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DIGITAL MODULATION SCHEMES FOR HIGH SPEED TRANSMISSION THROUGH LOW BANDWIDTH LOWPASS ANALOG LINKS

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ABSTRACT

Existing NTSC standard will be phased out and replaced with HDTV standard within the next 10 years. Accordingly, the existing video network system operated by NASA will become obsolete and requires either replacement or modification to accommodate digital transmission. Network replacement is extremely expensive, hence, several digital modulation schemes are investigated in this report to accomplish digital transmission over existing analog links saving NASA from the cost of network replacement. There are two competing transmission systems available for HDTV transmission over limited bandwidth channels. The cost and performance of the two competing schemes are remarkably similar. However, the input data rate in such a case is limited to 40 Mbit/s. Transmission of higher data rates is possible using simple signal processing techniques. On the other hand, a third transmission system, multilevel pulse amplitude modulation (M-PAM) is proposed. M-PAM is the first stage of the well known M-VSB. This M-PAM scheme is much simpler and uses the channel more efficiently. The three schemes are compared and preliminary conclusions were made. Despite of several similarities, each modulation scheme has it unique merits. To determine the suitability of each scheme, more investigations and laboratory tests for all schemes are needed.

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1. INTRODUCTION

1.1. Objective

To study present digital transmission technologies and their suitability for the new High Definition Television (HDTV) digital signals. Determine if the 12 MHz baseband of present video network can be economically utilized to transmit high data rates and save KSC from the expense of development and deployment of new network.

1.2. Motivations

The impact of HDTV will greatly enhance NASA's scientific, engineering and operational effectiveness. This includes improved resolution for TV images enhancing research, and technology activities, computational fluid dynamics, flow visualization, and material analysis. Moreover, NASA's requirement to disseminate information and video generated video to the public necessitates the prompt response to TV technology advances.

Video networks operated by NASA in general and KSC in particular will become obsolete within the next ten years. Several digital modulation techniques for terrestrial and cable broadcast have been proposed by HDTV Grand Alliance and other organizations. Unfortunately, none of these digital techniques is directly usable with the existing video network system operated by NASA. However, with some minor modifications, off-the-shelf components developed for terrestrial and cable digital broadcast could be utilized for digital transmission over the existing KSC analog links.

1.3. Scope

Recent advances in video compression techniques have spurred interest in the idea of digital television. Hence, the television industry is taking major steps toward a total digital television environment for both the existing National Television System Committee (NTSC) standard [1] and the new High Definition Television (HDTV) standard [2].

The Federal Communications Commission (FCC) has approved and tested the new, total digital, HDTV standard [3-5]. The FCC stated that the existing NTSC standard will be phased out and replaced with HDTV standard within the next 10 years. Accordingly, the existing video network system operated by NASA will become obsolete and requires either replacement or modification to accommodate digital transmission.

The Moving Picture Experts Group (MPEG) developed the MPEG-2 Video Standard which specifies the coded bit streams for high-quality digital video. MPEG-2 defines three profiles and three levels of picture complexity. The main profile has a low-level resolution of up to 288 lines/frame (VHS tape resolution), 30 frames/sec, 2.53 million pixels/sec and 4 Mbit/s. The main level has up to 576 lines/frame (NTSC studio quality resolution), 30 frames/sec, 10.4 million pixels/sec and 15 Mbit/s. The high level has up to 1125 lines/frame (high definition television resolution), 60 frames/sec, 62.7 million pixels/sec and 60 Mbit/s.

United States Advanced Television Systems Committee (ATSC; a subcommittee of the FCC,) has approved Digital Television Standard for High Definition Television Transmission on April 1995 [3-5]. Uncompressed Digital Television Standard HDTV bit rate is 1.2 Gbit/s. The Digital Television Standard describes a system designed to transmit high quality video, audio, and ancillary data over a single 6 MHz channel. This means that encoding a video source whose resolution can be five times that of conventional television (NTSC) resolution requires a bit rate reduction factor of 50 or higher. To achieve this bit reduction, the system is designed to be efficient in utilizing available channel capacity by exploiting video and audio compression scheme based on MPEG-2 syntax. The allowable values for the field bit-rate-value are application dependent. In the primary application of terrestrial broadcast, this field shall correspond to a bit rate which is less than or equal to 19.4 Mbit/s. In the case of cable systems the corresponding bit rate shall be less than or equal to 38.8 Mbit/s.

ATSC also approved 8 VSB (vestigial side band modulation with 8 discrete amplitude levels) for terrestrial broadcast in standard NTSC 6 MHz bandwidth. Furthermore, 16 VSB (vestigial side band modulation with 16 discrete amplitude levels) is approved for the high data rate cable mode. Other digital modulation techniques have been extensively investigated and tested for terrestrial and cable HDTV broadcast transmission [6-11]. Several vendors developed chips, chip sets, and evaluation kits to achieve digital transmission for terrestrial and cable broadcast applications.

2. PRESENT SITUATION

Kennedy Space Center (KSC) is currently utilizing thousands of fiber-optic links for video transmission. The fiber optic-links consist of the following three basic units:1) transmitter (5000TX-KSC); 2) fiber; 3) receiver (5000 RX-KSC). The transmitters and receivers are manufactured by Video Products Group (formerly known as PCO).

2.1 Communications Network Layout

These links are combined to produce a communication system that is primarily used to transmit, high quality, analog television from the launch pad areas to the appropriate control rooms and other areas. There are around eighty cameras for each of the center's two launch pads. The video signals are transmitted via TV-39 cable from the camera to a room under the launch pad, the Pad Terminal Connection Room (PTCR). From here the electronic signals are converted to optical signals and sent to the Launch Control Center (LCC). It is here that the quality of the signals can be monitored and the video signals are recorded. From the LCC the signals are sent to the Communication Distribution Switching Center (CDSC). Then the CDSC the signals are dispersed to the rest of the KSC. The distance that each link expands is relatively small.

2.2 Transmitter and Receiver Specifics

The signal that is to be transmitted has a nominal bandwidth of approximately 8MHz. To prepare this signal for transmission, it is passed through a pulse frequency modulator (PFM). The PFM's usable baseband bandwidth (3dB bandwidth) had been specified to be 12 MHz or greater [12]. The IF bandwidth is 32 MHz or greater. The signal is then transmitted using either a Light Emitting Diode (LED) or a Laser Diode (LD) through fiber. Either multimode or single mode fiber is used. The signal is then received and demodulated. The overall system has a baseband carrier-to-noise ratio (CNR) of 50dB or greater. Figure 1 shows a block diagram of the transmitter and receiver in some detail.

