SIGNAL PURITY CONSIDERATIONS FOR FREQUENCY SYNTHESIZED HEADEND EQUIPMENT

David L. Kelma

General Instrument, Jerrold Division

ABSTRACT

As cable television system bandwidths increase and frequency plans proliferate, more manufacturers are turning to synthesized frequency agile headend channel converters. With this new approach using phased locked loops and dual conversion come spurious signals and noise sources not encountered before in crystal controlled channel converters.

Important characteristics of these headend converters including phase noise, spurious signals generated by the comparison frequency, and residual frequency and phase modulation, are evaluated for their subjective impact on the output signal to the cable. Data is presented which shows the correlation between subjective picture degradation and measured headend synthesizer noise contribution.

INTRODUCTION

In the past, designers of cable system headend equipment hardly concerned themselves with phase noise. This is because most systems relied on crystal oscillators where the phase noise is not a major concern due to the inherent low noise and stability of such circuitry. The current trend is toward greater use of frequency synthesis and phase-locked loop controlled conversion processes. This is due to the attractiveness to both the manufacturer and use of frequency programmability in the multichannel environment and is further driven by the decreasing cost of associated components.

Noise is influenced by each section of the phase-locked loop system and adequate performance is obtained only by careful design of all circuits. Both product and system designer must determine the phase noise performance level that is required for subjectively acceptable signal quality in the intended application.

BASIC OVERVIEW OF THE PLL

Before we evaluate the system for its noise performance, let us first review the basic operation of a phase-locked loop. A simple phase-locked loop consists of a voltage controlled oscillator, or VCO, a digital divider, a phase detector, a reference frequency source, and an integrator or loop filter. Figure 1 represents such a system.

These system components function as a servo loop such that when the VCO is phase-locked to the reference, the output frequency and phase of the digital divider is equal to the frequency and phase of the reference. This makes the average output of the phase detector zero and, therefore, the output of the loop filter remains unchanged. Should a disturbance cause the VCO oscillating at "N" times the reference to shift frequency or phase, the digital divider output would not be coherent with the reference. This makes the output of the phase detector nonzero causing the loop filter to change its average DC output voltage, which forces the VCO back to the proper frequency and phase (REF. 1).

NOISE SOURCES IN A PHASE-LOCKED LOOP

Now let us take a look at the mechanisms that can produce noise within the phase-locked loop. Signals that are integer multiples of the reference frequency will inevitably be present at the output of the phase detector. These reference frequency components can cause spurious outputs by modulating the VCO. Optimum phase detector characteristics and the loop filter design can reduce these signals to an acceptable level. (REF. 2, 6, 8.)

Loop Filter Noise

Since the loop filter drives the VCO tuning line, any noise at the output of the loop filter produces phase noise on the oscillator output. Furthermore, any noise on the phase detector output is

C4APC OUTPUT PLL SYSTEM (SIMPLIFIED)

