Cascading of Noise and Digital Compression Artifacts

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Abstract

Contrary to popular belief, digital systems are not perfect. This is especially true when like and unlike digital systems are concatenated with other digital and analog transmission systems. These systems add thermal noise, quantization noise and, in the case of compressed systems, compression artifacts. Several questions and mis-beliefs exist as to how these degradations combine on a subjective and objective basis.

This paper presents both objective and subjective results of:

- *cascading quantization noise from linear PCM systems;*
- *the effects of combining quantization noise and thermal noise, and*
- *the effects of combining, thermal noise and compression artifacts.*

The industry is proficient at thermal noise measurements today. Quantization noise measurements are also becoming more consistent through the use of shallow ramp measurements. Compressed signals, however, still offer several challenges. Certain test scenes may look fine on a particular codec, while other scenes may cause significant artifacts.

The analysis of the test results collected during the evaluation indicate that qunatization noise adds similarly to thermal noise both objectively and subjectively. It also indicates that certain compression artifacts contribute subjectively as noise additions. This paper presents these results and analyzes the relationship for cascaded thermal noise, quantization errors, and compression artifacts.

INTRODUCTION

Digital delivery schemes are becoming the backbone for broadband communications networks. Many of the new services are being distributed in a digital format. These services include telephony (voice), data, and video. Through some parts of the cable systems they are distributed in a purely digital form (baseband) using TDM technology, statistical multiplexing, or multiple access schemes. In the coaxial RF part of the network and in some parts of the optical network they are distributed using FDM technology (so-called analog systems). Actually, it is a combination of TDM, statistical multiplexing technologies for efficient channel use, multiple access schemes, some complex modulations schemes (FSK, QPSK, QPR, different levels of QAM or VSB, etc.), and FDM technology.

Any signal, including digitized video, on its way from the originating point to a customer is affected by the transmission media. The industry developed a set of measurements to define analog impairments and correlate these measurements with the subjective picture quality. This correlation is the result of many years of experience and extensive effort by analog video providers. These measurements have also been continuously re-defined as analog video has become more complex, and as the acceptance levels of our customers changed. The challenge for the industry is to evaluate the impact of the transmission medium impairments on digital video in a quantitative way and to find a correlation between the measurements and the subjective picture quality.

VIDEO EVALUATION MEASURES

Analog Measures in Analog World

Over the years, the motion picture and television industries developed a set of measurements for TV picture quality. These measures were correlated to picture distortions and categorized into several categories depending on the required fidelity of the video transmission. Several bodies developed these specifications and measurement techniques, but the most commonly known is one endorsed by EIA [3].

Subjective Measures

Unfortunately, these parameters use test signals that can be processed by most digital video systems without significant degradation. Nevertheless, the same digital system may still provide very distorted signals and inadequate picture quality for certain video content. This inconsistency is well covered in references, [1] and [5]. The only universal and conclusive method of evaluating picture quality is to perform subjective testing. Rigorous subjective test methods were developed by CCIR and are described in [4]. These tests are very expensive and time consuming but cannot be avoided until a set of objective parameters are correlated to the subjective tests results for digital transmission schemes.

In these days of evolving standards for video compression, the subjective tests were unavoidable. Many testing and standard organizations developed a set of "killer" test tapes to test all picture aspects that can be affected by known digital video compression systems.

Many end users cannot afford this type of test every time they want to assess the quality of a digital video system (codecs). To avoid the expense, they usually perform a set of objective tests supported by a subjective evaluation by a limited number of expert viewers for a limited time. This situation must improve, especially with the numerous digital systems available and already in use today.

Objective Measures

The industry has worked hard to develop a set of measures to test digital video quality. The purpose was obvious: to be able to test different digital coding/decoding systems, both compressed and non-compressed, without relying on expensive subjective test methods or being subject to the inaccuracy of simplified subjective tests. The literature on this subject is exhaustive. Two references [1]&[2] present a summary of the current status on objective measures of digital video quality. The following summarizes the measures presented in [2].

Objective parameters using artificial test signals

Similarly to the parameters listed in the EIA standard, these parameters are tested using test signals (artificial video signals — video test waveforms) produced by signal generators. The following parameters are measured:

- average gain and level offset (contrast, brightness, and color intensity distortions),
- amplitude frequency response (affecting resolution),
- active video area,
- active video shift.

