A COMPATIBLE IN-BAND DIGITAL AUDIO/DATA DELIVERY SYSTEM

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0. Abstract

A system for adding digital data to an M-NTSC 6 MHz broadcast channel is described. The data capacity is sufficient to carry high quality digital stereo audio. The new system is shown to be compatible with the existing BTSC stereo system.

I. Introduction

The past few years have seen a rise and fall in the level of interest in high quality digital audio systems for cable television. At the 1983 convention a single paper was presented describing the basics of an efficient digital audio coding method.[1] In 1984, the final form of the ADM coding method was presented[2], and several papers either described the desireablility of digital audio, or prototype systems. 1985 saw more descriptions of prototype systems, and discussion of the advantages of digital audio. The '86 convention saw little discussion of digital audio; the emphasis was decidedly on making BTSC work, although one paper did suggest the replacement of the FM audio carrier with a digital audio carrier[3]. All of the prototype systems seemed to have faded away. There are two reasons for the fading of interest; the practical reality of having to deal with BTSC, and the impracticality of the digital audio system prototypes.

Digital audio offers the advantages of transparency and encryptability. Transparency means that the audio quality is unaffected by its travel from the cable headend to the subscriber (assuming all is working correctly). Minor effects like noise, IM distortion products, and reflections which would have a degrading effect on analog audio will have no effect on the digital audio (assuming they are within reason!). It is a simple matter to encrypt digital audio for program security.

The disadvantage of digital audio is that a lot of data must be put somewhere on the cable. Most systems have put the data out-of-band, at some frequency away from the associated video channel. This requires additional tuning, and channel tags for one tuner to follow another, etc. Some systems have put the data in-band, by utilizing the horizontal interval of the video signal. These systems are not compatible with normal receivers (they will no longer sync) so all subscribers have to be outfitted with new equipment. In order to achieve high quality, digital audio systems have had to use a very high data rate so that much bandwidth has been required. High precision D-A converters and sharp cutoff low pass filters required with PCM coding have increased the cost of systems.

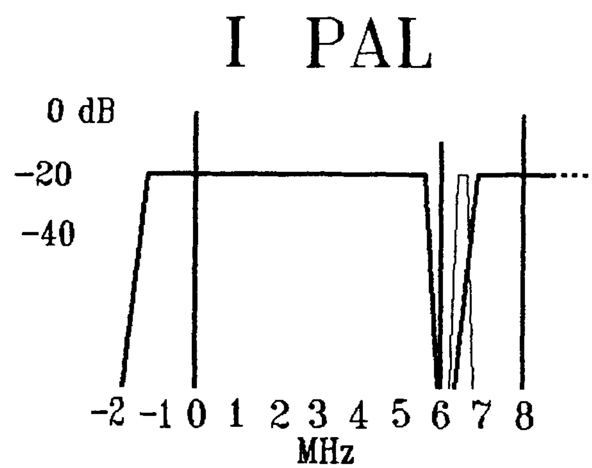
The system described here is in-band and compatible. The system may be used for broadcast or on cable. Stereo digital audio is incorporated into every 6 MHz video channel without removing (or even impairing) the BTSC audio signal or altering the sync interval. ADM audio coding is used, and the cost of incorporating reception hardware into a tv set is on the order of $10.

The BTSC stereo system which is now being incorporated into many CATV systems is theoretically capable of reasonably good performance. Unfortunately, the realities of intercarrier sound prevent this potential from being realized. The output of a BTSC stereo decoder invariably contains numerous 'birdie' and 'buzz' products. BTSC stereo quality is markedly inferior to all other common consumer audio formats: compact disc, compact cassette, FM radio, analog disc, VTR and video laser disc. The quality of BTSC is not a major issue at present. After all, it is "STEREO", and some tests have shown that consumers can't hear anyway[4]. The adoption of a stereo tv system has stimulated improvements in all areas of tv sound production. More care is taken during the production of stereo audio, and the use of audio noise reduction is becoming more common on the studio VTR. Eventually, the better quality source material and the quality conscious consumer will begin to meet in mass, and the BTSC stereo system will become a very noticeable limitation.