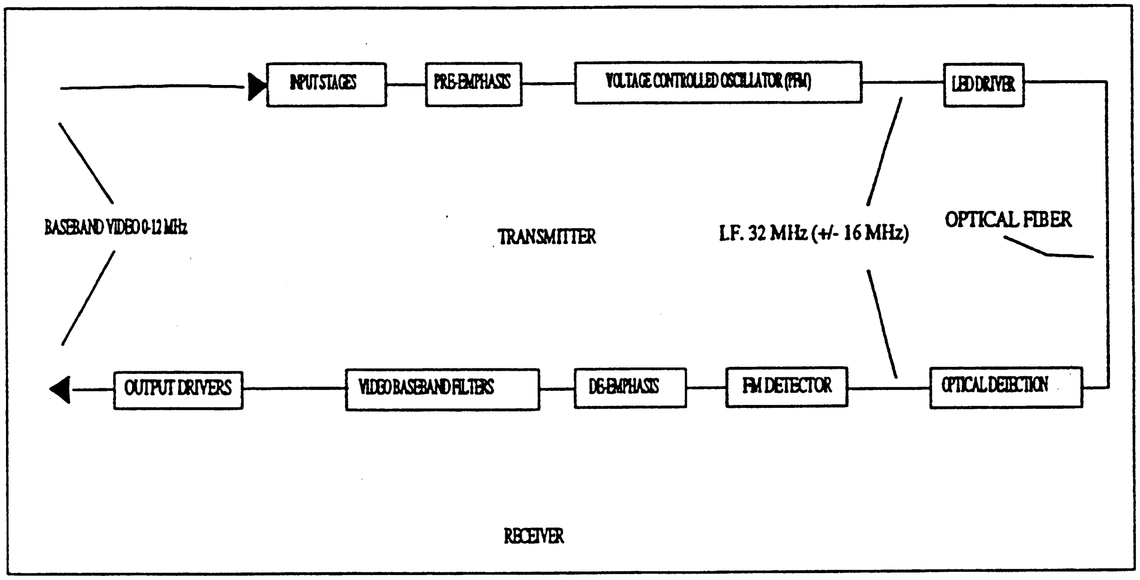


Figure 1: Block Diagram of Existing Systems

2.3 Investment

KSC has a considerable investment in the thousands of existing fiber-optic links. Each transmitter/receiver pair is purchased for approximately 5000 dollars. The lengths of fiber for each link range from one to seven km. The cost of the fiber (labor included) is estimated at twenty cents per meter. The initial cost of a link is estimated to range from $5200 to $6400.

2.4 Reliability

The existing system has been proven to be reliable. This particular equipment has been operating for 10 years with a minimum amount of failures. The majority of failures have been LED or ILD failures. Many of the optical fiber lines have been operating for 15 years without incident. The existing old copper links are still being updated to these fiber-optic links. Eventually the copper wire links will be phased out.

3. PROPOSED SOLUTIONS

Digital transmission over fiber is accomplished usually using base-band, on-off keying modulation, i.e. by switching the light-source on and off. However, long-haul digital transmission, where the spectrum is scarce, requires continuous wave (CW) modulation to generate a band-pass signal suited to the transmission medium- be it radio, cable, or hybrid fiber-optic/coaxial networks. In CW modulation [13], a digital signal can modulate the amplitude, or phase of a sinusoidal carrier wave. There are two competing band-pass modulation schemes for HDTV digital transmission systems: quadrature amplitude modulation (QAM), and vestigial side band modulation (VSB) [6]. Both QAM and VSB are bandwidth efficient, and have the same bandwidth efficiency. In this section, several conceptual and technical design considerations for the two competing transport schemes are presented. However, the KSC application is much simpler than what both of these two schemes are designed to do. A transmission scheme, uses a lowpass transmission channel, known as M-ary pulse amplitude modulation (M-PAM) is presented in Section 3.3 as an alternative for both two previous systems

3.1. Multilevel Quadrature Amplitude Modulation (M-QAM)

Multilevel Quadrature Amplitude Modulation (M-QAM) techniques have been generally developed for implementing spectrally efficient modems used in a band-limited communication systems, such as telephone channel and microwave radio links. QAM is, a public domain, and mature modem technology requiring no license fees or royalty payments and it has a broad base of support.

The basic principal of quadrature modulation is to increase the spectral efficiency in transmission systems. In the basic QAM system shown in Figure 2, the symbol mapper divides the incoming serial bit stream into two parallel bit steams. Each od them is $M/2$ bits wide. The Digital-to-Analog converter (DAC) then converts the two digital signals to analog signals. The signals are then filtered and multiplied by two perpendicular sinusoidal signals with frequency equal to the intermediate frequency (IF). The sum of the two signals is a M-QAM signal with spectral efficiency r_b/B_T equal to:

$$r_b/B_T \approx \log_2 M \qquad \text{bit/s/Hz} \tag{1}$$

where r_b is the data bit rate, B_T is the transmission bandwidth, and M is the number of M-ary levels. Hence, for 256 QAM, $r_b/B_T = 8$. At the demodulator side the reverse operation is performed to retrieve the original transmitted data stream. Figure 3 illustrates the IF I-Q Constellation for QAM signal with M=16. Many attractive features can be found when this scheme is applied to HDTV signal transport.