Some of these distortions can be easily corrected by adjustments of the units (especially average gain and level offset).

Objective parameters using natural test scenes

The same set of "killer" test tapes used for subjective evaluation can be used for testing objective parameters of the codecs and transmission channels. The set of these parameters is presented in Table 1.

As can be seen from Table 1, many of the parameters quantify the increase in noise level, another estimate resolution degradation, and yet another quantify impairments specific to digital video. The hypothesis is that these subjective impairments that in the analog world cascaded with thermal noise will cascade with thermal noise in the digital world. Similarly, the impairment that in the analog world were masked by the noise (blurring, smearing) will be masked by the thermal noise in the digital world. As much as we would like to test this hypothesis in a formal and rigorous manner, our limited resources do not allow for that and we must leave it to the industry and standardization bodies. This paper presents initial results that support at least part of the hypothesis and were collected over several months during different codecs evaluation tests.

Table 1: Association of Objective Parameters and Impairments

	Objective Parameter	Impairments (as per ANSI T1.801.02)
1	Maximum added motion energy	error blocks, jerkiness, noise
2	Maximum lost motion energy	jerkiness
3	Average motion energy difference	jerkiness, noise, error blocks
4	Average lost motion energy with noise removed	jerkiness
5	Percent repeated frames	jerkiness
6	Maximum added edge energy	spatial edge noise, block distortion, tiling, noise
7	Maximum lost edge energy	blurring, smearing
8	Average edge energy difference	blurring, smearing, spatial edge noise, block distortion, tiling, noise
9	Maximum HV to non-HV edge energy difference	block distortion, tiling
10	Added edge energy frequencies	temporal edge noise, spatial edge noise, edge busyness
11	Maximum added spatial frequencies	spatial edge noise, block distortion, tiling, noise
12	Maximum lost spatial frequencies	blurring, smearing

TRANSMISSION CHANNEL IMPAIRMENTS

The parameters listed above (both for analog and digital video) are only part of the story. They do not include all impairments that can be contributed by the transmission medium, especially by RF coaxial network. The cable TV industry characterizes the network for such parameters as:

- thermal noise,
- phase noise,
- nonlinear products,
- level of ingress,
- level of echoes, and so on.

Through a meticulous effort, the industry set acceptance levels for these impairments. These levels are being updated from time to time when either a new technology evolves (for example, the switch from black & white to color picture required a new, redefined echo curve) or the acceptance level of our customers changes. From time to time, a new impairment is added to the list when industry becomes aware of it or the transmission technology introduces it. The impairments manifest themselves in a distinguished way in a picture and in many cases one type of impairment masks the other.

TEST RESULTS

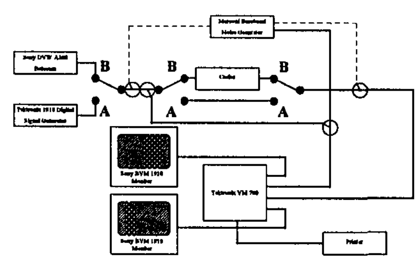
The test set-up diagrams are shown in Figures 1(a) and 1(b). The test set-up pictured in Figure 1(a) was used for most of the tests whereas the test set-up presented in Figure 1(b) was used to verify the results. The test set-up in Figure 1(b) closely resembles the real-life conditions. The test results indicated that both methods yield comparable outcomes. The tests were performed during the last 15 months and the test equipment used may have been different but it was always of equivalent quality and accuracy.

The objective (quantitative) tests were performed with an NTSC signal generator and VM 700, using standard test signals (shallow or full ramp and flat field for SNR result comparison).

The subjective tests were performed with a series of test tapes with the most often used moving and still patterns presented in Figure 2. These patterns were: Moving Zone Plate (Snell&Wilcox), Carousel, Flower Bed, and Still Zone Plate. The pictures were viewed by at least three expert viewers at good viewing conditions.

