COHERENT CARRIERS FOR CATV - STATE OF THE ART

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ABSTRACT

Distortion in CATV amplifiers has been analyzed by several authors, notably Simons (1) who calculated the decibel relationships between various types of distortion products. Consideration of the practical implications of such an analysis leads to some potentia-ly significant improvements in the subjective quality of television pictures transmitted through cable television systems subject to amplifier distortion. A reduction in the visibility of many third order distortion products is likely if the spacing between adjacent visual carriers is properly controlled. A further improvement is likely to be obtained if all visual carriers are harmonics of a 6 MHz master oscillator. In such a case all second and third order distortion products are "zero-beat" and it is suggested that the subjective effect of interference in such a case would be substantially lower than is presently the case with present visual carrier frequency allocations.

The use of harmonic, coherent carriers will improve system performance and will also make possible some simplification of receiver tuners and converters.

INTRODUCTION

CATV amplifier distortion is commonly analyzed in the form of a power series expression with three terms (1). Such an analysis gives rise to distortion terms that include second and third order harmonics and intermodulation products and double and triple beat products. Additional distortion terms describe cross modulation. DC shifts and gain expansion or compression also arises in the analysis but these effects may be considered very minor in practical CATV amplifiers.

Second order distortion components consist of second harmonics of the input signals and sum and difference products of the input signals. Third order distortion products consist of cross modulation, intermodulation, triple-beat terms, and third harmonics. Intermodulation is considered to be the interaction between two input frequencies. The third order intermodulation term of concern in this discussion is the one having the forms $2F_1 + F_2$ and $2F_1 - F_2$. Triple beat terms of concern here take the forms $F_1 + F_2 + F_3$, $F_1 - F_2 - F_3$, $F_1 + F_2 - F_3$ and $F_1 - F_2 + F_3$.

Aural carriers in cable television systems are usually run about 15 db below associated or next higher adjacent visual carrier. At these levels they are not considered as contributing to the distortion products in a cable television system and are usually omitted from analyses of the distortion problem

DISTORTION PRODUCTS IN PRACTICAL CABLE SYSTEMS

Second order distortion products do not interfer with the operation of conventional twelve channel cable systems since all harmonics, sums and difference of the twelve regular VHF television visual carriers fall outside the regular VHF bands. Second order distortion products do, however, seriously affect the operation of augmented cable systems carrying more than twelve channels. As examples we may note that second harmonics of low band carriers fall into the mid band, second harmonics of mid-band channels fall into the super-band. Differences between high band and super-band carriers fall into the low band. Sums of mid-band and low-band carriers fall into the high band.

Many CATV amplifiers in current use were designed to minimize third order distortion products, particularly cross-modulation, with no particular regard to the amplifier's second order distortion characteristics. It now becomes virtually impossible to add additional channels in such systems.

Third order distortion affects practical cable systems in several ways. The effects of cross-modulation are well-known and amplifier design has concentrated on the minimization of this particular distortion. Other forms of third order distortion products affect conventional twelve channel systems, but their effect on subjective picture quality is not clearly understood.

Third order harmonics of low band channels may be a problem in some amplifiers. Table I lists these harmonics:

TABLE I

Channel	Visual Carrier	Third Harmonic	
2	55.25 MHz	165.75 MHz	(mid-band)
3	61.25	183.75	(channel 8)
4	67.25	201.75	(channel 11)
5	77.25	231.75	(super-band)
6	83.25	249.75	(super-band

Simons states that third harmonics will be 15.5 db lower in voltage level than a triple beat component arising from input signals of the same voltage level. Because of the relatively low level of third order harmonics, visible interference from them is probably rare.

Triple beat products are probably significant contributors subjective picture quality degradation in practical cable systems. A discussion of these products should be separated into "near" and "distant" products. Triple beat terms in which both signs are either + or - will give rise to products relatively distant in frequency from the input signals being considered. Triple beats with alternating signs give rise to products quite near to the input signal frequencies.

