8/9	8-PSK	75	1.33	4.3	4.3	16
5	3/4	16-PSK	67	1.50	4.0	4.0	8
6	3/4	16-PSK	67	1.50	4.4	4.4	16
7	3/4	16-QAM (4X4)	67	1.50	5.3	2.5	8
8	3/4	16-QAM (4X4)	67	1.50	6.1	3.6	16
9	3/4	16-QAM (4,12)	67	1.50	4.7		8
10	3/4	16-QAM (4,12)	67	1.50	5.1		16
11	1	COHERENT 8-CPFSK H=0.125, N=2	67	1.50	-1.7		16
12	1	COHERENT MULTI-H CPFSK	67	1.50			256

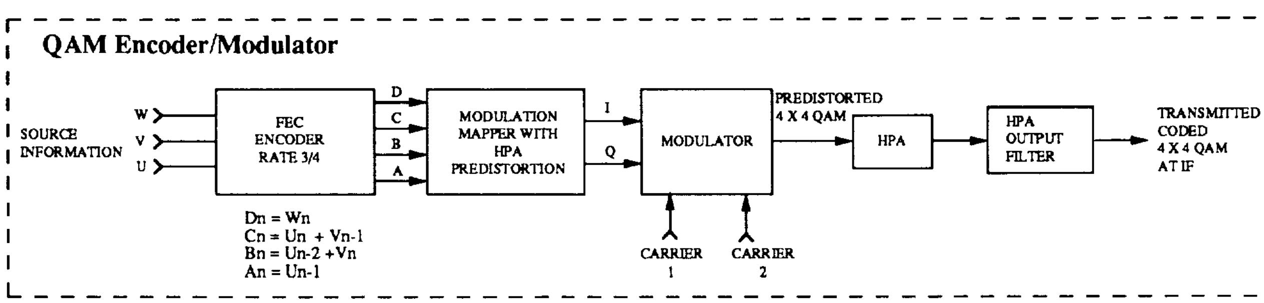
Modulation/Coding Choice

Coded 4x4 16-QAM was selected as the uplink modulation/coding choice for bandwidth efficiency, implementation simplicity, and power efficiency. Bandwidth efficiency is provided by using a large modulation alphabet of M = 16. The linear structure of the 4x4 square constellation allows some simplification in implementing the modulation and demodulation. FEC coding, soft detection, and Viterbi decoding provide power efficiency.

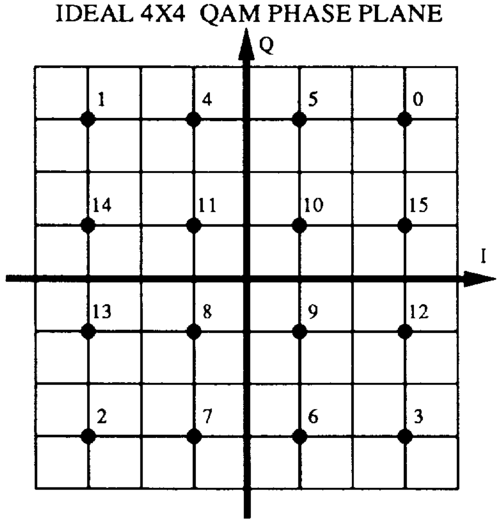
With the use of FEC coding of rate p = 3/4, coded 16-QAM conveys three information bits per 16-ary modulation symbol. Thus, an information rate of 201 Mbit/s can be obtained with a modulation rate of only 67 Msym/s, which can be sent in an allocated bandwidth of 100 MHz for a bandwidth efficiency of 2 b/s/Hz. The D bit of the encoded symbol causes modulation state changes with the highest minimum Euclidean distance, so it is left uncoded, allowing maximum coding for the other bits.

The nonlinear uplink channel is a traveling wave tube amplifier (TWTA). It is used at zero backoff and the nonlinearity is partially compensated for by adjusting the modulator to phase and amplitude predistort the constellation. Residual signal scatter however, will still exist due to ISI. The spectral regrowth from the HPA requires some filtering to suppress ACI [Rhodes, 1972], so the simulations also included a four pole elliptical filter at the HPA output with ideal group delay equalization.

The computer simulated BER performance of the selected modulation/coding system is shown below. It assumes a 64 symbol (192 info bit times) preamble length for carrier and clock recovery with independent operation of the automatic gain control (AGC). The simulations were made down to BER = 1×10^{-4} and extrapolated to extend to 1×10^{-7}. Curve A shows the Average White Gaussian Noise (AWGN) performance in a linear channel. Curve B is the performance in the nonlinear uplink channel. Curve C is the nonlinear channel performance with ACI. Curve D is the nonlinear channel performance with co-channel interface (CCI). These extended curves show that, at BER = 5×10^{-7}, the nonlinear channel itself degrades system performance 0.4 dB from the ideal theoretical case, leaving 1.6 dB for degradation due to hardware implementation. ACI degrades nonlinear channel performance by 0.5 dB (specification = 1 dB) and CCI degrades nonlinear channel performance by 1.4 dB (spec= 1 dB).