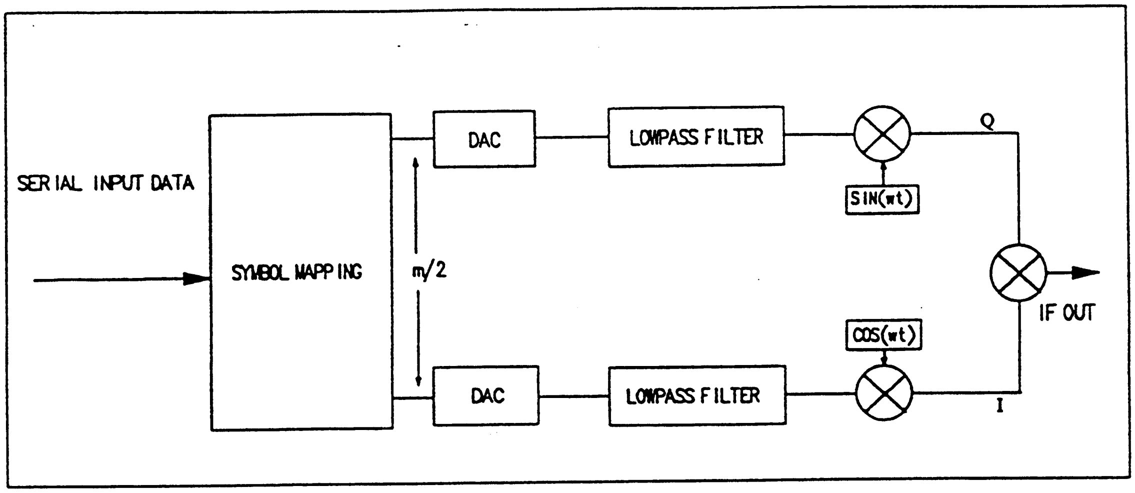


Figure 2: Block Diagram of Basic QAM

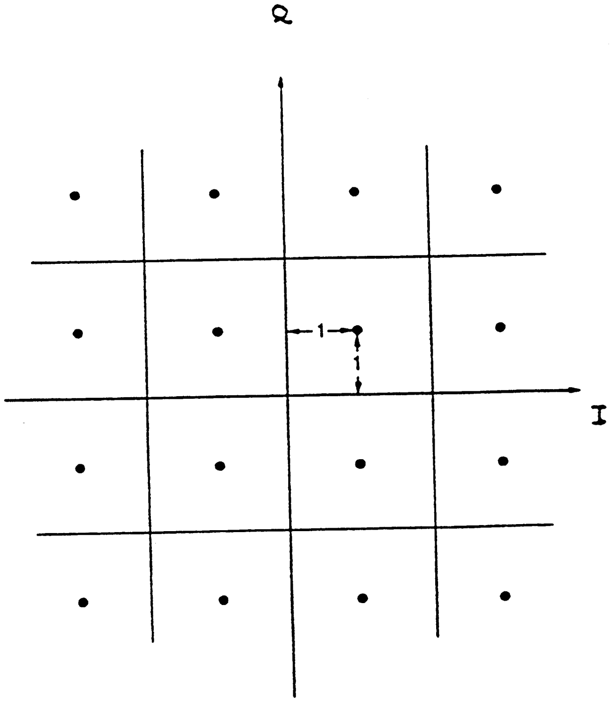


Figure 3: 16-QAM IF I-Q Constellation

The first feature is that this transport system can be economically implemented, has been tested, and proved its reliability. Recently, proponents of this modulation scheme produced reasonably priced VLSI modem chips [14-18].

The second feature is that, by using multilevel modulation, the efficient utilization of bandwidth becomes possible and, consequently, existing KSC analog links can carry relatively high bit rates. For 256 QAM, bandwidth efficiency is 8 bits/Hz, i.e. the maximum bit rate to be transmitted via 11 MHz of channel bandwidth theoretically is 88 Mbit/s.

The third feature is that multilevel QAM makes it possible to accept parallel bits more easily. The number of parallel bits to be accepted by the modulator as a function of the M-ary levels is given by:

$$m = \log_2 M \quad \text{bit/s/Hz} \tag{2}$$

where m is the number of parallel bits and M is the number of M-ary levels. Hence, for 256 QAM modulation the number of parallel bits to be handled is 8 bits.

3.1.1. Vendor Implementation of M-QAM Technology

Major proponents of QAM technology are Broadcom Corp., AT&T, Scientific-Atlanta, Samsung, Hewlett-Packard, and General Instruments [19]. To the best of authors' knowledge, the only 256-QAM modulator-demodulator chip set available in the market is developed by Broadcom (QAMLink™). The complexity of typical QAM modulators is greatly reduced by combining advanced digital signal-processing techniques (DSP) and high-speed VLSI fabrication. Broadcom's design elegantly removes the typical DACs from inside the chip to the outside significantly reducing its complexity and consequently its cost. Hence, using Broadcom's QAM modulator requires only a single, external DAC chip instead of the typical two DAC's used in classical QAM modulators. The QAMLink™ Modulator chip BCM3023 provides baseband filtering and quadrature modulation of a QAM signal at which the digital IF center frequency is equal to the baud rate [19]. Theoretically, 8 bit DAC is sufficient for error free operation ($2^8 = 256$ levels), however, the QAMLink™ Modulator chip BCM3023 has 12 bit outputs. For normal bit-error rate requirement, 10 bit DAC (such as Analog Devices AD9721) is adequate. For lower bit-error rates, 12 bit DAC (such as Analog Devices AD9713) is required. Due to a joint nondisclosure agreement between KSC and Broadcom Corp., the block diagram of actual QAMLink™ Modulator-Demodulator chip set (BCM3020 QAM Demodulator, BCM3021 QAM Adaptive Equalizer, BCM3022 QAM Synchronization IC, and BCM3023 QAM Modulator) can not be provided here for publication. However, all QAMLink™ Proprietary Information is available to interested individuals working with the KSC Communications Group.

Broadcom also manufactures more integrated chips such as the QAMLink receiver (BCM3100) and the QAMLink Dual-Channel Receiver with Forward Error Correction (BCM3115).

The BCM3100 integrates the BCM3020 QAM Demodulator, BCM3021 QAM Adaptive Equalizer, and BCM3022 QAM functions into one chip. It is a complete single chip digital IF receiver supporting programmable QPSK, 16, 64 and 256 QAM transmission. Moreover, the BCM3115 is a complete single chip digital IF receiver which accepts a high bandwidth (40 Mbit/s maximum) in-band data stream and low bandwidth (2 Mbit/s maximum) out-of-band data stream and delivers two demodulated, error corrected output data streams.