It is obvious that there is a very large number of distortion products in a multi-channel cable system. Muller (2) has calculated and tabulated some of the second and third order distortion products generated in a conventional twelve channel system which fall within the standard twelve channels. He tabulates a total of 353 distortion products arising in a twelve channel system and falling within the twelve channels. In an augmented channel system the number is considerably more.

Near triple beats in a group of adjacent channels fall close to a visual carrier. The "near" triple beats between channels 9, 10 and 11 illustrate this:

9V $\pm$ 10V - 11V = 187.25 + 193.25 - 199.25 = 181.25 MHz (8V)

9V - 10V + 11V = 187.25 - 193.25 + 199.25 = 205.25 MHz (12V)

The "near" triple beats between channels 9, 10 and 11 fall on channels 8 and 12. Similar results are obtained from other combinations of channels from an adjacent "group" when taken three at a time. Some of the "near" products fall immediately above or below the group, and if the group considered is the standard "high band" they would fall onto mid-band or super-band channels.

In a practical cable system the visual carrier frequencies are only nominally 1.25 MHz above the lower band edge. The actual visual carrier frequency depends on the offset assigned to the originating station, the accuracy to which a particular transmitter holds its operating frequency and the accuracy and stability of any frequency conversions which the cable system itself may make. Table II illustrates the variation that may be experienced in a practical cable system.

TABLE II

Channel	Visual carrier 10 a.m.	Visual carrier 4 p.m.	Note
2	55.25007 MHz	55.25007 MHz	Broadcast channel
3	61.26007	61.26010	Broadcast channel
4	67.23998	67.23997	Broadcast channel
5	77.25105	77.25094	Conversion 6 - 5
6	83.26031	83.26026	Modulator locked to 6
7	175.25994	175.25995	Broadcast channel
8	181.24342	181.24342	Conversion 9 - 8
9	187.25004	187.25003	Modulator locked to 9
10	193.24460	193.24569	Substitution oscillator
11	199.25951	199.25952	Broadcast channel
12	205.24539	205.24524	Closed circuit modulator
13	211.22754	211.29307	Substitution oscillator at 10 a.m., UHF conversion from channel 19 at 4 p.m.

Variations from nominal visual carriers (4 p.m. observation) run from -10.03 KHz to + 43.07 KHz. The near triple beats and inter-modulation products can be expected to fall within a similar range from the nominal visual carrier which they affect.

To illustrate this effect a set of third order distortion products arising from the twelve carriers in the system at the 10 a.m. observation in Table II were calculated and observed on a spectrum analyzer. All the triple beat and intermodulation products which would fall near a hypothetical carrier at 49.25 MHz were calculated in Table III and arranged in order of increased frequency in Table IV.

TABLE III	TABLE IV
2V + 2V - 3V = 49.24007 MHz	49.22389 MHz
2V + 3V - 4V = 49.27106	49.23517
2V + 5V - 6V = 49.24081	49.24008
2V + 7V - 8V = 49.26660	49.24081
2V + 8V - 9V = 49.24346	49.24346
2V + 9V -10V = 49.25551	49.24462
2V +10V -11V = 49.23517	49.25060
2V +11V -12V = 49.26419	49.25532
2V +12V -13V = 49.26792	49.25551
3V + 7V - 9V = 49.26998	49.25704
3V + 8V -10V = 49.25589	49.25889
3V + 9V -11V = 49.25060	49.25928
3V +10V -12V = 49.25928	49.26419
3V +11V -13V = 49.29204	49.26660
4V + 7V -10V = 49.25532	49.26792
4V + 8V -11V = 49.22389	49.26998
4V + 9V -12V = 49.24462	49.27017
4V +10V-13V = 49.25704	49.29204

All these products were identified in the system using the spectrum analyzer and digital frequency counter.

Similar clusters of distortion products exist around every visual carrier in the system, the exact number depending on the channel and total number of channels being carried.

The beats resulting from these particular eighteen interfering products give rise to a complex visual effect. Differences between interference products range from about 800 Hz to 22 KHz. The author has not been able to find any reports of studies relating picture quality degradation to multiple interference of this kind and it is proposed to study the effect by eliminating it as proposed later in this paper.