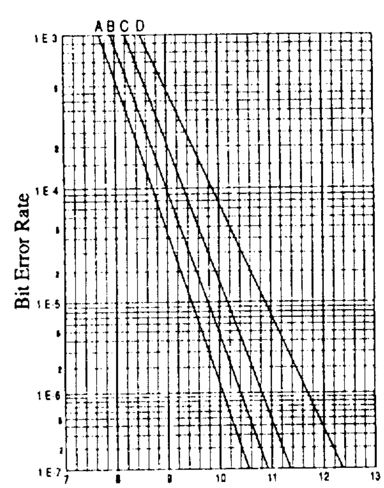


IDEAL 4X4 QAM PHASE PLANE



STATE # = 8D + 4C + 2B + A

CODED 4x4 QAM COMPUTER SIMULATION RESULTS



Es/No (dB)

DEMODULATOR/DECODER IMPLEMENTATION

Ringing Filters

Ringing filters (narrowband low-order bandpass filters) are superior to phase-locked-loops (PLLs) in TDMA communication systems. Although the two approaches have similar noise performance and the PLL is usually less complex, the absence of "hangup effect" in the ringing filter is a great advantage. The tuned filter (assuming it rings up from a "quenched" state) also exhibits an inherently faster phase transient. [Gardner, 1976]. Two sets of ringing filters are used in both the carrier recovery and clock recovery. Because of the extremely short guard time between bursts we "ping-pong" between the two sets of filters and quench one set while the second set is ringing up on the new burst. The carrier frequency is generated from the suppressed carrier QAM by remodulation techniques and separated from spurious products by the ringing filter. The clock frequency is generated from the detected data using a squaring nonlinearity.

Frequency Controlled Loop

Because of the various sources of frequency drift (such as the local oscillator in the transmitter, doppler offsets, and the tuning of the ringing filter) some method of frequency tracking is necessary. It is also desirable to downconvert the modulated signal to a frequency where lower cost components are available, so a frequency controlled loop is used. The carrier frequency is kept in the center of the filter by controlling the downconversion oscillator via detection of the average phase shift (over many bursts) through the ringing filter in the carrier recovery. The system design study showed the sensitivity of the system performance to inaccuracies in clock recovery to be much less than for carrier recovery making frequency control for the clock unnecessary.

Automatic Gain Control

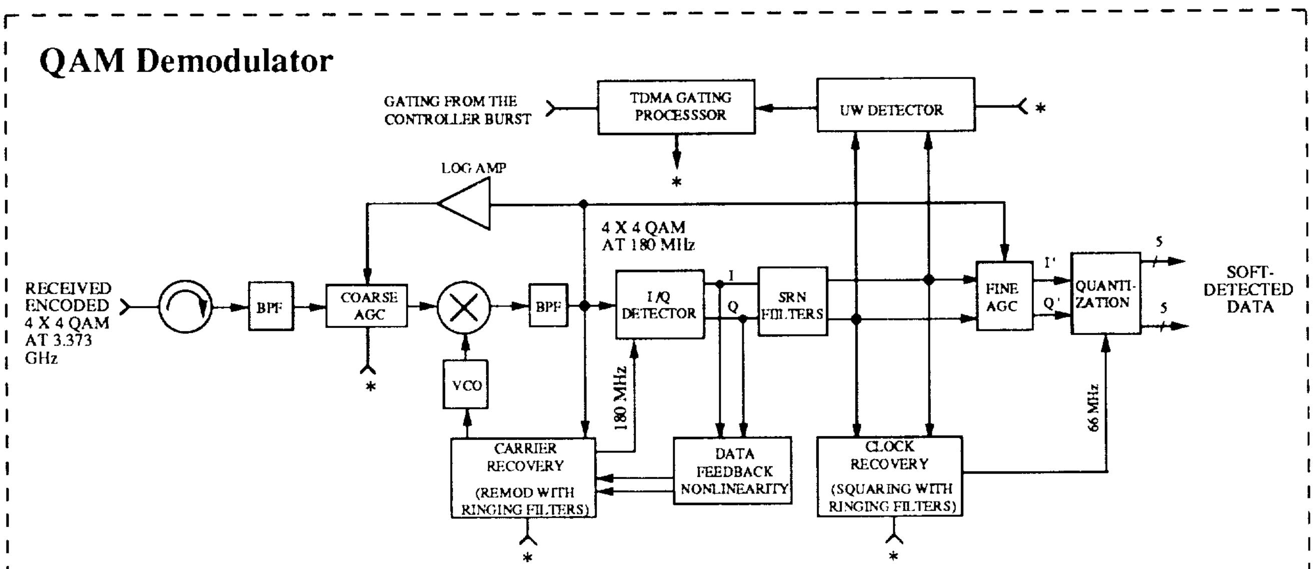
The 20 dB dynamic range of the input signal requires some form of gain control for correct detection and decoding. The AGC was implemented in the demod portion of the Demodulator/Decoder. The carrier recovery and I/Q Detection circuits are slightly sensitive to the signal power, so a "coarse" AGC is used in the front end to reduce the dynamic range to 2 dB as fast as possible. A "fine" AGC is then used immediately before soft detection to further reduce the range to a level acceptable for proper operation of the Viterbi decoder.