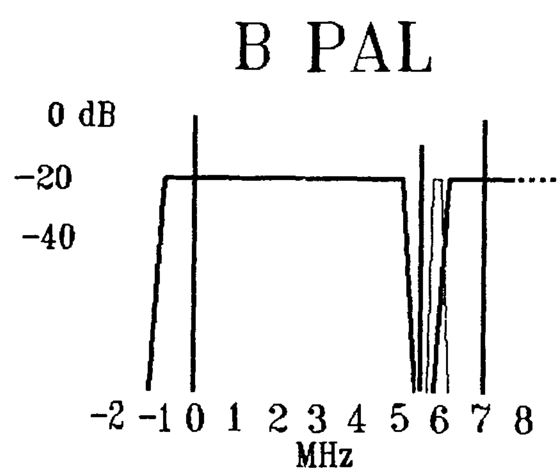
In 1983, the BBC conducted a series of tests at Wenvoe in South Wales of an experimental digital stereo sound system for television system I-PAL[5] (fig. 1a). The tests showed that the QPSK digital carrier which had been added was rugged, and could be received even under adverse reception conditions. In 1984, tests conducted in London showed good compatibility with existing tv receivers. Further tests have since been conducted in Hong Kong (I-PAL), and in Stockholm and Helsinki with system B-PAL (fig. 1b). The narrower bandwidth of the B-PAL broadcast signal makes it more difficult to insert the digital sound carrier without creating interference. In order to avoid interference, the Scandinavian broadcasters were attracted to the Dolby adaptive delta-modulation coding method which allows a 30% bandwidth reduction compared to a companded PCM system. Dolby laboratories became involved in supplying sound coding and digital multiplexing equipment for broadcast tests in Hong Kong, Sweden, and Finland. While observing the work being done in Scandinavia, and comparing the B-PAL broadcast spectrum to that of M-NTSC (fig. 1c), it became apparent that the results of those tests should be applicable here in N. America. Both the B-PAL and M-NTSC signals have the same 750 kHz spacing between the FM sound carrier and the corner of the adjacent channel lower sideband. Work thus began to determine whether a digital carrier could be included into the broadcast M-NTSC signal without creating interference to either the existing vision or BTSC sound signals.

Fig. 1 RF Spectra of TV Systems showing additional QPSK data signal.

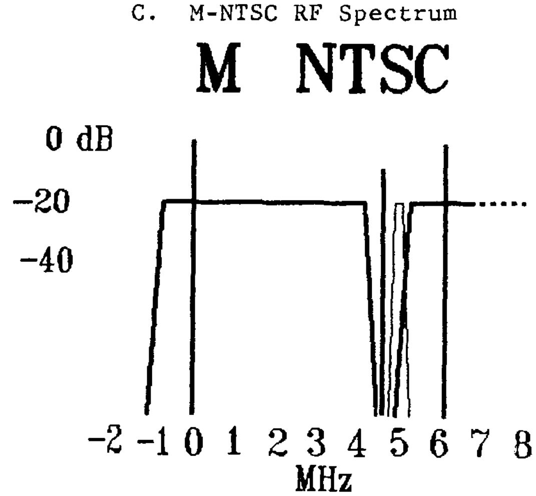
A. I-PAL RF Spectrum



B. B-PAL RF Spectrum



C. M-NTSC RF Spectrum



II. Basics of a New System

Based on work done in Scandinavia, and that reported on here, these are the tentative parameters of the new system:

Carrier Frequency	4.85 MHz above vision carrier
Carrier Level	-20 dB relative to vision carrier
Modulation	Differential QPSK
Bit Rate	512 kbits/sec
Audio Coding	Adaptive Delta-Modulation

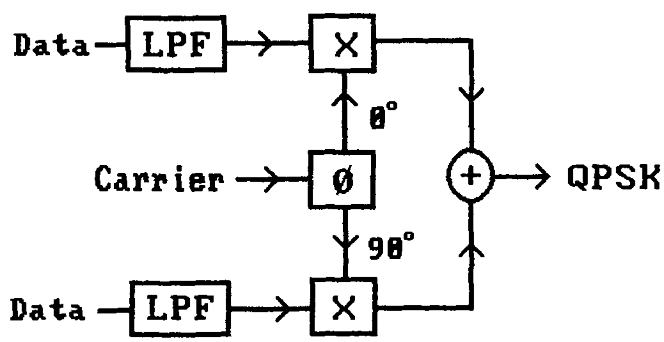
The most important requirement for the new system is that of compatibility; the new digital carrier must not interfere with the existing vision or sound signals. The spectrum of the new signal will resemble a band of noise since the transmitted data will appear random (if it isn't naturally random, scrambling with a pseudo random sequence will make it random). Any interference will appear as noise. There is the potential for interference into the BTSC stereo and SAP signals, and into the adjacent channel vision signal. The carrier frequency and amplitude are the equivalent to those chosen for use with B-PAL. The BTSC signal has a wider RF bandwidth than the mono FM signals in either I or B PAL, and thus there is more potential for interference from a new digital carrier here in the US than in Europe. In order to minimize the interference potential, the new carrier should have the minimum bandwidth necessary to convey stereo audio. A data rate of 512 kb/s has been chosen. Using an advanced form of adaptive delta-modulation coding, this rate is sufficient for two very high quality audio channels, along with synchronization and mode signalling bits, and 64 kbits/s of auxiliary data.