The 4 Mhz guard band between channels 4 and 5 causes third order "near" products which are space at 4, 10 and 16 MHz above and below other carriers instead of the usual multiples of 6 MHz. These products fall 2 and 4 MHz above visual carrier, areas that are not as sensitive to interference as the area immediately adjacent to the visual carrier.

Some third order "distant" products are of concern. Three such examples are:

11V - 6V - 3V = 199.25 - 83.25 - 612.5 = 54.75 MHz

13V - 6V - 3V = 211.25 - 83.25 - 612.5 = 66.75 MHz

13V - 6V - 4V = 211.25 - 83.25 - 67.25 = 60.75 MHz.

There are five more triple beat combinations that will give the same nominal frequencies as the above examples. These will result in clusters of distortion products at the nominal interference frequencies. There are many other third order "distant" products which are generated in multi-channel systems. Some arise from the offset of channels 5 and 6 due to the 4 MHz guard band between channels 4 and 5. Others arise from combinations in which the signs combining terms are either both + or both -. Simons, in an unpublished memorandum, has studied the number of such "distant" terms in more detail. He cites two examples. In the first example, using ten "standard" channels (2-4, 7-13) there are 176 in-band, third order distortion products of which 25 are not close to carrier frequencies. In a second example he cites a 21 channel system using the "standard" 12 channels, except that channels 5 and 6 are moved up 2 MHz, plus 9 mid band channels (A through I). In this case there are 2,137 in band third order distortion products of which 62 do not fall on carrier frequencies.

Our laboratory cross modulation test-set consists of a set of 12 "standard" channels generated using "up-converters" from conventional heterodyne signal processors. Eight mid-band channels (Channels B through I) have been added to the set using similar "up-converters". These up-converters are driven from a crystal controlled IF source. The output frequencies of this 20 channel test signal source were measured recently as being representative of frequency range to be expected in a 20 channel head end using extensive signal frequency conversion and without special attention to oscillator stability, i.e. using local oscillators which are crystal controlled but not temperature compensated or temperature controlled. The expected "near" distortion products at 49.25 MHz were calculated and verified with the spectrum analyzer. There were 42 such products, compared with 18 in the 12 channel case. They ranged in frequency from 40.23698 MHz to 49.26973 MHz, a range of 32.75 KHz.

PROPOSED REMEDIES

It is obvious that the clustering of distrotion products would be eliminated if all the visual carriers were separted by exactly the same frequency. Since channels 4 and 5 are separated by 4 MHz instead of the usual 6 MHz we must drop the channel 4-5 spacing from the present discussion. If all the other channels are separated by exactly the same spacing the third order "near" distortion products will fall directly on a visual carrier instead of close to it. The interfering products would be "zero beat" and would slightly increase or decrease the carrier level according to their relative phase. The modulation side bands associated with each interfering carrier would still be present but it is suggested that this would manifest itself as a slight increase in cross modulation and that this effect would be less objectionable that the quality degradation due to the present clustering of interfering beats around each visual carrier. Simons noted that a triple beat in a 12 channel system would be expected to be about 21 db below the cross-modulation level. If 20 additional third order products resembling cross modulation were added we might expect the level of these products to rise about 16 db above the expected triple beat level. This would still put them about 5 db below the cross modulation level already present and would therefore contribute very little additional cross modulation. This interpretation is still speculative and experiments are now underway.

It is proposed that cable television head ends be designed so that the three major groups of adjacent channels be spaced individually by the same amount, i.e. that the spacing between adjacent channels should be locked to a master 6 MHz spacing oscillator. Phase locking techniques now make such a head end quite practical. Heterodyne processors capable of locking the output visual carrier frequency to an external frequency reference will soon be available and could be employed in the construction of such a head end. The principle can of course be extended to mid-band and super-band channels. Additional channels above and below the regular high band should be contiguous and use the same master spacing oscillator. Some channels may of course be omitted so long as the spacing between channels is eith 6 MHz or a multiple of the master 6 MHz oscillator.