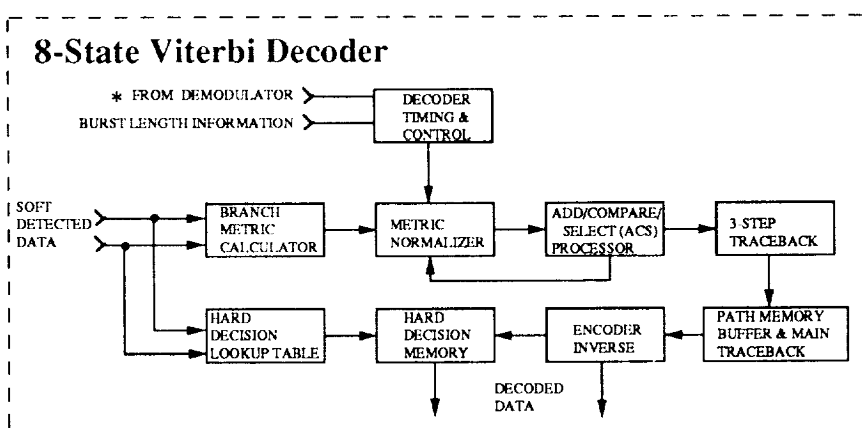
Detection Filter

Achieving 2 bits/s/Hz bandwidth efficiency requires a highly bandlimited system. Correct regeneration of an original impulse stream can be obtained in a minimum bandwidth by avoiding intersymbol interference (ISI) through the use of special channel filtering. The basic filter characteristic is an ideal linear-phase "brick wall" filter, having a single-sided cutoff frequency of half the symbol rate ($f_C = f_S/2$), although practical filters are realizable since cutoff symmetry is allowable. [Nyquist, 1928]. For optimal BER performance the Nyquist filter is equally split between the modulator and the demodulator [Feher, 1983]. An inverse sinc amplitude function is also included in the modulator to account for the pulse shape of the nonreturn to zero (NRZ) data stream that is used.

Decoder

The encoder leaves one uncoded information bit in each symbol and has 3-bit memory, implying 8 code states with 4 input branches for each state. The uncoded bits (1 bit for each symbol) are decoded by a hard decision, with the correct axis chosen at the completion of the decoding process. The branch metric calculations are made using a lookup table, and the results are used by the state metric calculator to compute the accumulated path metrics. Selection of the minimum path metric is performed in parallel by 6 high speed comparators, and normalization is used to prevent accumulated path metrics from overflowing. The traceback is partitioned into a 3-step traceback (to lower the traceback rate by a factor of three, allowing the use of TTL/CMOS logic) and a main traceback with an 8 symbol path memory length. Finally, the encoder inverse transforms the estimates of the input state sequence into information bits and selects the appropriate axis for the hard decisions.