There are a large number of digital modulation methods available which range from simple and inefficient to complex and highly bandwidth efficient. There are inherent tradeoffs between efficiency, ruggedness, and complexity. A good compromise between these factors is offered by quadrature phase-shift keying (QPSK). Bandwidth efficiency can approach 2 bits/Hz and IC chips to demodulate QPSK are now available from at least two sources.

III. QPSK Modulation

QPSK modulation involves sending a carrier which takes on one of four phase states (0, 90, 180, or 270) degrees during each data symbol period. Since there are four states to choose from, each data symbol carries two data bits. It is perhaps easiest to consider a QPSK modulator as a pair of bi-phase modulators working in quadrature as shown in figure 2. Each of these modulators handles half of the data, or 256 kbits/s.

Fig. 2
QPSK Modulation

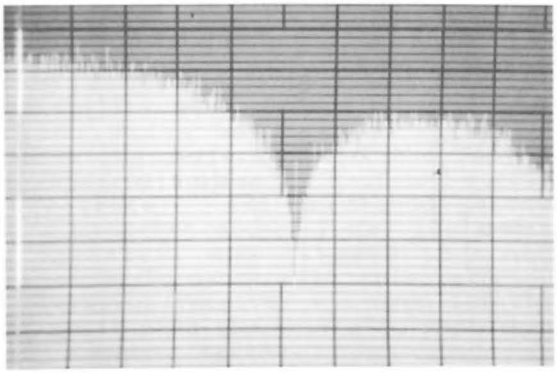


A digital data stream is low pass filtered to constrain the data spectrum. The spectrum of a random 256 kbits/sec data stream is shown in figure 3a. The spectrum extends to infinity with nulls every 256 kHz, and repeating lobes of diminishing amplitude. Only the first two lobes are shown. In theory, it is only necessary to transmit half of the main lobe, or up to 128 kHz (achieving 2 bits/Hz bandwidth efficiency). In practice it is necessary to send somewhat more, and a parameter known as Alpha specifies the fractional excess bandwidth. In figure 3b, the effect of two different data filters are shown; Alpha = 0.3 (the narrower spectrum) and Alpha = 0.7. The sharper the filtering used, the narrower the RF spectrum which will be transmitted and the less interference which will be caused.

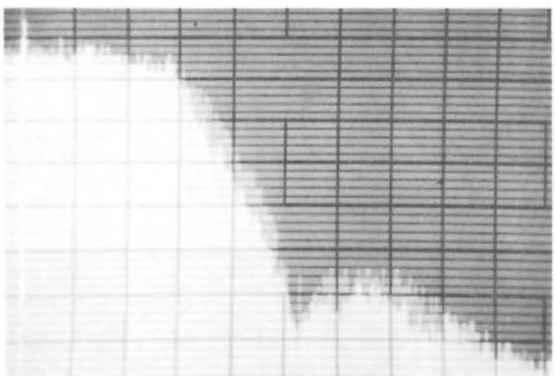
Sharply filtering the data has the undesirable effect of making the system less tolerant of some transmission impairments, and requires tighter tolerances on circuit elements. This is due to the time domain effect of filtering on the transmitted digital pulses. Figure

Fig. 3 Baseband data spectra of 256 kb/s psuedo-random data. Vertical scale 10 dB/div. Horizontal scale 50 kHz/div.

A. No filtering.



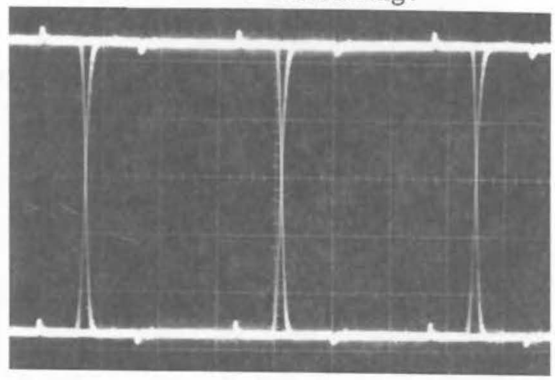
B. Alpha=0.3 (bright) and Alpha=0.7 filtering.