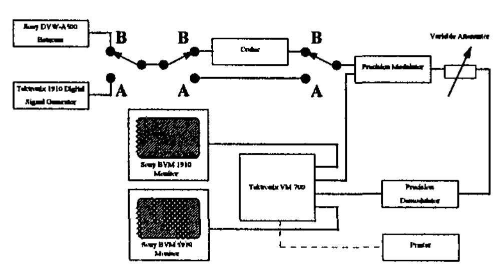
Figure 1: Test Set-Up

1(a) Noise Addition at Baseband



Note: Combiner symbols used to simplify the drawing. A VDA or loop through capabilities of the test equipment was used in actual test.

1(b) Noise Addition at RF



Quantization Noise and Thermal Noise

To separate the quantization noise from other impairments, including compression artifacts, linear PCM systems were used for this test. These systems deliver uncompressed digital video with the quantization noise defined by the resolution of sampling (number of bits per sample) and by additional digital processing of the signal. Systems from two different manufacturers were used. The resulting noise was measured objectively according to the industry standards for quantization noise and subjectively. The tests were performed over a period of four months in 1994 and 1995.

The detailed results are summarized in Tables 3 and 4. The results of the SNR test showed that the cascading of the quantization noise followed the standard power addition rule ($10 \bullet \log$) for a low number of cascaded units. The combined effect for four units was greater than defined by the formula. The thermal noise and quantization noise cascaded according to the rule.

An interesting subjective assessment was that the thermal noise added to the source (codecs input) resulted in higher subjective degradation than the thermal noise contributed by the transmission channel (added to the codecs output).

The test results show that the quantization noise of short cascades of codecs (most common case) adds on the $10 \bullet \log$ basis. The quantization noise and thermal (white) noise also cascade on $10 \bullet \log$ basis. Subjective tests confirm the objective results.

Table 3: Cascading of Quantization Noise

Linear PCM Unit	Measured SNR (Ramp) in dB (unified weighting)	Calculated SNR (Ramp) in dB
#1	59.4	NA
#2	60.2	NA
#3	59.9	NA
#4	60.3	NA
#1&#2	57.2	56.8
#3&#4	55.3	57.1
#1, #2, #3, & #4	52.1&51.4	53.9
#1, #2, #3, & #4 (51.4) plus thermal noise (51.8) on input	48.9	48.6
#1, #2, #3, & #4 (51.4) plus thermal noise (51.8) on output	48.9	48.6
#6	63.2	NA
#6 plus thermal noise (50.3)	50.1	50.1
#7	68.1	NA
#7 plus thermal noise (50.3)	50.1	50.2

Table 4: Subjective Evaluation of Cascading Effect

Linear PCM Unit	Measured SNR (Ramp) in dB (unified weighting)	Subjective SNR (Ramp) in dB
#1	59.2	56.9[1]
#1, #2, #3, & #4	51.7	52.7

Artifacts and Thermal Noise

Similar testing was performed for a series of codecs with compression. The units were from two different manufacturers and employed different intra-frame compression algorithms. The codecs did not employ any inter-frame compression algorithm. Codecs with two levels of compression were used for testing:

- single-channel DS3 codecs, and
- dual-channel DS3 codecs.

The test results are summarized in Tables 5 and 6. The results clearly indicate a cascading effect of thermal noise and the type of the artifacts that were perceived as noise (increased busyness of the picture with noise-like pattern).

NEXT STEPS FOR INDUSTRY

The test equipment industry is working on development of a test set to measure the parameters presented in [2]. We, as the industry that will have to characterize the digital transmission media must challenge the test equipment manufacturers to make these test sets affordable.

Correlation with standards

The standard organizations with our support should correlate the objective measures with the subjective results. Some of the organizations and vendors reported in [5] a correlation factor ranging from 84% to 95%. If the upper correlation factor could be achieved consistently, the industry would be able to perform objective testing with an affordable test equipment without relying on expensive subjective testing. The subjective testing would have to be repeated to achieve new correlation figures when a new technology is introduced or customer expectations change.

Limits

When the correlation is known, we can set impairment limits (parameter values) to define several categories of service at different quality levels, much the same as EIA standard [8] defines it now.

Common Standards

The authors, while reviewing document [2], noticed that many if not all of the parameters listed there (see Table 1) accommodate subjective measures of the picture quality. Moreover, their nature does not seem to be digital-specific. A natural question arises whether these parameters can be used to characterize any video quality whether digital or analog. A positive answer to this question would bring about a uniform standard of evaluating video quality instead having two

[1] The difference due to the difficulty of subjective assessment of high SNRs.

separate standards, one for analog video and one for digital video. This would make the testing process and test equipment independent of the transmission technology.