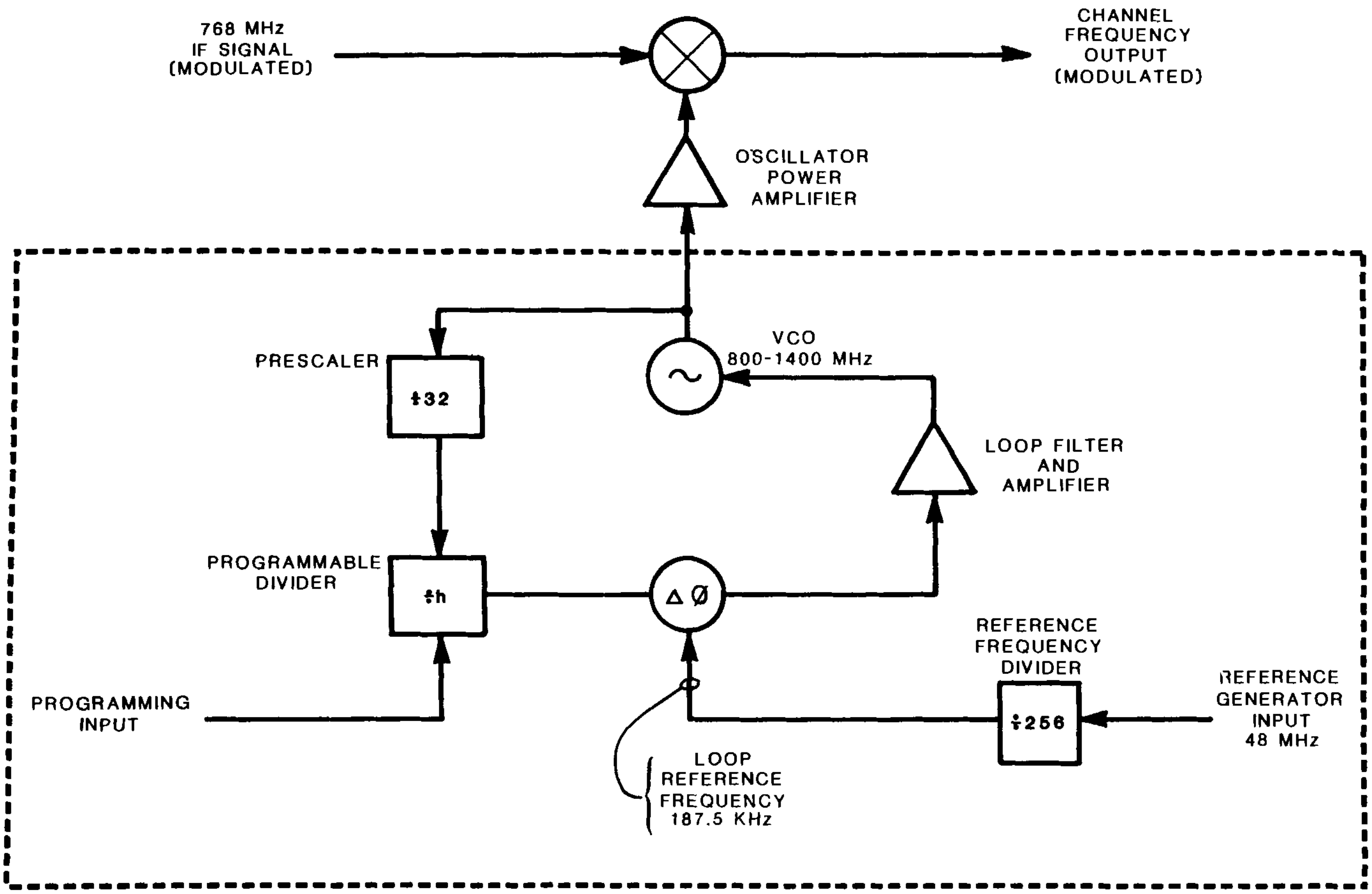


FIGURE 1

modified by the filter transfer function, added to the loop filter output, and modulated onto the VCO. The amount of oscillator phase noise is a function of the tuning sensitivity, Kv, and the amount of noise reaching the VCO's tuning port.

For example, let's look at a VCO with a sensitivity of +35 MHz per volt and assume that the VCO output frequency is 1000 MHz with 0 volts on the control line. At this sensitivity, a positive 1 volt dc average value on the control line would give an output frequency of:

F out = F nominal + (Vdc times Kv)

F out = 1000 MHz + (1 volt times 35 MHz / volt)

F out = 1035 MHz

If the 1 volt signal had been 1 volt RMS random noise then the output would have been 1000 MHz plus and minus 35 MHz RMS of residual phase and frequency noise modulation. (REF. 8)