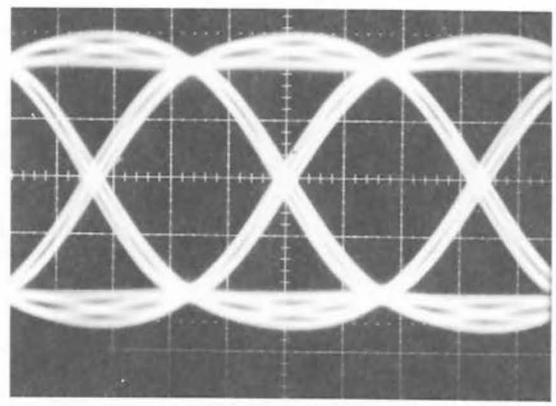
4a shows the 'eye pattern' (the eye pattern is the overlap of many pulses) of an unfiltered baseband data stream. This is what a decoder looks at in order to demodulate the data. This pattern has a 'wide open' eye and no data transition jitter. Figure 4b shows the effect of an Alpha = 0.7 data filter. The eye is now only maximally open at one point in time, and there is some data transition jitter. The eye pattern of an Alpha 0.3 filter is shown in figure 4c. The pattern is quite a bit more complex, the maximum opening is narrower in time, and there is a lot of data transition jitter. The reason that the eye pattern becomes more complex with tighter filtering is that each data pulse 'rings' for a longer time, and thus has the potential to effect the demodulation of more of the other pulses. With ideal filtering this ringing can be controlled so that it does not create a problem, but any deviation from the ideal degrades a narrower band system sooner than a wider band system. Another problem with narrow filtering is that the longer ringing pulses create more havoc if multipath is present, because more pulses can interfere with the pulse being detected. The complexity of the eye pattern correlates

Fig. 4 Eye patterns at data demodulator.

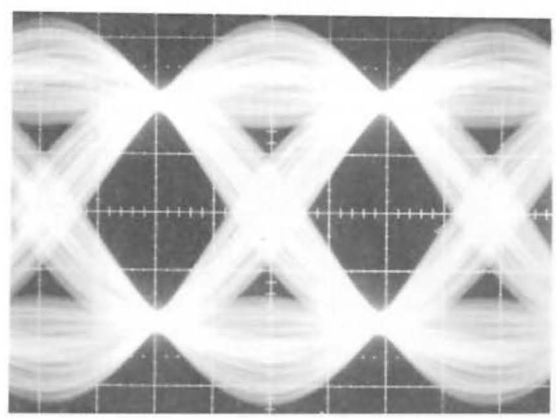
A. No filtering.



B. Alpha=0.7 filtering.



C. Alpha=0.3 filtering.



directly to the ruggedness of the data when passed through channels with imperfect amplitude flatness and non-linear phase response. The more complex eye pattern will degrade rapidly when exposed to any additional filtering, or effects such as multipath. For a consumer system, it is desireable to keep things simple and non-critical and thus the Alpha = 0.7 filter is preferred.

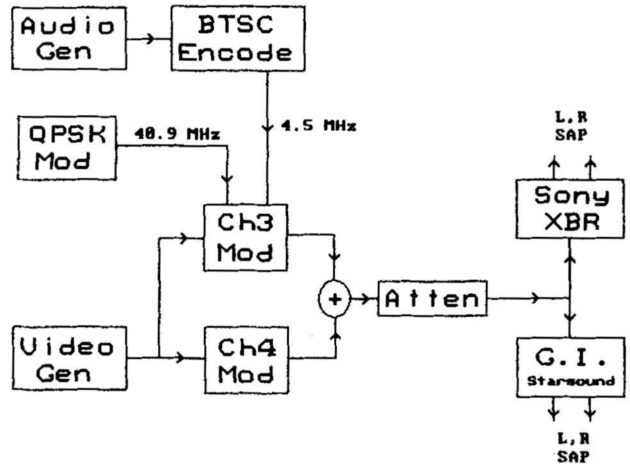
In the QPSK modulator of figure 2, one filtered data stream modulates a 0 degree carrier which results in a 0 or 180 degree phase shifted output. The original baseband data spectrum is shifted up to the carrier frequency and becomes doubled sided. Since each sideband contains the same information, half of the bandwidth is wasted. The other data stream modulates a 90 degree quadrature carrier. Its' output is either 90 or 270 degrees. When the two carriers are summed, the result will have one of 4 phase states. The two quadrature carriers occupy the same bandwidth, and the composite signal now has different upper and lower sidebands, thus fully utilizing the spectrum. The absolute phase is not available to the decoder. The decoder can only detect phase changes, so the data must be encoded differentially. The phase change from one data symbol to the next (a change of 0, 90, 180, or 270 degrees) carries the two bits of information. This requires some additional digital circuitry at each end.