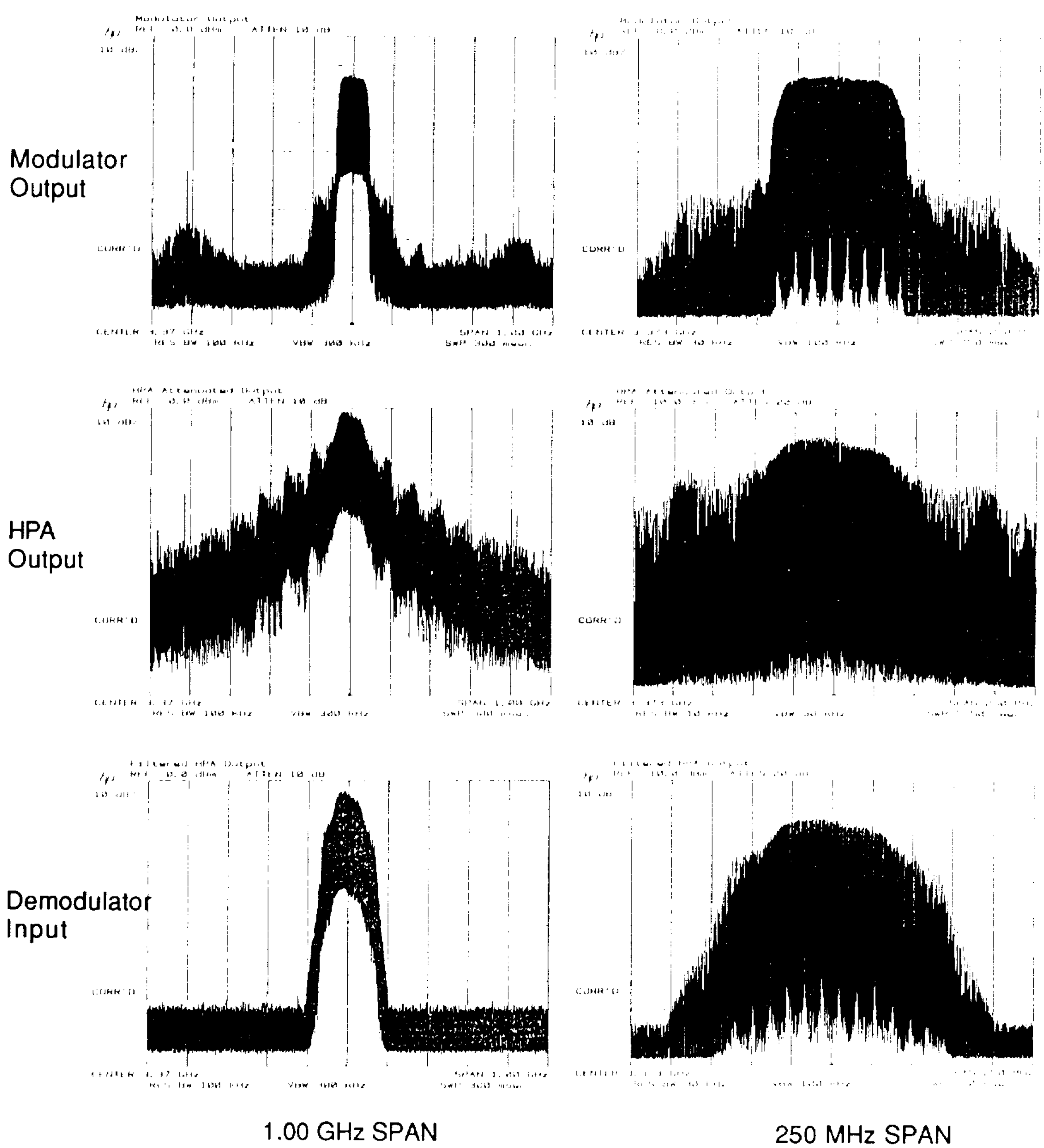
PERFORMANCE RESULTS

Bandwidth Efficiency

The bandwidth efficiency is a function of several parameters: Channel bandwidth (100 MHz), modulation alphabet size (16 = 4 bits/symbol), symbol burst rate (66.666 MSymbol/sec), coding rate (3/4), guard time (2 Symbols), unique word length (4 Symbols), preamble length, and the length of the data portion of the burst. All of these parameters except the last two have been predetermined by the system design. A preamble length of 64 symbols (192 information bit times) was chosen in the system design phase but the hardware is variable. This length results in a maximum length burst efficiency (burst length = 1ms) of 1.998 bit/s/Hz, and a minimum length burst efficiency (data length = preamble length) of 0.955 bit/s/Hz.

