Tektronix

Technical Brief

Signal to Noise Relationships In 8-VSB

This technical brief describes the effect various transmitter impairments have on the output signal's Signal to Noise ratio (S/N) in 8-VSB DTV transmission. These effects were determined by generating a large number of 8-VSB signals, each with a single impairment. After generation, each signal was measured with an 8-VSB measurement test set to determine its S/N ratio and, in the case of non-linear impairments, to determine the amplitude of the spectral regrowth at the channel edge (e.g., the "shoulder" amplitude).

The definition of S/N is given, followed by a brief description of the methodology used, including descriptions of the laboratory generator, the 8-VSB measurement test set, the mathematical models used to generate the impairments, and graphical presentation of the results. While the impairment models used are only approximations, being based on various polynomial curvatures (e.g., linear, square law, etc.), in most cases, the results group themselves together closely enough to be able to draw conclusions about the relationship between the impairment and the resulting S/N degradation from that cause. It has been found that the various S/N impairments are relatively un-correlated. This allows a straight-forward process of budgeting various transmitter impairments to yield a predetermined S/N performance. An example budget is given for a 27 dB S/N source.

I. Introduction

In digital television (DTV) transmission, all that counts is the value of each symbol. If successfully decoded at the receiver, a series of correct symbol values will create a perfect result, resulting in a happy viewer. (Keeping emissions within the mask specified by the FCC is also important! This is discussed below.) Signal to Noise or S/N is an all-in-one measurement of the difficulty the receiver will encounter. Because of the extensive forward error correction within the 8-VSB broadcast signal, a small number of symbol errors per second are allowed. As the number of errors increases, at some point the ability of the forward error correction to make corrections will suddenly fail and the picture is lost. The difference between a perfect picture and no picture at all is about 1 dB of S/N. This is the so-called "cliff" effect.

Noise is defined as anything that degrades or impairs the signal, including distortion products, inter-symbol interference caused by frequency response or group delay errors, or ordinary white noise. Receivers located in the deep fringe where signal amplitude causes S/N to be marginal may find that the noise from transmitter impairments cause the signal to fall below threshold. That is, poor adjustment of the transmitter, resulting in a marginal decrease in S/N, can result in coverage loss.

Determining exactly what value of transmitted S/N is sufficient is a difficult problem, and is beyond the scope of this technical brief. One industry source indicates that a transmitted S/N of 27 dB is sufficient to prevent excessive loss of signal coverage [REF 1]. There is a possibility that research in this area may determine that some forms of transmitter impairments are more important than others. For this technical brief, all impairments will be considered equally important.

Definition

Signal-to-noise in an 8-VSB system is defined as the average power of ideal symbol values divided by the noise power; that is, the difference between the ideal signal and the actual signal as demodulated along the real axis. One industry authority says S/N is "the ratio of ideal signal to everything else" [REF 2]. Or:

$$S/N = 20\log\left[\frac{\sqrt{\frac{1}{N}\sum_{j=1}^{N} I_j^2}}{\sqrt{\frac{1}{N}\sum_{j=1}^{N} \delta I_j^2}}\right]\text{dB}$$

where:

I_j is the ideal in-phase or real axis (i.e., aligned with the pilot signal) symbol value transmitted at the jth interval, (I_j is taken as the signal without the offset used to insert the pilot signal).

δI_j is the difference along the real axis between the ideal signal value and the value actually received in the jth interval.[1]

It is beyond the scope of this technical brief to describe the 8-VSB signal at length [REF 3]. The ideal value, I_j, is determined by slicing the data along the real axis as defined by the pilot signal. Once found, the noise component can then be calculated by subtracting the ideal symbol value from the actual value as received. S/N is identical to Modulus Error Ratio (MER) except it is restricted to measurement along the real axis.

S/N is also closely related to Error Vector Magnitude (EVM) which, for 8-VSB, is defined as:

$$EVM = \left[\frac{\sqrt{\frac{1}{N}\sum_{j=1}^{N}(\delta I_j^2 + \delta Q_j^2)}}{\sqrt{I_{max}^2}}\right]100\%$$

where:

δI_j and δQ_j are the differences along the real and the quadrature axis, respectively, between the ideal signal value and the value actually received in the jth interval. (It should be noted that $\sqrt{\delta I_j^2 + \delta Q_j^2}$ is the magnitude of a vector drawn from the ideal signal value to the actual signal value; thus the name Error Vector Magnitude.)