IV. BTSC Compatibility Tests

The effect of the new signal on the BTSC stereo and SAP channels will be one of additive noise. This is due to the fact that the transmitted data spectrum is noiselike. The data multiplexer contains a pseudo-random noise sequence generator. All data is scrambled by the PN sequence and thus no matter what the original data spectrum, the transmitted spectrum is essentially noiselike. At the receiving de-multiplexer the same PN sequence is used to unscramble the data to recover the data. The interference into BTSC will be worst into SAP since the SAP signal spectrum extends farthest away from the 4.5 MHz FM sound carrier (the 'pro' channel is being neglected here). Interference will be less severe into the L-R signal, and still less into the L+R signal. Testing for BTSC compatibility involves measuring the additional noise caused by the new signal.

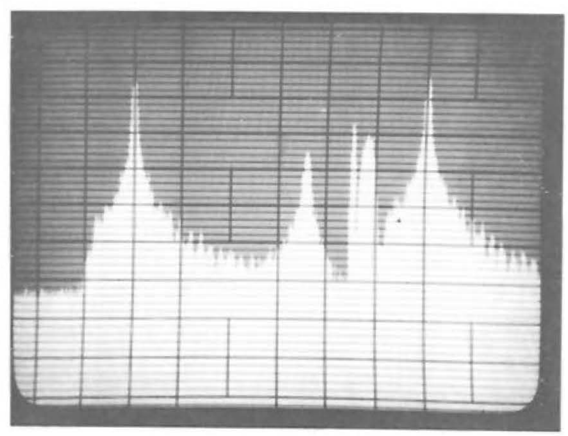
The test setup is shown in Figure 5. Adjacent channels 3 and 4 are generated by a pair of high quality CATV modulators (GI/Jerrold Commander IV with SAW filters). The RF level is controlled by

Fig. 5 Test Setup



an attenuator before entering the receivers. The tested receivers include a very high quality consumer tv set (Sony XBR) and the best quality BTSC decoder available (GI/Jerrold Starsound). Figure 6 shows the spectrum delivered to the receivers.

Fig. 6 RF spectrum of signal at receiver showing Ch3 vision carrier, color subcarrier, FM sound carrier, QPSK data carrier, Ch4 vision carrier.



Because the SAP and L-R channels are heavily companded, we can't simply measure the no-signal noise level to determine the extent of the interference caused by the new digital carrier. We must 'open up' the companding with a test signal and then measure the noise in the presence of the test signal. Since more companding is done at high frequencies, we use a test signal of 5 kHz at full amplitude. So that we are most sensitive to the QPSK caused interference we want to use the best reception equipment with a relatively high RF level. The RF level chosen for these tests was 4 mV RMS or +12 dBmV. Figure 7 Shows the SAP output spectrum of the Sony XBR with video modulation (color bars) on (upper trace) and off (lower trace). Since the audio is significantly degraded by the presence of video modulation, we will be able to see the effects of interference most easily if the video is left unmodulated. All BTSC compatibility measurements were performed with no video modulation. Figure 8 compares the performance of the Sony XBR (upper trace) to the GI StarSound receiver (lower trace). The Starsound receiver uses a separate detector for the L-R and SAP signals[6], and is able to achieve superior performance with this technique. The Starsound receiver was used for these tests as it gave the best BTSC performance of any receiver tested.

Figure 9 shows what happens when the QPSK signal is turned on (upper trace) and off (lower trace). Since the distortion components still dominate, it is not really feasible to measure noise with a SINAD (notch out the fundamental and read what's left) measurement. With an HP3561A FFT based analyzer it is feasible to set up a band noise measurement. The vertical dotted lines in Figure 9 delineate a frequency band from 6200 Hz to 9600 Hz. There are no distortion or 'birdie' products in this band, so the total energy in the band can be used as a relative noise indicator. The FFT analyzer will conveniently display the total energy in the band.

To test for interference from the digital signal we measure the noise in the band 6200 Hz to 9600 Hz as a function of:

1) QPSK carrier frequency [4.80, 4.85, 4.90 MHz above vision carrier]
2) Data filtering applied [Alpha = 0.7, 0.3]
3) QPSK carrier level. [-10 dB and lower, relative to vision carrier]

The absolute numbers obtained are not significant. What we are looking for is the amount of noise increase caused by the presence of the QPSK signal, which will be a measure of compatibility. If the noise is only increased a little bit, then the new signal is compatible. If the noise is increased a lot, then the new signal is incompatible. This judgement is a subjective one, and different judges will likely come to differing conclusions given the same data.

Fig. 7 Sony XBR SAP output. SAP modulated 100% with 5 kHz. Video modulated with color bars (top trace) and un-modulated (lower trace).