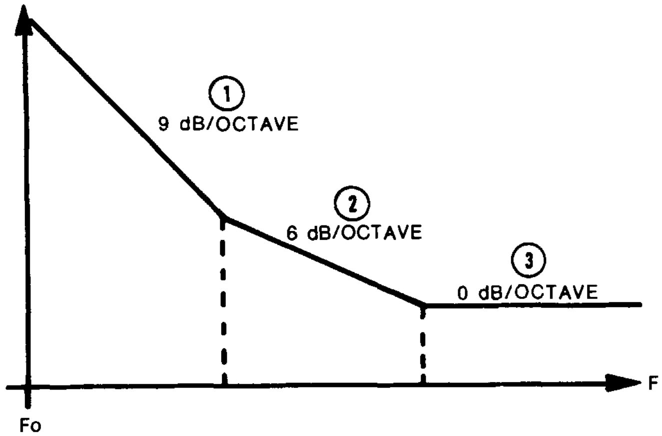
VCO Noise

One of the more significant contributors to output noise is the VCO itself, although all of the phase-locked loop components add noise to the output spectrum. The noise analysis of oscillators is difficult because the active device is operating in its nonlinear region. However, if we examine the oscillator as an amplifier that has as much gain as the feedback network has loss, we will be able to get a reasonable approximation of the phase noise performance. Using the basic relationship for thermal noise, we note that: kTB = -174 dBm/Hz (decibels relative to 1 milliwatt per hertz) is the noise floor of any amplifier input. For a 1 Hz bandwidth, adding the amplifier noise figure, and adding the gain gives the corresponding amplifier output noise floor. This will be the oscillator noise floor far removed from the carrier. The phase noise performance close into the carrier will depend upon whether it is a bipolar or field effect transistor. Rather than give a rigorous mathematical description here, let us take a look at some measured phase noise characteristics. Figure 2 shows that there are 3 basic areas of phase noise:

1) The close in portion, where the oscillator phase noise is proportional to the transistor's low frequency noise characteristic.

2) A region that is a little farther removed from the carrier where the noise is related to the Q of the frequency determining circuit.

OPEN LOOP VCO PHASE NOISE



FOR REGION:

1 $\left(\frac{F_o}{2Q}\right)^2 \left(\frac{a}{F_m^3}\right)$

2 $\left(\frac{F_o}{2Q}\right)^2 \left(\frac{F_{osc}\,kT}{2P_s F_m^2}\right)$

3 $\frac{F_{osc}\,kT}{2P_s}$

Fo = AVERAGE OSCILLATOR FREQUENCY
Q = LOADED QUALITY FACTOR OF OSCILLATOR'S RESONATOR
a = A CONSTANT WHICH IS PROPORTIONAL TO THE FLICKER NOISE AMPLITUDE
Fm = F - Fo
Fosc = EFFECTIVE NOISE FIGURE OF THE AMPLIFIER USED IN THE OSCILLATOR CIRCUIT
k = BOLTZMAN'S CONSTANT
T = TEMPERATURE IN DEGREES KELVIN
Ps = RF OUTPUT POWER OF THE OSCILLATOR

FIGURE 2

3) The far removed noise floor of the oscillator.

The second item is significant because a VCO that has a wide tuning range necessarily has a lower "Q" and therefore, has more phase noise.

Also, all three regions are related to frequency. This means that the higher the frequency of operation in an oscillator, the higher the phase noise, all other parameters being the same. (REF. 4, 5, 7, 10)

Divider Noise

Increasing the output frequency of the VCO inherently leads to a larger frequency divider which, of course, means higher divider noise. Generally speaking, the output phase noise of a digital divider is equal to the input phase noise divided by the circuit divisor plus the inherent divider noise. This manifests itself as a minimum attainable noise floor. The practical noise limits are -170 dBc/KHz (decibels relative to the carrier per kilohertz) for TTL types and -155 dBc/KHz for ECL dividers. CMOS dividers, working up to a frequency of about 10 MHz are similar to TTL devices, except that they have slightly higher noise between the carrier frequency and about 10 Hz away from the carrier. (REF. 3)

Unfortunately, digital circuits have another side effect, crosstalk. This causes the input signal to appear at the output as both feedthru and stray pickup. Most synthesizer systems are limited by other factors and this effect adds less than 1 dB to the noise level. (REF. 3)

Phase Detector Noise Response

In most synthesizer applications, the phase detector is chosen for reasons other than noise performance, such as acquisition and hold-in range. This is because the synthesizer phase detector does not normally operate near its noise threshold. For this reason, phase detectors are evaluated for their noise response and not as a noise source themselves. (REF. 9, 11, 12, 13)

Reference Signal Noise

Finally, we should consider the phaselock reference signal and realize that the output signal can be no more stable than the reference frequency stability times the digital divider ratio. Generally, we can dismiss this as a problem, by recognizing that the reference frequency in a synthesizer system is fixed. This allows us to use a high stability, low phase noise circuit such as a crystal controlled source.