This will cause most in-band third order modulation products to fall directly on visual carriers with consequent elimination of visible beats. Cross modulation will be increased somewhat. A few in-band third order products will still be present but these will be very few in number and not in sensitive portions of the channel. As the number of channels in a system rises about 12 it appears that intermodulation becomes the limiting system performance characteristic. A coherent head-end using common 6 MHz master oscillator spacing significantly reduces third order modulation and triple beat products. The exact value of this mode of operations will be determined from experiments within the next few months.

Several variations are possible to suit special local conditions. It may be desirable to lock one of the cable channels to a local broadcast channel. This is accomplished by making the local broadcast channel act as the reference frequency to whicha 6 MHz harmonic comb is added to produce the other reference frequencies. This may be extended to locking to two local channels by deriving the 6 MHz master oscillator from the difference between two local channels. Unless one of the local channels is channel 5 or 6 the difference between any two local channels will always be divisible by six and the required 6 MHz master frequency can be derived by digital division of the difference frequency between two local television carriers. If one of the local channels is 5 or 6 it can be locked to independently of the others. In such a case it would be possible to lock to three local carriers, one of them being channel 5 or 6.

A COMPLETE SYSTEM

It will be noted that the system of locking to a 6 MHz master spacing oscillator does not overcome second order distortion problems or triple sum or triple difference products. Beats involving the spacing between channels 4 and 5 are not handled either. A more complete remedy would be to use visual carrier frequencies which are harmonics of a master 6 MHz oscillator. In such a case all harmonic, sum, difference, and intermodulation products of all orders will be "zero beat". A head end for such a system can be effected in the way previously recommended, using phase-locking heterodyne processors and modulators, but the cable channels will not be receivable on ordinary television receivers because all channels (except 5 and 6) will have been lowered 1.25 MHz in frequency. Channels 5 and 6 will effective have been moved up by 0.75 MHz. Actually many receivers would be able to tune the new channel allocations (except new channel 6) because most fine tuners would have the tuning range to accommodate the new carrier allocation. Many receivers would, however, not tune the new carriers.

Many new systems are being built to handle more than twelve channels and are using tunable set-top converters in every installation. In some cases set top converters are being used to overcome local pick-up problems. In such cases the proposed harmonic carrier allocations could be used because it is just as easy to align a set-top converter to the proposed harmonic channels as to the present channels.

The required reference carriers would be generated by a master oscillator and harmonic generator.

Use of harmonically related visual carriers would cause second order products to "zero beat" but this does not completely eliminate their effect. The modulation sidebands associated with the mixing carriers also contribute to interference and the subjective effect of these sidebands is not yet known. It is expected that they would probably result in slightly increased cross modulation and that the overall effect would be an improvement over present operations. Systems with abnormally high second order distortion products might find that the resulting increased cross modulation would be excessive and might have to take additional steps to reduce second order distortion levels in their systems.

Hybrid systems which use harmonic carriers in a transportation trunk and regular carriers in local distribution can be considered. A multiple block converter can be designed that would shift harmonic carriers to regular channels in two blocks. Channels 2, 3, 4 and the high band would be one block and channels 5 and 6 would be the other block.

Some schemes for implementing augmented channel capacity require some of the channels to be "inverted", i.e. having visual carrier higher in frequency than the aural carrier. Such systems can be implemented with locked spacing or with harmonic carriers since this discussion of distortion products deals with only visual carrier spacing and frequencies. Associated aural carriers can be located above or below the visual carriers, as desired, so long as channels do not overlap in the transition between normal and inverted channels.

The reference carriers for a coherent head end can be generated in a number of ways. One practical way is to have a 6 MHz master oscillator drive a "comb generator" whose harmonic output comb is then mixed with a suitable base oscillator for each band of reference frequencies. All channel references can be based on a single base oscillator and 6 MHz comb, except for channels 5 and 6 whose base frequency must be offset by 4 MHz.