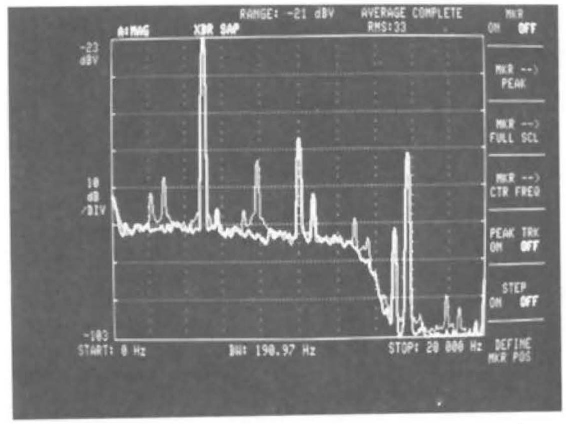


Fig. 8 SAP output of Sony XBR (upper trace) and GI Starsound (lower trace). SAP 100% modulated with 5 kHz. Video unmodulated.

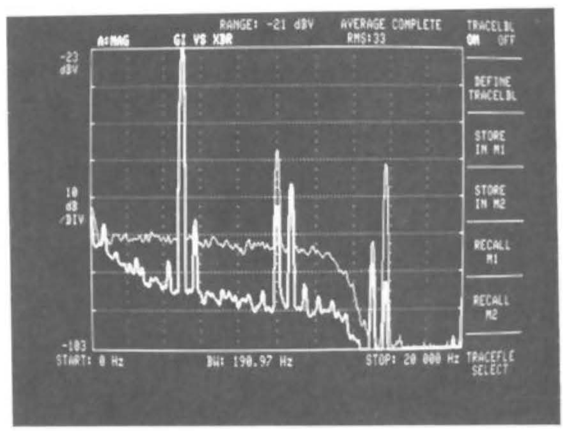
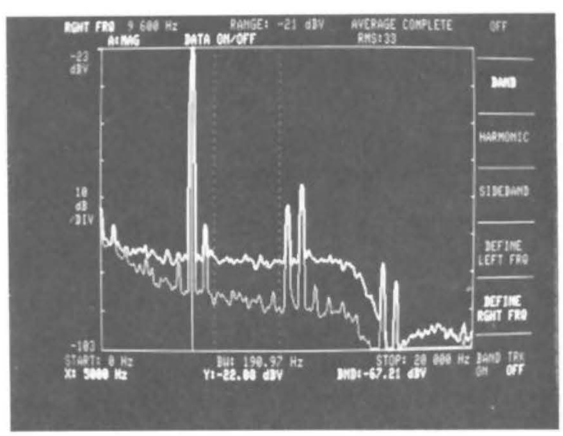


Fig. 9 SAP output of GI Starsound. SAP 100% modulated with 5 kHz. QPSK data signal on (upper trace) and off (lower trace).



The SAP channel test results are shown in Figure 10. As expected, the noise level is worst with the QPSK carrier closer to the FM sound carrier (4.8 MHz) and with the wider data filter (Alpha = 0.7). As the QPSK carrier level is reduced, the noise level drops. Using a narrower data filter (Alpha = 0.3) with the 4.80 MHz offset moves about half way to the curve of the wider filter (Alpha = 0.7) with a 4.85 MHz offset. The difference between Alpha 0.7 and 0.3 filtering would imply a narrowing of the spectrum by about 50 kHz, but since the filtering is split between the transmit and receive filters, the actual narrowing in the channel is more like 25 kHz. At the target operating point of 4.85 MHz, Alpha = 0.7, -20 dB, the degradation to SAP is approximately 5 dB. If the carrier frequency is lowered, the interference rises rapidly. 4.85 MHz appears to be the closest the QPSK carrier can be placed to the 4.5 MHz sound carrier. Operation at 4.90 MHz would only create about 2 dB of degradation, but may create problems with adjacent channel operation.

The 5 dB noise penalty must be put in perspective. The noise penalty only occurs when:

1) A relatively high RF level is used (+12 dBmV).
2) A special receiver is used (Starsound).
3) No video modulation is present.

Figure 11a shows the SAP with the QPSK on (4.85 MHz, -20 dB, Alpha=0.7) and with video modulation on (upper trace) and off (lower trace). Even with the noise made 5 dB worse, the output spectrum is still totally dominated by distortion products. This might lead one to question whether the extra noise is even audible. Figure 11b shows the same situation but with the video left on and the QPSK turned on (upper trace) and off (lower trace). The increased noise in the spectral holes between the distortion products is apparent and can be heard. It is not as objectionable at the distortion.

The penalty for the addition of the QPSK signal is a noise penalty in the SAP channel which is audible under ideal conditions. Under practical conditions the noise change would probably not be noticeable.

Of more concern is the change in noise level in the stereo signal. This is shown in figure 12. While the individual curves at the bottom are hard to make out, the significant finding is that if the carrier frequency is 4.85 MHz or higher, there is no effect on the BTSC signal. At the target operating point, the interference causes less than 1 dB increase in noise level.