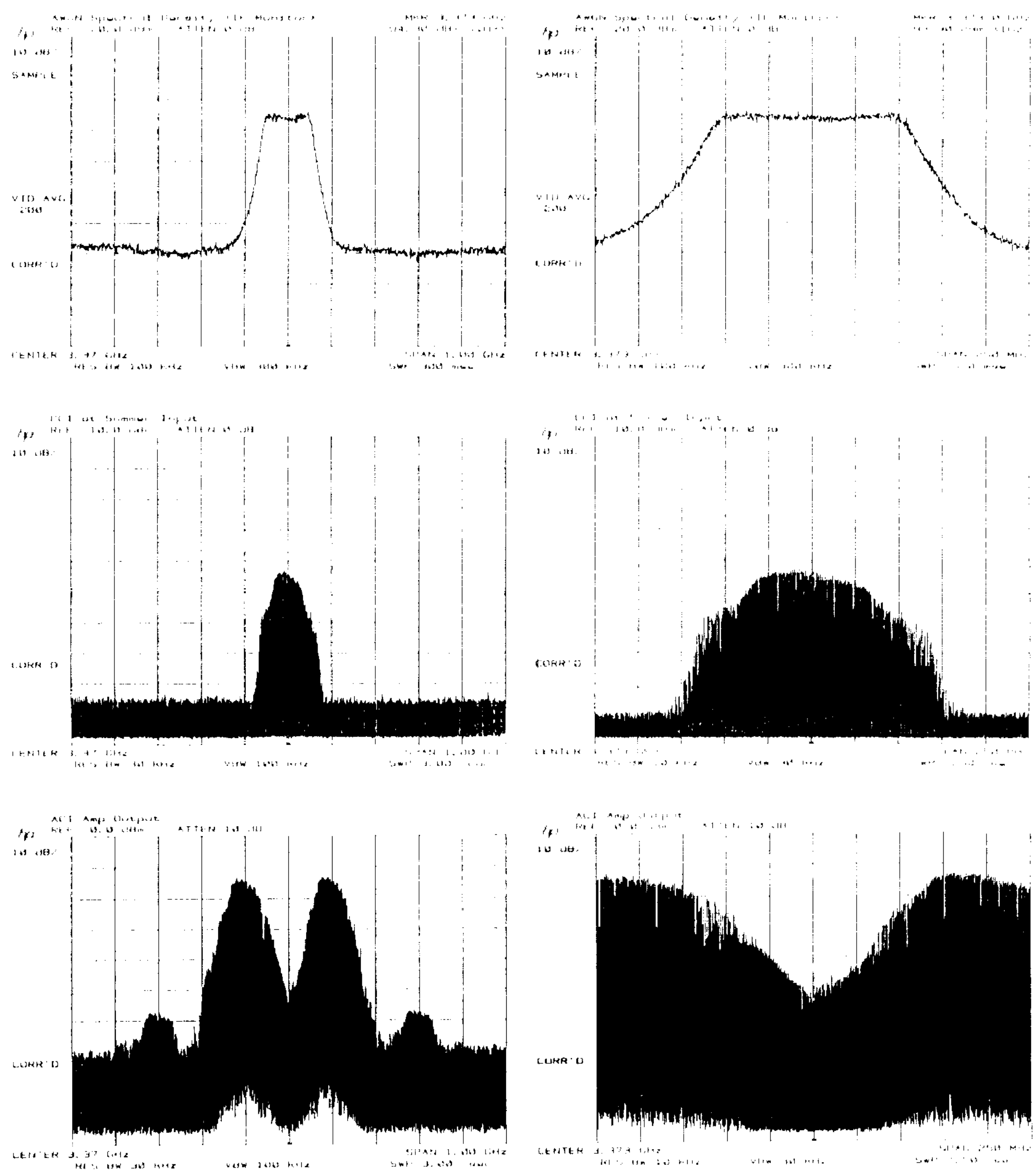
Signal Power Spectrum

Spectra for the modulated signal, the effects of the nonlinearity (the HPA) on spectral regrowth, and the effect of the HPA output filter on the reduction of ACI are shown below. The simple case of BPSK was used to obtain these plots. The ±414 MHz spurs at the modulator output are expected to have no impact on BER performance or E_S/N_O measurement, but will be eliminated before BER testing of the entire system begins. Note that the main lobe of the modulator output is spectrally flat and 67 MHz wide, while all spectral components outside of the 100 MHz channel bandwidth are suppressed by greater than 35 dB.



Interference Spectra

The flatness of the AWGN noise source is shown below. The noise density was measured and a calibration factor of +2.24 dB was computed for E_S/N_O measurements. The CCI appears spectrally identical to the desired channel and 20 dB lower in power. The ACI displays some third order intermodulation, but it is entirely out of the desired channel and should not affect BER performance. The spectra of the two adjacent channels are spread which will cause more interference than actual adjacent channels. The ACI noise floor has also been amplified significantly by a high gain amplifier, but the it is still low enough that it won't effect the measurement of BER performance.



AWGN

CCI

ACI

1.00 GHz SPAN

250 MHz SPAN

PERFORMANCE RESULTS (continued)

Envelope Deviation

The modulator performance is seen from the IF envelope at the modulator output and the baseband quadrature signals. Predistortion is turned off, so the wideband modulation displays four equally spaced levels for each quadrature signal, and three distinct IF envelope amplitudes. The effect of square root Nyquist filtering is also shown. The first half of each photograph is a short preamble followed by a 4 symbol unique word. The variation in the envelope during this time, which should be constant and at peak amplitude, reflects a misalignment in the RF section of the modulator. The second half of each picture is the beginning of a pseudo-random bit sequence (PRBS). The baseband I signal has multiple traces because we had problems with one of the PRBS generators at the time of the test. All errors will be corrected before final testing of the system.

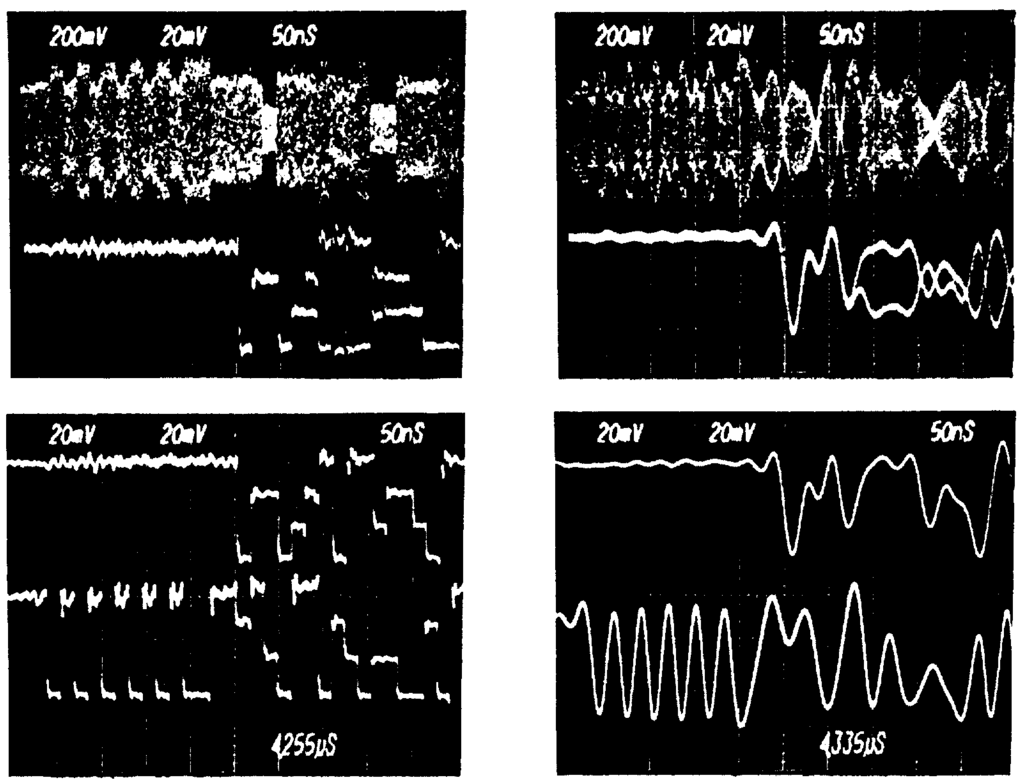
Wideband 4x4 QAM Modulation | SRN Filtered 4x4 QAM Modulation