SYSTEM IMPACT

In order to discuss how we expect the perceived signal to be degraded in the presence of phase noise, we must consider how the receiver circuits respond to this type of noise. First, we will determine what common effects receivers will experience. Second, we will take a look at the video and sound demodulators. It is necessary to evaluate the video and sound signals separately, because the difference in the modulation type for the two carriers will cause their respective demodulators to respond differently to phase noise. Finally, we will look at the effect of a signal with phase noise on broadband system distortion.

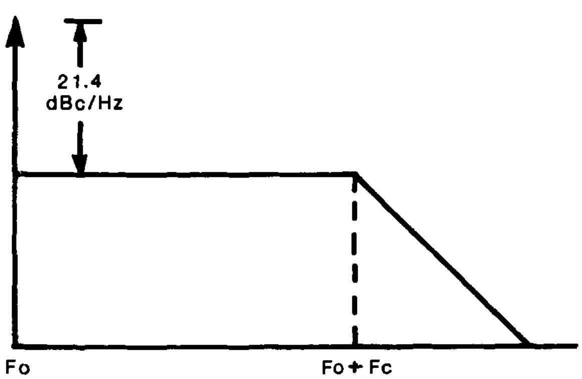
Nyquist Filtering

All television receivers have a Nyquist IF filter in front of their video detector circuits for proper demodulation of the vestigial side band video signal. The slope of this filter will translate the residual FM noise into an amplitude modulation. The video demodulator circuit will then detect this AM noise just as any other portion of the video signal. Assuming a carrier to noise ratio objective of 60 dB and using the ideal Nyquist filter slope, we can perform a simple calculation of the allowable residual FM at the input of the Nyquist filter. The ideal Nyquist filter slope starts at 45.00 MHz with 0 dB attenuation and has infinite attenuation at 46.5 MHz. This represents 100% amplitude modulation as the result of an FM input signal with 750 KHz deviation. A noise level of 60 dBc on the detector output would then correspond to AM modulation of 0.1%. To find the residual FM input necessary to produce this amount of AM, use the following equation:

$$\text{RFM} = (\text{Residual FM}) = \frac{(750{,}000\ \text{Hz})\ (\%\ \text{AM on filter output})}{100} = 750\ \text{Hz}$$

Thus, a synthesizer design objective might be to obtain 750 Hz RMS of FM noise or better.

CLOSED LOOP OUTPUT PHASE NOISE



Fo= VCO OUTPUT FREQUENCY
Fc= LOOP FILTER CUTTOFF FREQUENCY
Frms= ROOT MEAN SQUARE RESIDUAL Fm

FIGURE 3

We can derive an equation for the signal to phase noise ratio of a carrier by defining F1 and F2 as the lowest and highest frequency offsets of interest with respect to the carrier. From this we will make the assumption that between frequencies F1 and F2 the slope of the noise power versus frequency is a straight line. Next, we will let F1 = 0 and F2 = Fc, the phase-locked loop cutoff frequency. In looking at Figure 3, we notice that the synthesizer has a white noise characteristic below the loop cutoff frequency of 500 Hz, i.e., the slope is 0. This is typical of a closed loop phase-locked system. (REF. 14) Our derivation leads us to the following equation from which we calculate the phase noise floor.

$$\text{NP} = 10\ \text{LOG}\ \frac{3(\text{Frms})(\text{Frms})}{2(\text{Fc})(\text{Fc})(\text{Fc})} = \frac{3\ (750)(750)}{2\ (500)(500)(500)} = -\ 21.4\ \text{dBc/Hz}$$

Although this noise floor seems to be very high, we must remember that this is phase noise and will not be directly demodulated by the video detector.