Fig. 10 SAP noise level in band 6200 Hz to 9600 Hz. GI Starsound receiver. FM sound carrier level -15 dB rel vision carrier. SAP 100% modulated with 5 kHz. Video unmodulated. QPSK modulated data at 512 kb/s. QPSK carrier frequency at 4.80, 4.85, 4.90 MHz above video carrier. Data filtering Alpha=0.7, 0.3.

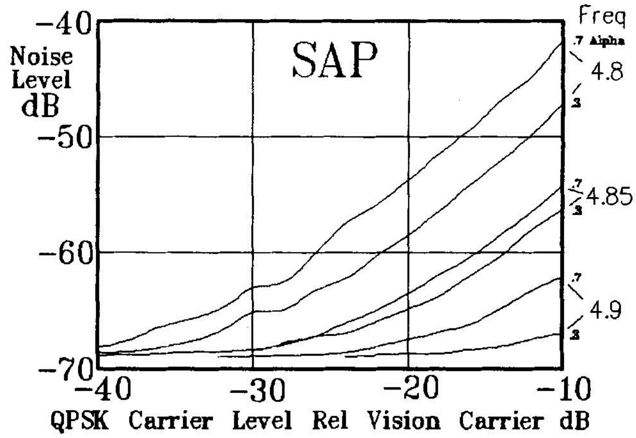
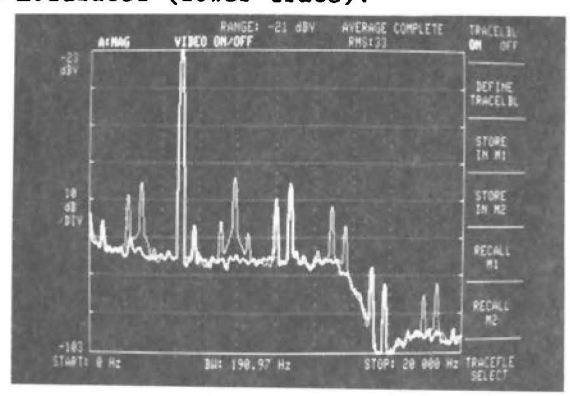


Fig. 11 SAP output of GI Starsound receiver. SAP 100% modulated with 5 kHz.

A. QPSK data on. Video modulated with color bars (top trace) and video un-modulated (lower trace).



B. Video modulated with color bars. QPSK data on (upper trace) and off (lower trace).

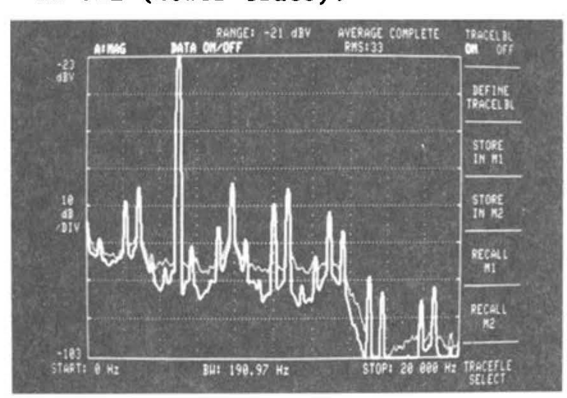


Fig. 12 Left channel noise level in band 6200 Hz to 9600 Hz. GI Starsound receiver. FM sound carrier -15 dB rel vision carrier. L channel 100% modulated with 5 kHz. Video un-modulated. QPSK carrier frequency at 4.80, 4.85, 4.90 MHz above video carrier. Data filtering Alpha=0.7, 0.3.

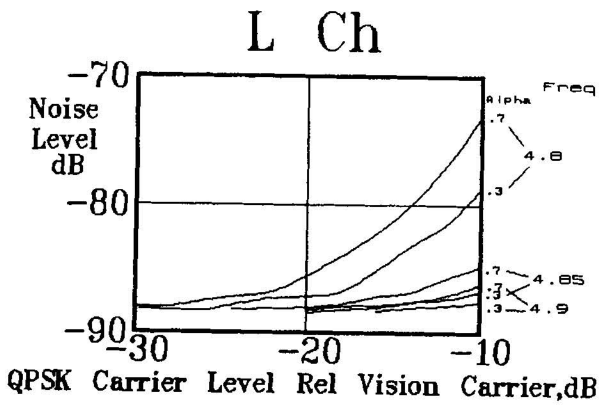
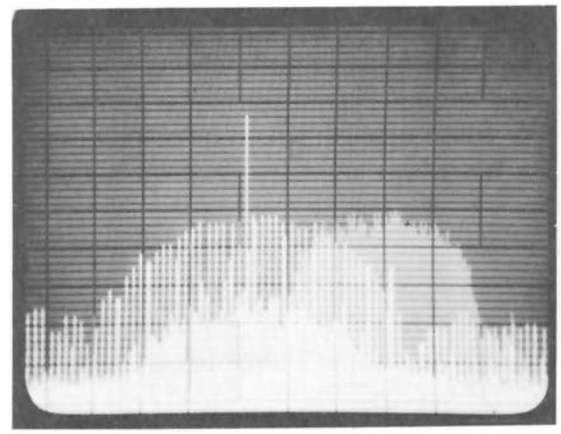


Fig. 13 Spectrum of pulsed FM sound carrier and QPSK data signal. 10 dB/div vertical. 100 kHz/div horizontal.