3.2. Multilevel Digital Vestigial Side band Modulation (M-VSB)

This Digital Vestigial Side Band Modulation (M-VSB) method (shown in Figure 4) applies Nyquist pulse shaping to a polar input signal producing a band limited modulating signal with a bandwidth B given by [13]

$$B = (r/2) + \beta_N \tag{3}$$

where r is the symbol rate, and β_N is the rolloff factor. For theoretical brick-wall filters $\beta_N = 0$ (0 % rolloff), while $\beta_N = r/2$ for the spectrum with smooth rolloff filters (100% rolloff). The Symbol rate r can be expressed in turns of the data bit rate as

$$r = r_b / \log_2 M \tag{4}$$

where r_b is the data bit rate, and M is number of M-ary levels. The VSB filter then removes all but a **vestige** of width β_V from one side band so the transmitted signal looks like Figure 5, a band limited spectrum with bandwidth B_T where

$$B_T = (r/2) + \beta_N + \beta_V \tag{5}$$

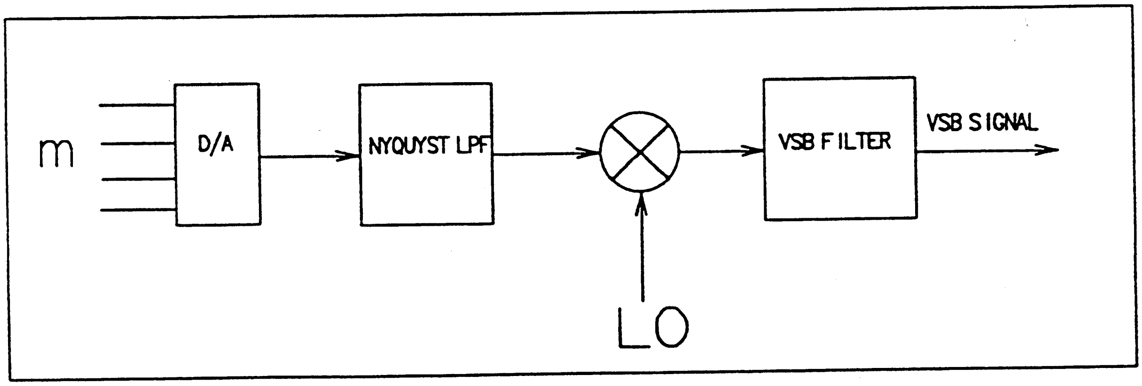


Figure 4: Block Diagram of Basic VSB Modulation

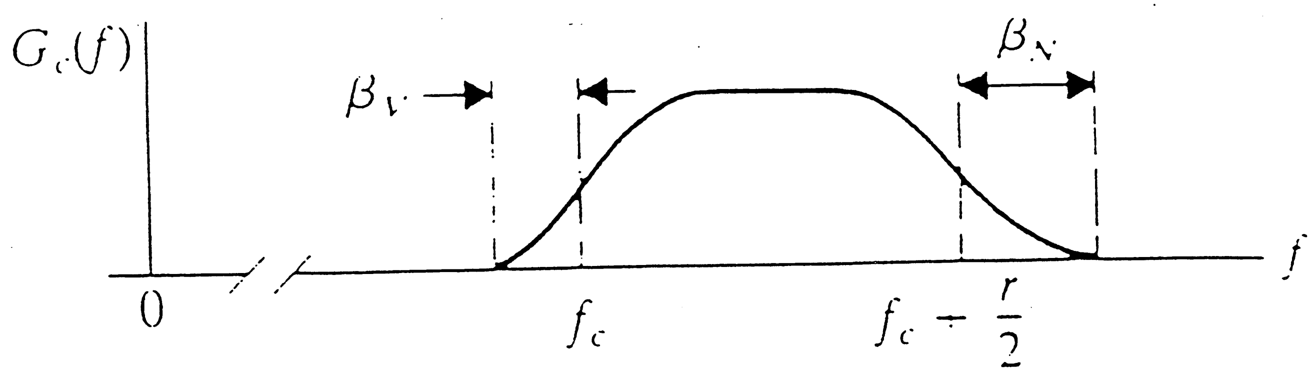


Figure 5: Digital VSB Power Spectrum

Hence, the upper limit for the spectral efficiency r_b/B_T is equal to:

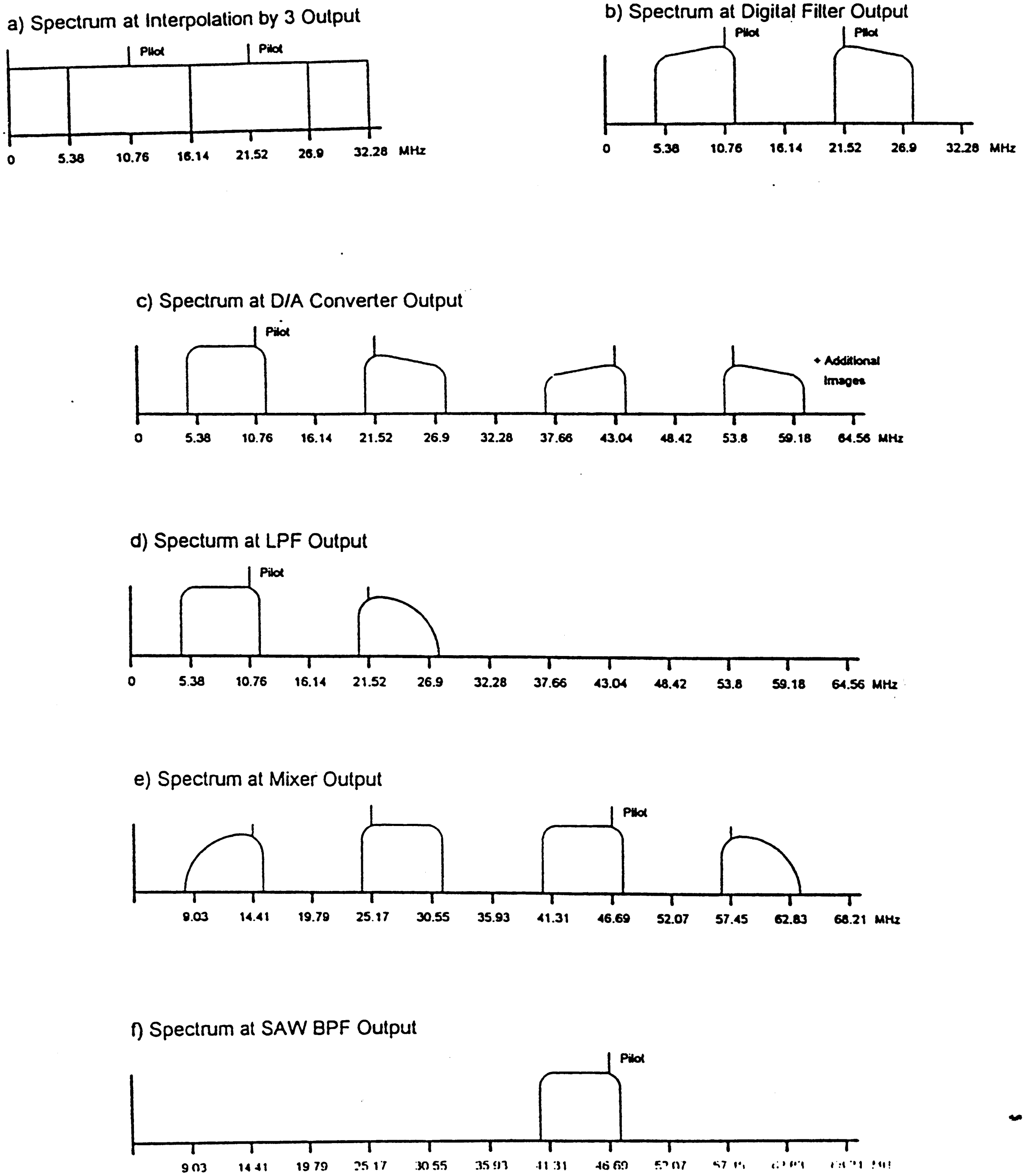
$$r_b/B_T = 2 \log_2 M \quad \text{bit/s/Hz} \tag{6}$$