VECTOR DIAGRAM OF CARRIER, VIDEO AND PHASE NOISE

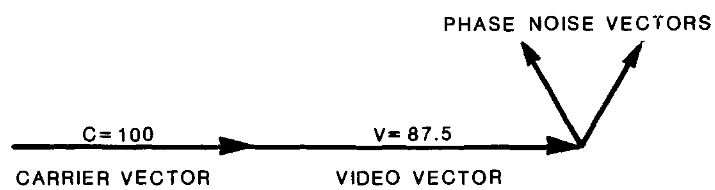


FIGURE 4A

Envelope Demodulation

We would expect an envelope demodulator to be the most sensitive type of detector to phase noise because it will detect the video amplitude noise caused by the phase noise spectrum plus the Nyquist slope converted AM noise. Figure 4a shows the complete vector diagram of the carrier, video, and phase noise. We will let the carrier amplitude be 100 units and the video equal to 87.5 units.

Next, we will take the phase noise level of -21.4 dBc/Hz and convert it to a linear form, remembering to multiply by the signal level. This is done in the following equation.

$$Rpn = \left(10^{\left(Np/20\right)}\right)(87.5) = 7.45 \text{ units}$$

Figure 4c shows, by application of the Pythagorian theorem, that the detected level of the noise is:

$$No = 20 \text{ LOG}\left(\frac{R1 - R2}{R2}\right) = -48.7 \text{ dBc}$$

where R1 = square root ((Rpn)(Rpn)+(V)(V)) and R2 = V.

PHASE NOISE RESULTANT

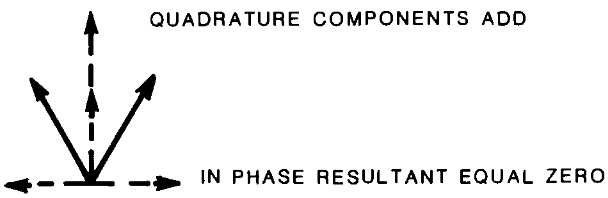


FIGURE 4B

This shows that the main contributor to picture degradation in an envelope detector is the directly detected component of the phase noise, and not the Nyquist FM to AM noise at - 60 dBc. Moreover, noting that the phase noise is predominently low frequency due to the phased locked loop in the headend synthesizer, the detected noise will be of low frequency. This suggests that the subjective video degradation for the envelope detector will be in the form of horizontally streaked noise.

PHASE NOISE INDUCED AMPLITUDE ERROR

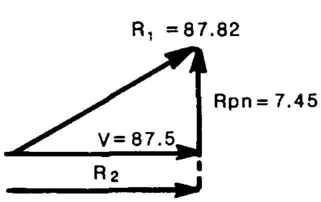


FIGURE 4C

Synchronous Detection

In theory, we would expect the synchronous detector to be better in noise performance than the envelope detector because it will track out the residual FM. In looking at the vector diagram of Figure 5b, we see that the synchronous detector only responds to the modulation vector which is in phase with the carrier: however, the detector follows the angle produced by the phase noise component as well. The phase noise directly contributes nothing to the amplitude component; therefore, none of the phase noise is directly detected.

Unlike the envelope detector, the synchronous detector has a threshold which determines the level of noise induced phase - frequency deviation it can track. This threshold is determined by parameters within its own phase or frequency locked loop. At noise levels below this threshold, we would expect the subjective effect of FM noise to be similar to that of the envelope detector, but to a lesser degree. This is because the detector doesn't actually hold zero phase to the carrier as the FM noise approaches the hold-in threshold, but instead has a small offset. This offset allows the detection of a small amount of the phase noise, which increases toward the threshold. Exactly at the hold-in threshold, the synchronous detector will jump in and out of lock following the peak noise induced FM. The result will be cycle slipping, an effect which should be familiar to anyone who has operated a satellite receiver under poor signal to noise conditions. This appears as random tearing of the picture horizontally, associated with random loss of vertical sync.

Serious degradation should occur at a lower input phase noise level than that of the envelope detector because of the dependence of the synchronous demodulation loop on the ability to follow the FM noise as a result of the synchronous demodulator threshold.