IF Envelope

Baseband I Signal

Baseband I

Baseband Q



Power Consumption

The demodulator consumes about 86 Watts of power; primarily using ±15 Volts for operating RF amplifiers and high speed opamps, and ±5 Volts for logic operations. The decoder consumes three times as much power due to the complexity of the digital processing.

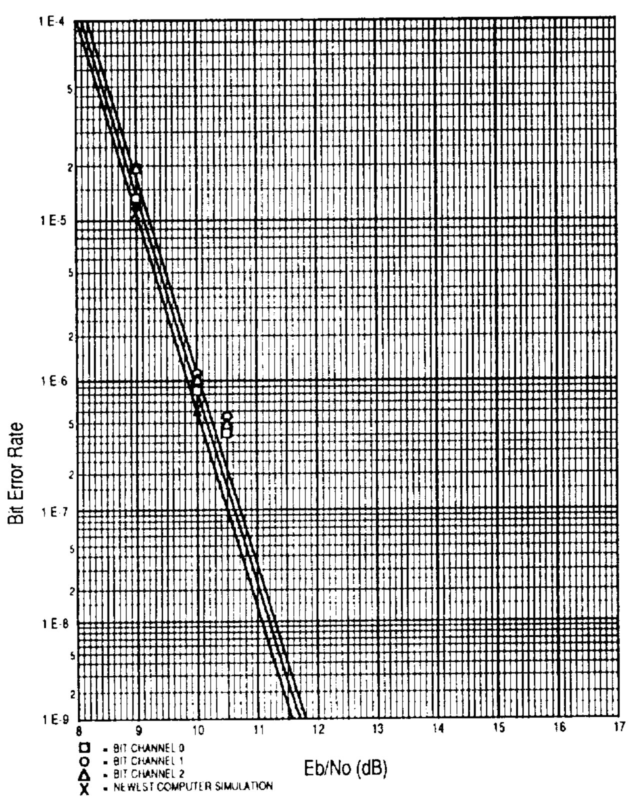
	DEMODULATOR		DECODER	
Voltage	Current	Power	Current	Power
+15 V	1.64 A	24.60 W		
-15 V	1.40 A	21.00 W		
+5 V	1.04 A	5.20 W	38.70 A	193.50 W
-2 V			14.17 A	28.34 W
-5 V	6.89 A	34.45 W	10.61 A	53.05 W
	Total Power =	85.25 W	Total Power =	274.89 W

Subsystem BER Performance

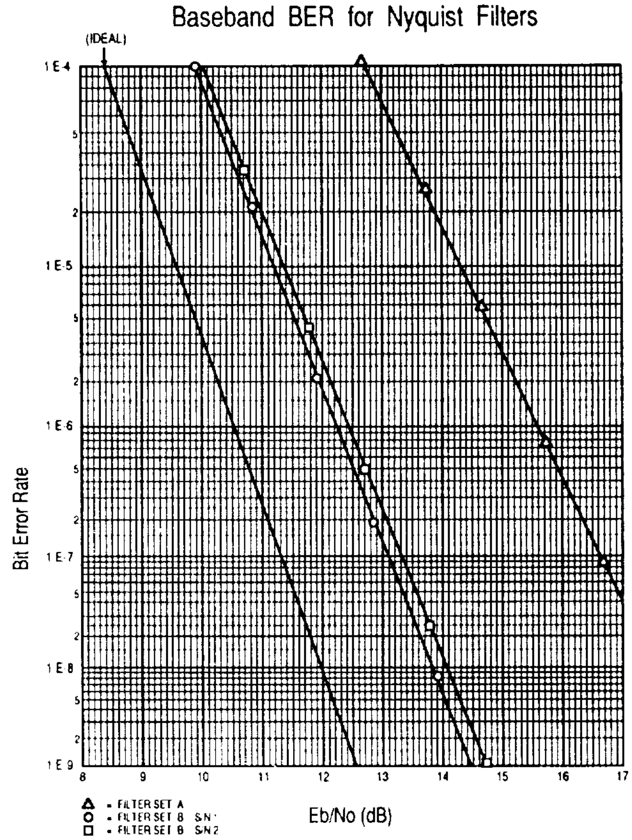
The encoder/decoder portion of the system has been completed and separately tested for BER performance. Worst case degradation from ideal performance was 0.2 dB at BER = 5×10^{-7}. The new ideal performance curve, as predicted by computer simulation, is different from the reference curve in the system performance section. A more accurate model was used and is slightly less optimistic. The results for each of the three information bits per symbol are shown. The decoder actually outputs nine different bit channels, but the remaining six exist because symbols are processed in groups of three after the three-step traceback circuit. The corresponding bit channels from the other two symbols performed identically to the first three. The measured performance degrades at high Eb/No because of limitations of the digital noise simulator used to test the encoder/decoder.