This upper bound holds when $\beta_N \ll r$ and $\beta_V \ll r$.

3.2.1. *Vendor Implementation of M-VSB Technology*

Major proponents of VSB technology are Zenith, Philips, Compression Labs Inc.(CLI), and HDTV Grand Alliance. The Grand Alliance, in cooperation with the FCC's Advisory Committee on Advanced Television (ACATS), concluded extensive testing of Zenith's "VSB" and General Instrument "QAM" digital transmission systems. Based on simplicity, ruggedness, and Grand Alliance recommendation, ACATS approved Zenith's VSB system as the standard for terrestrial broadcast of high-definition television (HDTV).

M-VSB method applies Nyquist pulse shaping [13] to a symbol train with a bandwidth r. For a 6 MHz channel, the theoretical maximum (Nyquist) rate is 12 Msymbol/s but is unachievable because it requires "brick-wall" filters. Using surface acoustic wave (SAW) filter technology, 10.76 Msymbol/s is economically feasible [20]. At this symbol rate, if binary symbols are transmitted the maximum data rate to be transmitted will be 10.76 Mbit/s. If 4-level symbols are sent, the maximum data rate to be transmitted is 21.5 Mbit/s. For 8-level and 16-level symbols, the maximum data rate to be transmitted is 32.3 Mbit/s and 43 Mbit/s respectively. Zenith VSB modem is actually designed to handle 2-, 4-, 8-, and 16-level VSB modes. The VSB receiver will be able to automatically lock with modes under head end control. The IF frequency response of Zenith's 16-VSB can be seen in Figure 6.


a) Spectrum at Interpolation by 3 Output

b) Spectrum at Digital Filter Output

c) Spectrum at D/A Converter Output

d) Specturm at LPF Output

e) Spectrum at Mixer Output

f) Spectrum at SAW BPF Output

Figure 6: Zenith's 16-VSB Modulator Frequency Spectrum

3.3. M-ary Pulse Amplitude Modulation (M-PAM)

Similar to the first stage of M-VSB modulation, this digital Pulse Amplitude Modulation (M-PAM) method applies Nyquist pulse shaping to a polar input signal producing a band limited modulating signal with a bandwidth B given by equation (3) [13]

$$B = (r/2) + \beta_N$$

where r is the symbol rate, and β_N is the rolloff factor. For theoretical brick-wall filters $\beta_N = 0$ (0 % rolloff), while $\beta_N = r/2$ for the spectrum with smooth rolloff filters (100% rolloff). The Symbol rate r can be expressed in turns of the data bit rate given in equation 4 as

$$r = r_b/\log_2 M$$

where r_b is the data bit rate, and M is number of M-ary levels. Unlike VSB, this filtered pulse train is directly applied to the input of the low pass transmission channel achieving the same spectral efficiency and performance as the two previous schemes.

4. COMPARISON OF PROPOSED TRANSMISSION SYSTEMS

4.1. Feasibility Study

The three proposed digital transmission systems theoretically have many differences and very few similarities. However, practically they have many similarities and very few differences. Laboratory tests and simulations [6] showed that the first two schemes (M-QAM and MVSB) have very close behavior (almost similar) for the following:

- spectrum efficiency,
- C/N vs. bit error rate,
- carrier recovery (without inserting pilots), and
- susceptibility to jitter.

No practical information is available for the M-PAM modulation scheme in the literature, however, theory indicates that its' performance should be identical to M-VSB if not better.

4.1.1. *Spectrum Efficiency*

Theoretically, spectrum efficiency for 256-QAM, 16-VSB, and 16-PAM, as given in equations (1) and (6), are the same and it is equal to 8 bit/Hz. However, practical spectrum efficiency is less than ideal. In QAM systems, spectrum spill over limits the spectrum efficiency to ~7.2 bit/Hz. Similarly for VSB scheme, roll-off of both Nyquist filter and VSB filter limit the spectrum efficiency to the same as the QAM. Theory indicates that the spectrum efficiency for M-PAM is in the same range as the two other schemes if not little bit better.

4.1.2. *Minimum Required Carrier-to-Noise Ratio*

Bit error rate (BER) for any M-ary system is a function of the carrier-to-noise ratio (CNR) and the number of M-ary levels (M). According to theoretical and laboratory research, the behavior of all systems is identical [6]. Therefore, the performance of the QAM system is explored then, by induction, the performance of the M-VSB and M-PAM systems are estimated.