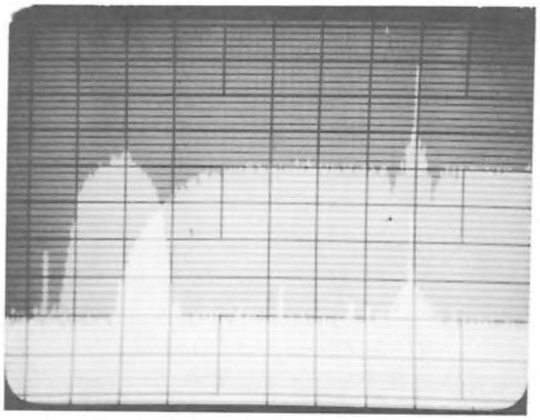
V. Compatibility with Video Scrambling

The new system has not been fully tested with video scrambling systems. Because of the low level and noiselike spectrum of the data signal, it is very unlikely that any additional interference into video or analog audio will occur. It is possible, however, that the techniques used in some video scrambling systems may create some interference into the digital signal. The worst case would be sync suppression scrambling systems which pulse the FM aural carrier to convey sync information to the descrambler. The spectrum of such a system is shown in figure 13, along with the QPSK data spectrum. The pulsing of the FM carrier level at the horizontal rate creates a comb type spectrum which is bandlimited by a band pass filter in the scrambler. The high side of the comb overlaps the QPSK spectrum. Even with this substantial overlap, the data was correctly received without errors, though the margin against error was significantly reduced. In order to handle this situation with sufficient margin against errors, it will probably be necessary to either raise the QPSK carrier level a few dB, or to filter the FM carrier with a notch type filter to attenuate some of the energy above 4.65 MHz.

VI. Adjacent Channel Video

There is the potential for interference from the upper adjacent channel video into the digital signal. There is an overlap of the upper adjacent channel lower vestigial sideband and the QPSK signal spectrum as shown in figure 14. This display was produced by modulating the upper adjacent channel video with a 100 IRE frequency sweep, and setting the spectrum analyzer to peak hold. The shape of the modulators' SAW vestigial sideband filter is revealed. The QPSK data spectrum is displayed on a background trace, and the bright area is the overlap. High level video signals with a frequency of 1.0 to 1.1 MHz do intrude on the QPSK spectrum. With this particular modulator this did not cause data errors, but the margin against error was reduced. It may be necessary to add some additional filtering of the lower sideband to assure adequate margin against error.

Fig. 14 Overlap of adjacent channel lower sideband and QPSK signal. 10 dB/div vertical. 200 kHz/div horizontal.



There is also the potential for the QPSK data signal to interfere into the adjacent channel video signal. TV receivers can be separated into two classes: those that can handle adjacent channel operation and those which cannot. Newer sets with SAW filters handle adjacent channels, and the presence of the digital carrier with its noiselike spectrum, without ill effects. Older sets do not yield excellent video quality with adjacent channel operation, and the appearance of a very slight bit of noise from the new signal is difficult to detect; the patterns and noise caused by the adjacent channel video, chroma, and FM sound carriers totally dominate. Older sets can give acceptable performance when used with a cable converter which contains filtering to remove adjacent channel energy. Since these filters have not been designed to remove the new digital carrier, they will only attenuate it a small amount. This is an area which will require a lot of additional study. It is probable that only tests on a number of real cable systems will reveal whether this is a significant problem. If only a few sets are affected, the addition of a trap at 60.10 MHz (for a Ch 3 output converter) in those installations would solve the problem.

VII. Conclusion

An in-band digital carrier may be added to every cable tv channel in a way which is compatible with the BTSC stereo audio system. Further tests are required to prove compatibility with adjacent channel operation with all tv sets and converters. Further tests are also required to determine if there is adequate margin against error when the FM carrier level is pulsed by video scrambling systems. The digital carrier may contain purely digital data, or a combination of one or two channels of high quality audio and axillary data. The audio may be program audio related to the video signal, or may be a completely unrelated audio program.

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