The Nyquist filters were also tested separately from the system. Filter set A was originally built, but performed poorly with 5.1 dB of degradation at BER = 5×10^{-7}. The degradation for the entire system is specified at 2 dB. The filter requirements were refined and two new filter sets were developed, one for each quadrature baseband signal. Both new filters performed much better than the A version, but still with significant degradation at 1.9 dB worst case. The actual filter parameters and their effect on BER performance is discussed on the following page.

Encoder/Decoder BER Performance



Baseband BER for Nyquist Filters



Nyquist Filter Parameters

The pulse response, eye pattern, and group delay of the Nyquist filters give us insight into the BER performance. The pulse response of both filter versions is similar in the square root Nyquist (SRN) case, but there is significant degradation for the full Nyquist response of version A. The eye patterns show the actual amount of intersymbol interference (ISI) at the ideal sampling point more clearly. The eye closure for both filter sets is similar in the SRN case again, but actually gets worse for the full Nyquist response of version A. This suggests that the second half of the version A filter is the main source of it's degradation. One of the prime requirements of Nyquist filters is minimal group delay variation in the passband. The version A filter set has about 18 ns of group delay ripple which is significant relative to a 15 ns symbol period. The version B set has 6 ns of ripple, although it's mostly at the bandedge.

Version A Filter Set

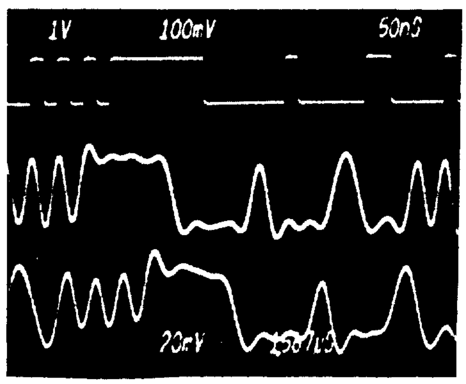
Version B Filter Set (S/N 2)