Channels normally processed by "on-channel" heterodyne processors will be shifted only slightly in frequency when locked to the coherent reference carriers. This requires careful shielding within the processor so that the input frequency, which is not coherent with the desired output frequencies should not leak through into the output, causing undesirable beats.

The accuracy and stability of the master 6 MHz oscillator and the base oscillators are not critical but should be chosen so that the final spectrum has accuracy and stability characteristics meeting applicable system specifications. Since +- 10 KHz accuracy is probably required at the highest channel, +- 5 KHz accuracy would be required in the base oscillator and the highest used harmonic of the master 6 MHz oscillator. This is approximately 5 KHz in 100 MHz in each oscillator so that .005% accuracy and stability should suffice.

THE CROSS MODULATION PROBLEM

1. Suppressed Carrier

The use of coherent harmonic carriers should practically eliminate problems associated with harmonics and intermodulation products. Actually the products are not eliminated but their subjective effect is drastically reduced. Cross modulation still remains and may indeed be effectively increased by the intermodulation between modulation sidebands.

A direct approach to the problem is to "unload" the amplifiers by suppressing the carriers. The system would operate as a double side band, suppressed carrier system. Actually a vestigial lower sideband system would still be used but the spectrum immediately around the carrier is double sideband and this is important in considering some of the problems associated with suppressed carrier. Benefits to be obtained may be estimated from consideration of RF envelopes for normal and suppressed carrier waveforms. Reduction of approximately 6 db in peak envelope are likely. This is a significant advantage since it effectively reduces amplifier outputs by about 6 db. This reduces second order products by 6 db and reduces third order products such as cross modulation and third order inter-modulation by 12 db. Alternately the additional 6 db margin can be used to improve signal to noise ratio by raising amplifier input levels appropriately. Unfortunately signal to noise ratio increases only 1 db for each 1 db increase in signal level, whereas cross modulation declines on a 2 for 1 basis. The 6 db improvement can "buy" 6 db of noise improvement of 12 db of cross modulation improvement. Operators would be able to take their choice.

Suppressed carrier channels are easy to generate using balanced modulators, but rather difficult to achieve through heterodyne processing of conventional TV carriers.

Re-insertion of the carrier for reception by conventional TV receivers is a difficult problem. A variety of techniques are available. The presence of both sidebands makes it important to achieve both correct frequency and phase for the re-inserted carrier. The presence of both sidebands also makes it possible to establish the carrier by squaring the DSBSC wave, filtering the component present at twice the carrier frequency and then electrically dividing this frequency by two (3).

Other carrier recovery systems are possible. One technique takes advantage of the special specular characteristics of television modulation. Envelope detection of a DSBSC television signal is not directly usable but is rich in horizontal scan frequency components. Envelope detection with an arbitrarily inserted carrier yields spectral components which can be compared with the H components from the detected DSBSC signal. A phase control sytem could adjust the re-inserted carrier to the proper position.(3)

Systems could probably be developed using carrier "bursts" during video sync pulses in a manner analogous to the transmission and detection of colour subcarrier in the NTSC colour system. Assuming a random phasing of sync pulses between channels in the system, the bursts of carrier should not significantly affect the overall system loading, since it would be unlikely that more than two or three such carrier bursts would occur simultaneously.

Suppressed carrier might make coherent carrier operation unnecessary, but the use of coherent carriers might make it easier to re-establish the carrier at the receiver terminal. Carriers could be re-established by resynthesizing from a pilot distributed in the system. A 6 MHz pilot tone could be multiplied into a spectrum comb which could then be mixed in with all the suppressed carrier channels simultaneously. Correct phasing would still be a problem but could probably be achieved.

It would be desirable if low cost carrier re-insertion could be achieved in a set-top converter. It is too early to judge the prospects for this kind of converter. We do expect to be using suppressed carrier techniques between major head ends in a large system within a year. This will allow us to test suppressed carrier effectiveness while working on the problems of low cost reception of DSBSC TV signals.