CONCLUSIONS

Several conclusions become clear. The first is that quantization noise in cascaded linear PCM systems (encode/decode) adds objectively quite close to way the thermal noise does. In short cascades it added exactly on a 10•log basis. For longer cascades noise added on a slightly higher than 10•log basis. The quantization noise that predominated the noise created by these systems presented similar subjective disturbances as thermal noise.

Quantization noise cascaded with thermal noise on a 10•log basis both objectively and subjectively. When the source video had thermal noise added prior to digitization, the addition effects were much worse and unpredictable.

Several compression artifacts, especially those that appear as high frequency busyness, also add subjectively to thermal noise in much the same way as thermal noise does. These artifacts are difficult to measure objectively. Also, these disturbances are often not specified and even when they are, they are typically not calculated into the overall noise budget.

All noise sources must be considered when planning network architecture. Historically these noise sources have been primarily limited to thermal noise, but today they come from a variety of analog and digital sources, all of which accumulate and all of which must be considered in your end to end performance budgets.

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[2] ANSI T1.801.0x-yyyy, "Digital Transport of One-Way Video Signals - Parameters for Objective Performance Assessment" (Draft).

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[4] CCIR Recommendation 500, "Method for the Subjective Assessment of the Quality of Television Pictures", 1990.

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[6] T1Q1.5 Technical Report No. 16, "A Technical Report on DS3 Transport for Contribution Application of System M-NTSC Television Signals Analog Interface and Performance Objectives", November 1992.

[7] Tony E. Werner, "Regional and Metropolitan Hub Architecture Considerations", SCTE 1995 Conference on Emerging Technologies.

Table 5: Cascading of Compression Artifacts and Thermal Noise

Codecs	Test Pattern	Measured SNR (Ramp) in dB (unified weighting)	Subjective SNR in dB	Thermal Noise Level	Measured Cascaded	Subjective Cascaded (measured)	Subjective Cascaded (calculated)
#1	Several patterns	60.8	57.5, 60.7, & 62.3	NA	NA	NA	
#1	Snell & Wilcox	60.4	52.9	NA	NA	NA	
#2	Snell & Wilcox	58.5	51.4	49.1	48.7	46-48	47.1

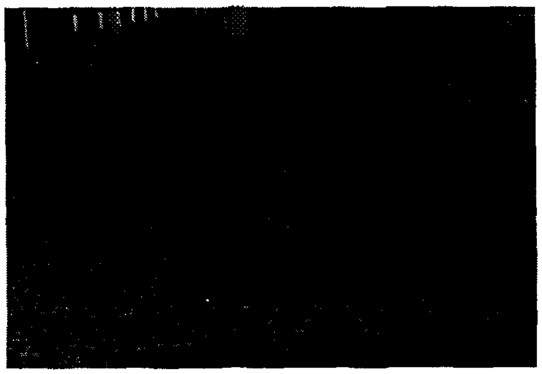
Table 6: Cascading of Compression Artifacts and Thermal Noise

Thermal Noise Level (SNR *unified weighting) in dB*	Codecs #3 (SNR at 59.3 dB, unified weighting)		Codecs #4 (SNR at 62.4 dB, unified weighting)	
	Test Pattern		Test Pattern	
	Zone Plate	Flower Bed	Zone Plate	Flower Bed
Subjective Assessment of SNR in dB	41.7	48.3	61	59.3
62	no degradation		clearly noticeable degradation (≅3 dB)	noticeable degradation
59	no degradation		significant degradation	clearly noticeable degradation (≅3 dB)
56	no degradation	barely perceptible degradation	thermal noise dominates	significant degradation
53	barely perceptible degradation	perceptible degradation		thermal noise dominates
50	perceptible degradation	noticeable degradation		
47	noticeable degradation	clearly noticeable degradation (≅3 dB)		
44	noticeable degradation	significant degradation		
41	clearly noticeable degradation (≅3 dB)	thermal noise dominates		

Figure 2: Test Patterns and Scenes

a) **Carousel**

b) **Flower Bed**



c) **Moving Zone Plate (Snell&Wilcox)**

d) **Still Zone Plate**