The symbol error rate of a QAM signal is [9] defined as

$$P_s(e) = 2(1 - \tfrac{1}{\sqrt{M}})Q\Big(\sqrt{\tfrac{3}{M-1}(CNR)}\Big) \tag{7}$$

where $Q(x)$ is defined as

$$Q(x) = \tfrac{1}{\sqrt{2\pi}}\int_x^{\infty} e^{-t^2/2}dt \tag{8}$$

In addition, if the multilevel signal is assumed to be Gray coded, as is conventionally adopted, the bit error rate $P_B(e)$ is given by

$$P_B(e) \approx \tfrac{P_s(e)}{log_2\sqrt{M}} \tag{9}$$

From equation 7 and equation 9, the bit error rate $P_B(e)$ can be written as

$$P_B(e) = \tfrac{2}{log_2\sqrt{M}}(1 - \tfrac{1}{\sqrt{M}})Q\Big(\sqrt{\tfrac{3}{M-1}(CNR)}\Big) \tag{10}$$

For bit error rate $P_B(e)=10^{-9}$, $M = 256$ levels and using equation (10), minimum *CNR* is then calculated to be equal to 34.6 dB.

Present analog TV has a CNR equal to, or better than 50 dB [12], Therefore, either system (256-QAM or 16 VSB) will achieve a bit error rate $P_B(e) \leq 10^{-9}$. Figure 7 shows the relationship between the probability of error vs. CNR for both QAM and VSB systems with and without forward error correction (FEC).

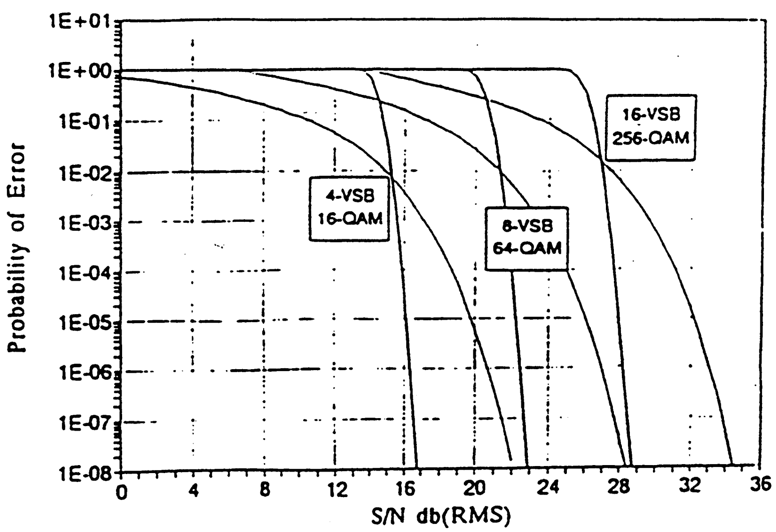


Figure 7: The probability of error vs. CNR for both QAM and VSB systems with and without forward error correction (FEC)

4.1.3. *Local Oscillator Frequency Selection*

With data bit rate of 40 Mbit/s, the upper corner frequency of the signal is less than 12 MHz for both Broadcom BCM3023 QAM Modulator (256 levels) or Zenith VSB modulator kit (before the mixer) [20]. **Therefore, no further frequency processing is needed.** However, the output of both evaluation kits, has an IF center frequency much higher than the upper 3-dB corner frequency of the channel. In such case, a frequency mixer is needed to shift the signal's spectrum down to PCO lowpass channel range (i.e. 10Hz-12MHz range.) Following is a procedure for the selection of a local oscillator frequency to shift the spectrum of Broadcom's Evaluation System down to lay within the lowpass bandwidth of the PCO transmission channel. Similar procedure is valid to shift the spectrum of Zenith's VSB Evaluation Kit.

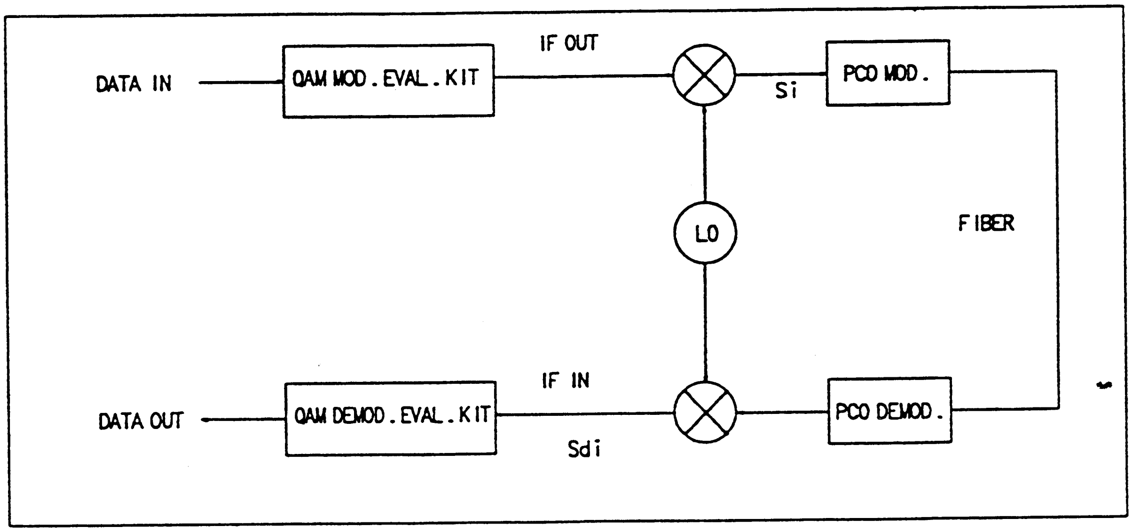


Figure 8: Block diagram of experiment setup using Broadcom BCM93100 QAMLink Development System

If the evaluation kit has an intermediate frequency (IF) of ω_{if} rad/s. The PCO input signal S_i is equal to

$$S_i = a(t) cos(\omega_{if} t + \gamma(t)) cos\,(\omega_{lo} t)$$

$$= \frac{a(t)}{2}\{cos[(\omega_{if} - \omega_{lo})t + \gamma(t)] + cos[(\omega_{if} + \omega_{lo})t + \gamma(t)]\} \quad (11)$$