2. Coherent Video

TV carriers have maximum envelope amplitudes during sync pulses. Amplifier loading depends on the complex envelope representing the "sum" of the envelopes of multiple carriers. If the envelope peaks could be made to coincide on all channels maximum amplifier loading would occur at a known and controlled time, namely during picture blanking (horizontal and vertical) on _all_ channels. In between sync pulses the carrier envelopes would be significantly lower representing the envelope peaks reached by normal picture "blacks". Normal picture blacks would reach only about 66% of peak envelope. Peak envelope during picture content interval would therefore be about 3.6 db lower than during sync interval. NCTA specifications call for amplifier cross modulation measurements to be made with all video synchronous and measures the cross modulation from these synchronous video channels onto an unmodulated carrier. This is the worst case since all the channels except the one being measured have co-incident RF envelope peaks. Coherent video would make RF envelope peaks co-incident on all channels and the cross modulation resulting would come from RF envelopes corresponding to random picture content in all the channels. Cross modulation should be significantly reduced since the amount of cross modulation depends not only on the envelope peak but on the modulation index of the channels in the system. Most visible cross modulation arises from the blanking bars of other channels corresponding to their sync pulses. Since these aspects of cross modulation will never be visible, occuring during the vertical and horizontal blanking of the channel being watched, we may expect cross modulation reductions corresponding at least to the difference in modulation level between sync tips and normal picture blacks, about 3.6 db.

Coherent video can be achieved but at great economic cost. The problem is really phase coherence rather than frequency coherence. Virtually all TV stations today use colour sync generators with high quality colour subcarrier oscillators as the basic frequency standard. Normal tolerance is +- 10 Hz in 3.58 MHz equal to about 3 parts in 100 accuracy. Most sync generators are better than this. The relative phase of sync pulses will be quite arbitrary depending on transmission routes and distances and the phase in which a picture source happens to start. Phase and frequency can be adjusted by the use of "time base correction". Time base correction is used in quality video tape recorders and "black boxes" for general purpose time base correction are just now becoming available. Such correctors now achieve an "H lock", i.e. they lock the horizontal sync rate of two video sources. "V lock" can be achieved in video tape machines but is more difficult to achieve in a general purpose "black box" since it would require the ability to shift + or - ½ field, a rather long time span, compared to the half H line shifts required for arbitrary H lock. At the moment it appears that time base correction to permit "coherent video" is too expensive to contemplate in CATV systems. We are, however, watching developments in the video time base correction field with a view to possible implementation at a future date.

EFFECT ON CONVERTER DESIGNS

The use of coherent carriers which are harmonics of a master 6 MHz oscillator makes possible the consideration of some interesting converter and tuner designs.

The problem of image rejection and local oscillator radiation has forced converter designers to abandon the commonly used IF of 45.75 MHz in favour of substantially higher IF and local oscillator frequencies. IF frequencies are now often about 400 MHz and local oscillator frequencies are about 500 - 700 MHz.

It is difficult to make selective IF's at these frequencies and the potential usefulness of the converter as a "preselector" for TV receivers which do not have enough preselection of their own is lost.

If we select an IF frequency which is also a harmonic of 6 MHz, our local oscillators can also be coherent harmonics of 6 MHz. Any local oscillator leakage back into the system will be zero beat with system carriers. Since the local oscillator is not modulated it will not significantly affect the system carriers. An IF frequency of 42 MHz could be chosen for the visual IF. The local oscillator could be generated from a master 6 MHz pilot carrier transmitted through the system. Phase lock loops could lock the IF to a master 42 MHz reference or synthesizer techniques could be used to generate the required local oscillator frequencies. Imgae rejection would have to be controlled by appropriate RF selectivity. Images would be also be coherent and the system would probably be less sensitive to image interference for this reason. Use of a relatively low IF frequency with stable local oscillators would permit building adjacent channel selectivity into the converter. Surface wave filter technology is now being developed for use in TV IF's at 45.75 MHz. It is likely that these techniques will be adaptable to a 42 MHz IF, making low cost, very stable IF sections.

The desirability of a suppressed carrier system has been suggested and there will be efforts to combine all these techniques into a single, high performance, reasonably priced converter.

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