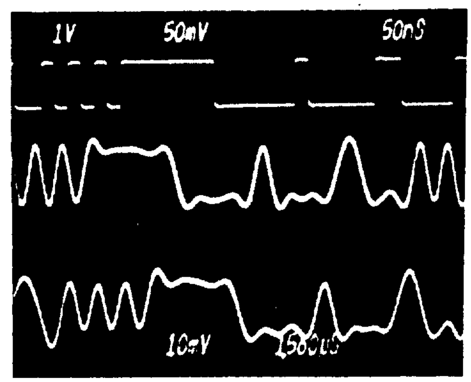
Pulse Response

NRZ Source

SRN

Full Nyquist



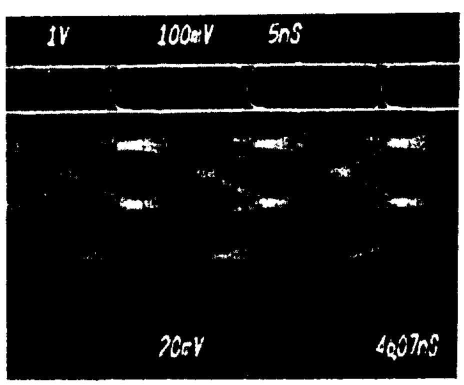


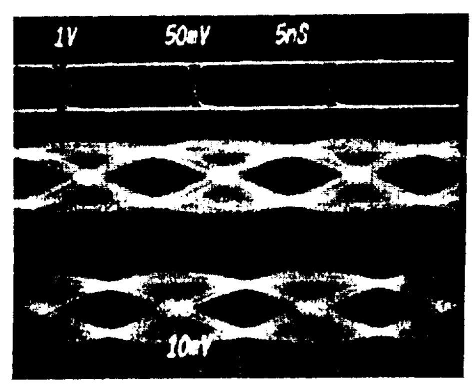
Eye Patterns

NRZ Source

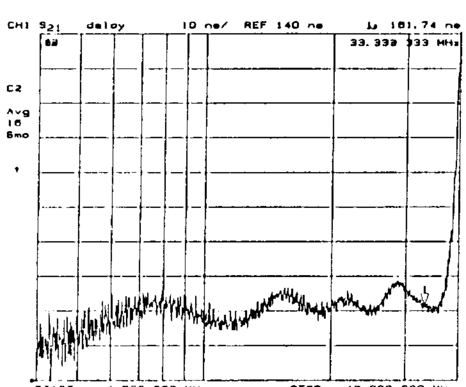
SRN

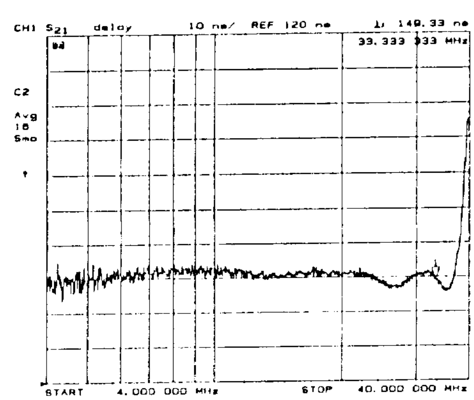
Full Nyquist





Full Nyquist
Group Delay



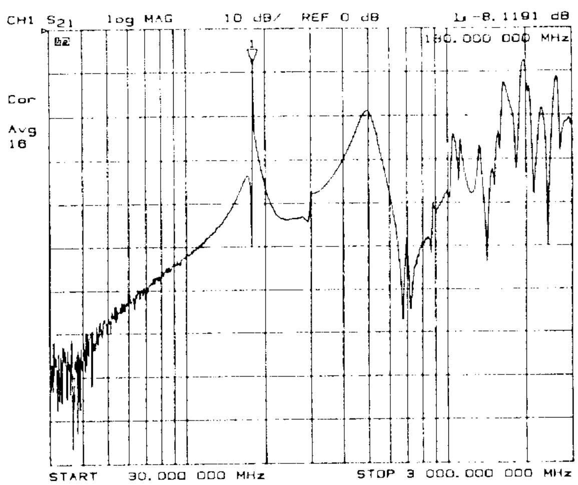


PERFORMANCE RESULTS (continued)

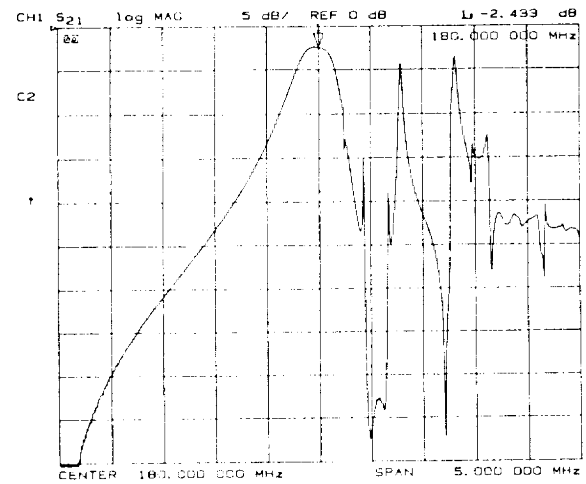
Ringing Filters

The simulations for 4x4 QAM showed the BER to be highly sensitive to the RMS phase error of the recovered carrier which makes the ringing filters in the carrier recovery a critical component. The narrowband spurious response is of greatest concern because some of the spurious products from the remodulation process will significantly add to the phase error of the recovered carrier. The actual BER performance degradation that can be expected is unknown at this time.

Typical 180 MHz Crystal Filter Passband (S/N 3A)



Wideband

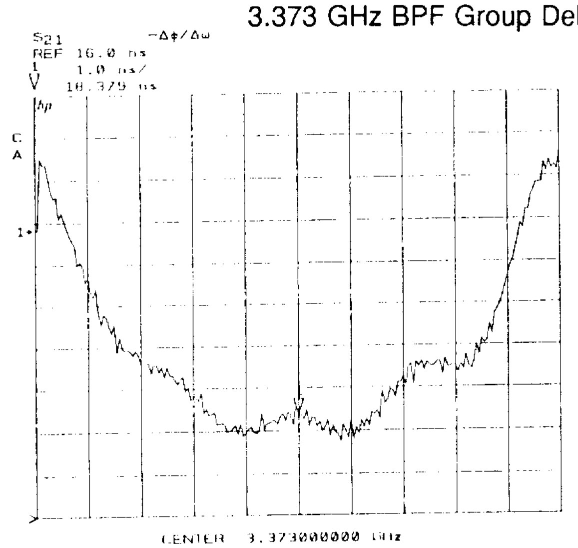


Narrowband

Bandpass Channel Filters

Another source of BER degradation is group delay variations in the bandpass filters used on the QAM signal in the demodulator. The filter centered at 3.373 GHz is at the input to minimize ACI effects, and the filter at 180 MHz is directly after the downconversion. The filter at 180 MHz has less fine grain ripple in the center of the band but degrades more rapidly at the edges. Both filters introduce less group delay distortion than the Nyquist filters so the impact on BER performance will be relatively small.

3.373 GHz BPF Group Delay



180 MHz BPF Group Delay