If $(\omega_{if} + \omega_{lo})$ is selected much larger than the upper 3-dB frequency of the transmission channel, then the signal $cos[(\omega_{if} + \omega_{lo})t + \gamma(t)]$ is filtered out. At the receiver side, the QAM demodulator input signal S_{di} is given by:

$$S_{di} = Ka(t)[cos(\omega_{if} - \omega_{lo})t + \gamma(t)) cos\, \omega_{lo} t]$$

$$= \frac{Ka(t)}{2}[cos(\omega_{if} t + \gamma(t)) + cos((\omega_{if} - 2\omega_{lo})t + \gamma(t))] \quad (12)$$

where K is a constant (function of received signal level). To avoid aliasing the following condition should be observed:

$$\omega_{if} - (2\omega_{lo} - \omega_{if}) \geq 2\pi(BW)$$

$$\omega_{if} - \omega_{lo} \geq 2\pi(BW)/2 \quad (13)$$

Where BW is the bandwidth of the IF signal. For Broadcom BCM93100 QAMLink Development System, the IF frequency is 43.75 MHz, $BW = 11$MHz (for $r_b = 80$ Mbit/s with 256-QAM). Hence, if we select $f_{lo} = f_{if} - (BW/2)$, *i.e.* $f_{lo} = 38.25$ MHz, we find that the difference between these two frequencies ($f_{lo} - f_{if}$) is equal to 5.5 MHz, which is the center of the transmission band. While the distance between two adjacent images after the receiver mixer is $2f_{lo} = 76.5$ MHz, that is to say, no aliasing will occur at the receiver's side.

Differences between the two competing techniques and the associated advantages and disadvantages are listed in the following sections

4.2. Differences

4.2.1. *Carrier Presence*

One of the most significant differences is the fact the VSB do not need carrier while QAM needs two perpendicular carriers (M-VSB with no carrier converges to M-PAM.) This makes VSB more suitable for transmitting high data rates on lowpass channels. **However, for data rates limited to 40 Mbit/s, the IF signal, before the up-converter, fits directly within the lowpass transmission band.** Thus this point becomes irrelevant for low data rate transmission systems.

4.2.2 *Compatibility with Future HDTV Set*

The FCC's Advisory Committee on Advanced Television Service (ACATS) endorsed VSB technology for cable and terrestrial digital transmission. Therefore, it is more likely that consumer's HDTV sets will be equipped with VSB receiver and demodulator. On the other hand, in case of QAM transmission, both the receiver and the demodulator has to be provided to users as a set-top box.

4.2.3. *Required CNR For Acquisition*

VSB as proposed by Zenith, transmits a pilot tone at the carrier frequency, which is in the roll-off of the transmitted VSB signal. The pilot is easily made by adding a DC bias at baseband. The pilot increases the transmit signal power by 0.3 dB, resulting in an effective signal-to-noise (SNR) loss of 0.3 dB. However, this pilot signal enables the acquisition of 16-VSB signal to be possible even at CNR = 0 dB compared to minimum CNR = 18 dB for 256-QAM.

4.2.4. *Availability Of The Technology*

VLSI modem chips for both modulation techniques are readily available of-the-shelf manufactured by Broadcom and Zenith. However, if carrierless VSB is used (i.e. Digital M-PAM), all components needed are readily available from vendors other than the aforementioned two vendors. This may reduce the cost of the system.

5. RECOMMENDATIONS

The performance and inherent cost of QAM and VSB are remarkably similar for high speed digital transmission over analog links. Therefore, both modulation techniques should be investigated and their suitability for KSC networks should be carefully examined. This section proposed a plan consisting of three phases. These phases may be implemented in orderly fashion or more than one phase simultaneously.

Phase one concentrates on the transmission of relatively low data rates (40 Mbit/s or less). This rate is sufficient to transmit two 19.3 Mbit/s HDTV compressed signals or one distribution quality HDTV signal. Moreover, the first phase will give KSC engineers and scientists more understanding for vendor's VLSI chip design, pinout, and system design. During this first phase, more understanding for the suitability of each scheme will also be acquired. Transmission of higher data rates will be experimented during phase two. Data rates up to 80 Mbit/s 256-QAM with shifted carrier will be experimented on existing fiber-optic transmission systems. Baseband carrierless VSB (M-PAM) also should be simulated and practically tried with data rates higher than 40 Mbit/s. Selection of the most suitable scheme, design, experimentation and documentation of the selected modulator/ demodulator pair will be accomplished during this last proposed phase (phase three) of the project.

5.1. Phase I

- Procurement of the following evaluation systems:

System	Cost
- Broadcom BCM93100 QAMLink™ Development System;	$30,000
- Zenith VSB Modulation System Test Transmitter and Receiver	$9,800
- Miscellaneous (filters, mixers, connectors DACs, ADCs, etc.)	$5,200
TOTAL	**$45,000**

- Experiment in laboratory the transmission of 256-QAM IF signal with input data rate of 40 Mbit/s. The QAM center frequency and the bandwidth of the IF signal is within the limits of KSC low pass transmission band. The power frequency spectrum of KSC superimposed on the power spectrum of the QAM signal is shown in Figure 9.
- Experiment in laboratory the transmission of 16-VSB IF signal after the LPF and just before mixer as depicted in Figure 7 (d). The power frequency spectrum of KSC superimposed on the power spectrum of this VSB signal is shown in Figure 10.