SYNCRONOUS DEMODULATION

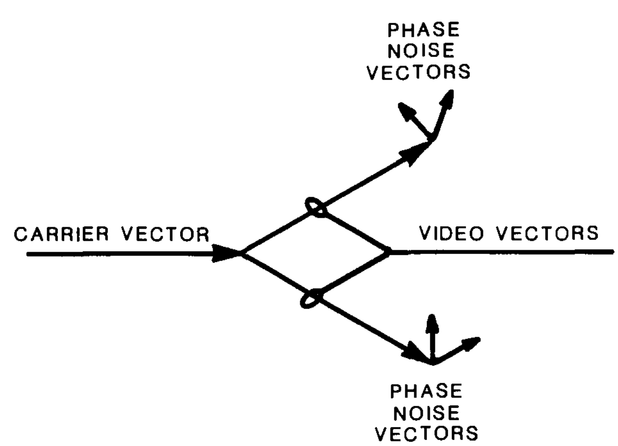


FIGURE 5A

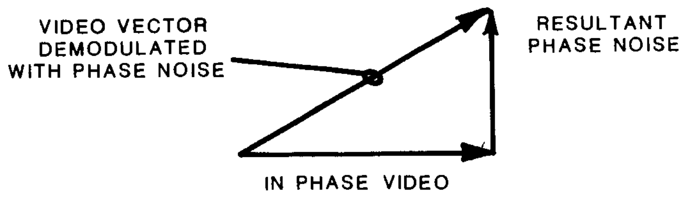


FIGURE 5B

Sound Degradation

Considering that phase noise produces a noise related FM deviation and that the sound carrier is FM modulated, we expect that the perceptibility of the noise will depend on its spectrum. The noise spectrum of the sound carrier will be the same as that of the video carrier. This makes the level of perceptibility mostly dependent upon whether a split or an intercarrier sound detection scheme is used.

Split Sound

In a split sound system, the sound carrier is detected independently from the video, therefore demodulating all the noise on the sound carrier. The noise spectrum at the output of the detector, will have a parabolic spectral shape. After deemphasis, the noise spectrum is relatively constant at the low frequencies, falling off at the mid audio frequencies at approximately 20 dB per decade. This noise response is similar to pink noise which sounds like the rushing noise made by a running shower.

Intercarrier Sound

In the intercarrier sound demodulator, the phase noise spectrum is cancelled by mixing the sound carrier with the video carrier, both of which have the same phase noise modulation. Indeed, the singular advantage of the intercarrier process is the cancellation of frequency and phase modulations common to picture and sound carriers. The degree of cancellation will be reduced by processes that independently modify the phase or frequency modulations of each carrier.

Reduction of Intermodulation Benefits of Coherent Carriers

It was anticipated that the presence of phase noise would reduce the beneficial effects of HRC operation on the visibility of system intermodulation. The improvement factor results from "hiding" the carrier intermodulation products behind a given picture carrier by causing the distortion to be coherent with the carrier. To the extent that this coherency is modified by phase noise, it was expected that the subjective intermodulation improvement would be degraded. As with the other phase noise effects, this should appear as horizontally streaked low frequency noise.

Summary of Phase Noise Effects

When signals with phase noise are introduced to a cable system, the receivers exhibit perceptible video and sound degradation depending on the types of demodulation circuits employed in any particular receiver. The video and sound signals were presented separately because of the difference in modulation processes. Both envelope and synchronous video detectors, along with split and intercarrier sound detection schemes were considered with their perceptual appearances. Also, the problems of Nyquist residual FM to AM conversion and system triple beat reduction were covered. Now let's see the results of our testing.

TEST RESULTS

The video and audio tests were performed using a phase-locked modulator to produce controlled phase noise conditions. A synthesized signal generator provided the phaselock reference signal. The generator was frequency modulated by a continuously variable white noise signal. The noise level control was calibrated for root mean square FM noise deviation by using a modulation analyzer. The subjective test results are the average of 10 expert and non-expert viewers randomly selected from laboratory personnel.

System testing for intermodulation distortion and triple beat performance was done using a "typical" cascade of 17 trunk amplifiers, followed by one line extender amplifier. The cascade was loaded with 52 HRC phase-locked channels. Phase noise was added to the carriers of the channel selected for viewing. This was done by injecting the calibrated noise source directly into the phase-locked loop of the associated IF to channel converter. The program material on the channels not being viewed included both live video and a standard color bar pattern.