I_{max} is the magnitude of the distance along the real axis to the outermost state of the constellation. (I_{max} is taken as the signal without the offset used to insert the pilot signal.)

Both quantities are measures of signal quality often used in quantifying digital RF transmission errors. Because each defines the error signal in a different way, it is not possible to write a rigorous definition of the relationship between them. As an approximation, it can be assumed that summed over the record length, the quadrature-squared error is equal to the real-axis-squared error:

$$\text{Signal}_{S/N} = \sqrt{\frac{1}{N}\sum_{j=1}^{N} I_j^2} =$$

$$\sqrt{\frac{1}{8}\quad(2(7^2 + 5^2 + 3^2 + 1^2))}$$

$$\text{Signal}_{S/N} = \sqrt{21}$$

In the EVM definition, the signal term is defined as:

$$\text{Signal}_{EVM} = \sqrt{S_{max}} = \sqrt{49} = 7$$

Assuming that:

$$\sum_{j=1}^{N}(\delta I_j^2 + \delta Q_j^2) \approx 2\sum_{j=1}^{N}(\delta I_j^2)$$

And using the signal relationships above, EVM can be expressed in terms of S/N as:

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1 Clearly the 1/N terms in the numerator and denominator cancel. Their presence facilitates the comparison between S/N and EVM in the discussion that follows.

$$EVM \approx \left[10^{\frac{39.3 - S/N\ (dB)}{20}}\right]\%$$

And S/N can be expressed in terms of EVM as:

$$S/N \approx 39.3 - 20\log[EVM(\%)]dB$$

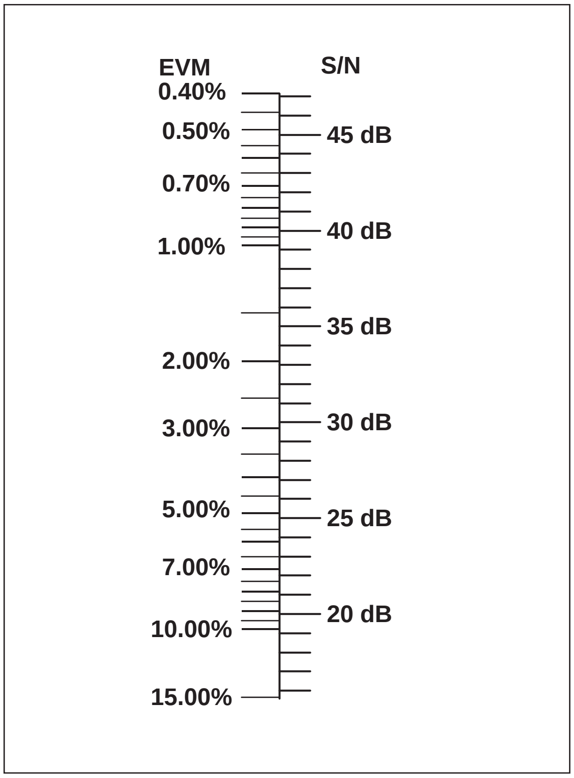

Figure 1. Relationship Between EVM and S/N.

These relationships are shown graphically in Figure 1.

Sources of S/N

There are seven known causes, or impairments, that cause S/N reduction in 8-VSB signal sources. They group into three broad categories:

Linear Errors:

- **Frequency Response Error:** A magnitude response that differs from the correct root-raised cosine frequency response [REF 4].
- **Group Delay Error:** A group delay characteristic that differs from flat or zero across the TV channel.

Nonlinear Errors:

- **Amplitude Error:** Caused by amplifier gain variation as a function of signal amplitude. Sometimes called AM/AM conversion.
- **Phase Error:** Phase variations as a function of signal amplitude. Sometimes called AM/PM. Known as ICPM in analog TV transmitters.