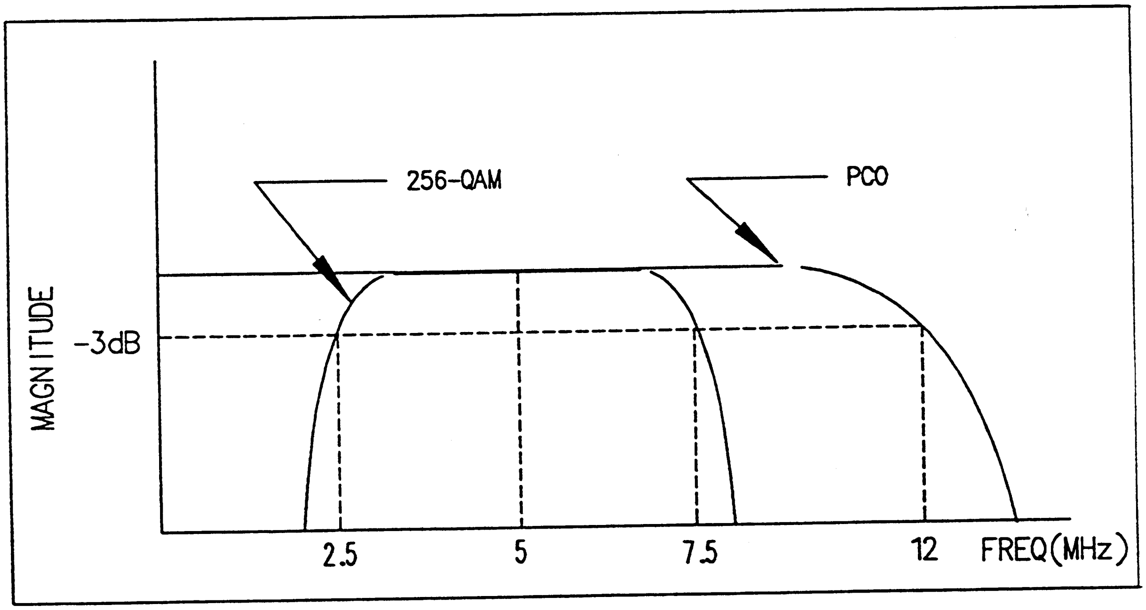


Figure 9: Power Frequency Spectrums of KSC Channel Freq. Response and 256-QAM With Input Data Rate of 40 Mbit/s

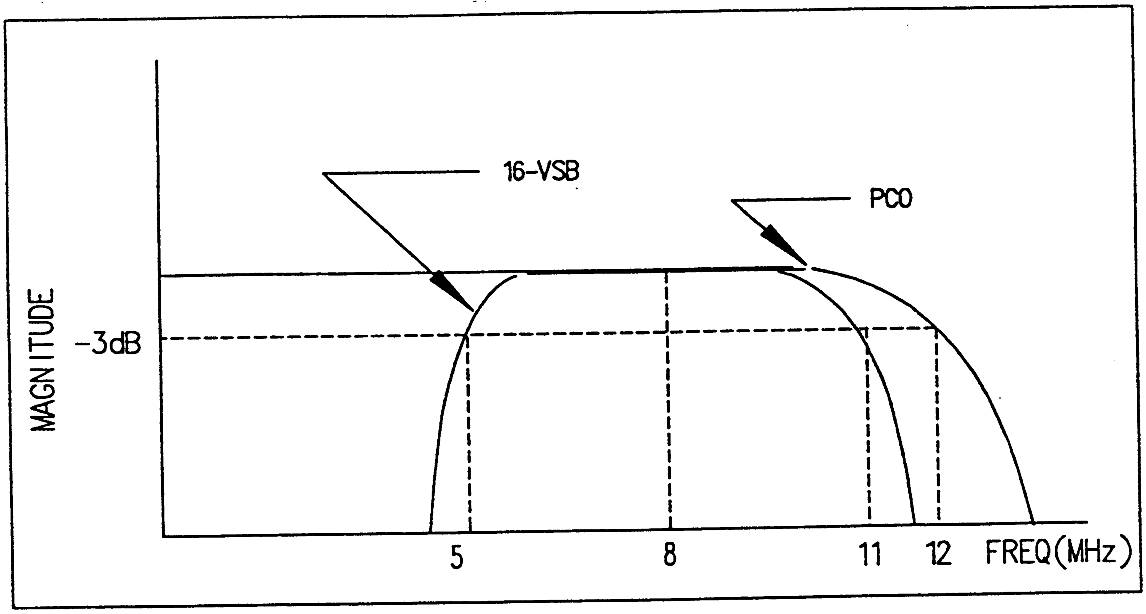


Figure 10: Power Frequency Spectrums of KSC Channel Freq. Response and 16-VSB With Input Data Rate of 40 Mbit/s

- Measure the bit error rate for both schemes as a function of CNR.
- Measure the bit error rate for both schemes as a function of the jitter.
- Using computer simulations, predict the behavior of both schemes under unsymetrical distortions and unsymetrical attenuation.
- Experiment in laboratory the behavior of both schemes under unsymetrical distortions and unsymetrical attenuation. Simulation results should be used as a guide to avoid any discrepancies.

5.2 Phase II

- Increase the input data rate for the 256 QAM system while shifting the IF spectrum to fit within existing low pass transmission band.
- Simulate and implement VSB base band transmission (carrierless VSB or Digital M-PAM as illustrated in Section 3.3) for data rates higher than 40 Mbit/s. Simulation will determine the order of filters required and expected system performance.
- BER vs. CNR and BER vs. jitter for high data rates for both schemes will also be experimented.
- Evaluate all schemes under consideration and discriminate results to other NASA centers.

5.3 Phase III

- Select the more suitable scheme or schemes. Most probably more than one scheme will be used depending on the specific application.
- Design and build a prototype for the selected modulation schemes.
- Test and build a prototype modulator/demodulator system using the selected scheme.
- Write documentation and maintenance manual for the system.

6. CONCLUSION

Either one of the two competing modulation schemes, M-QAM or M-VSB, could be used for transmitting digital signals over KSC's analog links. The cost and performance of the two competing schemes are remarkably similar. In the simplest form, the IF signal output from the modulator chip, could be transmitted with no further frequency shifting or processing. However, the input data rate in such a case is limited to 40 Mbit/s. Theoretically, KSC video communications network is capable of carrying bit rates up to 90 Mbit/s Therefore, vendor's VLSI chip implementation of the two schemes do not take full advantage of the video network of KSC, i.e. the transmission channel is not used the optimum way.

To use the transmission channel more efficiently shifting the IF signals to occupy the low pass frequency range, of both systems is essential. Better off, a simplified version of M-VSB (M-PAM) is proposed. This M-PAM scheme is much simpler and uses the channel more efficiently. With either shifted M-QAM IF carrier, or M-PAM, transmission of data rates close to the maximum possible rate is feasible.

Hands-on experience is needed for all modulation schemes to definitely rule out the suitability of each scheme. Therefore, the procurement of Broadcom's evaluation kit and Zenith's test board is recommended. Since there is no system available yet to evaluate the M-PAM scheme, a small extra funding is recommended to build a system for testing and evaluate the M-PAM scheme. This evaluation system could easily be built and tested here at KSC laboratories.

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