Video Test Results

As predicted, the two envelope detectors tested were the least sensitive to phase noise. A residual FM of 1565 Hz RMS was the average level of perceptibility for both envelope detectors tested. This corresponds to a demodulated signal to noise ratio of 36.7 dB, as calculated by the formulas presented.

A precision demodulator was used to perform the synchronous detector testing. It was operated in three different phase-locked loop sampling modes and with two loop bandwidths. The results presented below are the average for these different operating conditions. The synchronous detector displayed the same subjective noise characteristic as the envelope detector, but perceptibility occured at a lower residual FM level. Also, as suspected, the synchronous detector lost lock very quickly after the appearance of noise in the picture due to the failure of its phase-locked loop to remain stable. The results of the video tests are tabulated below.

Residual FM for Definitely Perceptible Noise

env. det. 1	env. det. 2	synchronous
1347 Hz RMS	1783 Hz RMS	306 Hz RMS

As we can see from the table, the envelope detectors can withstand the greatest amount of phase noise before the picture is perceptually degraded.

Sound Test Results

An audio output signal to noise ratio criterion of 50 dB was used as the basis for the phase noise analysis. The phase noise level required to produce this signal to noise ratio was found to be 126 Hz RMS and 1530 Hz RMS for split and intercarrier sound detection, respectively. This was done by modulating a 1 KHz tone onto a channel with phase noise added as previously done for the video test. The aural carrier deviation was set to 25 KHz peak, demodulated using a precision detector, and a reference set on an audio voltmeter. The 1 KHz tone was then removed and the signal to noise ratio measured. The noise modulation was increased until a 50 dB ratio was achieved. The residual FM noise level was then recorded.

Listening tests confirmed that the subjective quality is one of random noise predominated by low frequencies. The sound has a "rain falling on a drum" characteristic.

System Testing for Intermodulation Performance Reduction

After setting the amplifier cascade signal level at a point where the intermodulation distortion was not a factor, phase noise was added to give a definitely perceptible degradation in picture quality. The resulting FM noise deviation was measured at 876 Hz RMS. The cascade signal level was then increased until intermodulation distortion was just perceptible. The effect of the phase noise was seen to increase as a result of increasing the cascade signal level; however, no new types of degradation appeared. In order to reduce the picture degradation due to the phase noise back to the previous perceptibility, it was necessary to reduce the residual FM to 349 Hz RMS. This brings us to the conclusion that additional degradation does occur when phase noise interferes with the coherent carrier intermodulation process. Furthermore, this degradation is on the order of 60% of the tolerable phase noise with no intermodulation distortion.

SUMMARY AND CONCLUSIONS

The phenomenom of phase noise in synthesized headend equipment has been discussed and shown to be a problem if not properly attended to early in the design stage of such equipment. A brief overview of the phase-locked loop and the major contributors to phase noise within the loop have been presented.

Perceptibility tests were performed for a video color bar pattern and tests show that the envelope detector was most insensitive to phase noise for video. These tests illustrate that a residual noise related FM of 750 Hz RMS should be subjectively acceptable when receiver envelope detection is used.

Sound testing was performed for a 50 dB signal to noise ratio and showed, as expected, that the split sound detector was inferior to the intercarrier detector. Furthermore, the type of noise heard was listened to and described.

System cascade testing to determine the impact on intermodulation performance in an HRC situation was also performed. Although not specifically proven, our expectations of a reduction in coherent carrier system advantage were partially fulfilled by the apparent increase in the level of phase noise observed; the absence of new distortion products was not expected.

Since the data presented here represents only a limited number of tests, and was obtained from a limited number of viewers, the results must be taken as preliminary. However, these results can serve as a relative basis for the evaluation of synthesized headend equipment.

ACKNOWLEDGMENTS

The author is appreciative of G. J. Palladino, P.E. for his time, guidance and technical assistance in the preparation of this paper.

The author would also like to recognize William T. Homiller who has been generous with his advice in the testing and editing phases of this paper.

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