Miscellaneous Errors:

- **Phase Noise**: Excessive random variation of the carrier's phase.
- **Broadband Noise:** Introduction of excessive wideband or white noise into the 8-VSB signal.
- **Software or DSP Noise:** Noise that is introduced if an insufficient number of bits of precision are used or if not enough of the effects of previous and following symbols are included in the calculation of the data

Of these, the linear and nonlinear will be effected by the adjustment of the 8-VSB source. The miscellaneous errors are typically pre-determined by the system design of the equipment. Most of the sources of S/N impairment act independently of each other; that is, the noise power caused by each source may be added directly to determine the total noise present. In principle, the noise power caused by frequency response errors and group delay errors can interact. If they do, their noise power cannot be directly added. In practice, this effect is rela-

II. Methodology

Signal Generation

A precision signal source suitable for the generation of laboratory quality 8-VSB signals was constructed. Its simplified block diagram is shown in Figure 2.

The signal, several 8-VSB segments in length, is pre-computed and placed in RAM. The RAM is configured to endlessly loop through the signal, replaying it over and over. If the signal is carefully constructed, there will be no transient or “bump” as the loop ends and the data flow starts reading from the top again.

After passing through the Digital to Analog (D/A) converters, the now-analog signal passes through a reconstruction filter. Note that instead of using baseband signals as is common, the signal at point A is already a modulated IF signal with a pilot frequency of 10.76 MHz. The signal at B is the Hilbert transform of the signal at A. When the two signals are up-converted to RF using quadrature mixing and summed together, the result is a single sideband up-conversion. That is, there is only one DTV signal present at the output, and it has a pilot frequency of 10.76 MHz plus the frequency of the Up-Conversion local oscillator.

This method of signal generation was used to create laboratory quality signals suitable for designing test equipment. Simulation of the effects of impairments to establish system requirements, combined with careful measurement of the generator with general purpose test equipment to establish that the requirements were met, leads us to believe that the inherent S/N limit of this generator is in excess of 43 dB. This belief was confirmed with the experience of building the measurement receiver described in the next section and making highly correlated measurements of the generator.

Signal Measurement

A very simplified block diagram of an 8-VSB measurement test set, suitable for precision measurements of a broadcast transmitter, is shown in Figure 3. Only the portion that performs the demodulation function is shown. Not shown are all of the AGC and frequency control functions plus another, narrowband, channel that is used to make spectral response measurements.

The block diagram of this instrument was chosen to provide all of the functions necessary to qualify and maintain a broadcast transmitter. At the same time, it inherently provides very accurate measurements of the RF signal’s characteristics because minimal compensation and correction are required for its own impairments. All the measurements below were made by this receiver.

Creation of Test Signals

The test signal is created for the precision source by pre-computing an appropriate sequence of values. To create a signal that does not contain a transient at the point where the loop-back occurs takes special care. There first must be an integer number of pilot signal cycles, of symbols, and of segment sync intervals in each file. Further, the contributions from 80 symbols on either side of the instant being computed must be included in the calculation to insure a minimal software impairment to S/N. This requires carefully “wrapping” the ends of the file so that the file’s beginning experiences the effects of the file’s end and that the end is effected by the beginning.

The files for the precision source typically consist of random data, five segment sync periods in length modulated into the 8-VSB format. Segment sync is then inserted every 832 symbols. Data field sync was not inserted.

Starting with an ideal signal, various impairments were

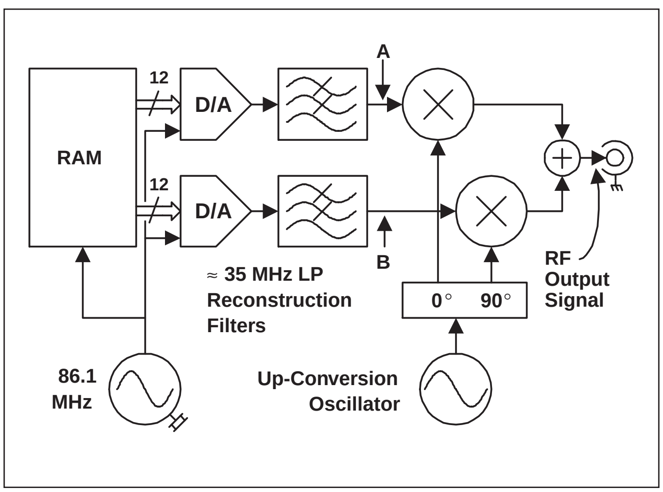

Figure 2. Simplified block diagram of precision 8-VSB source.

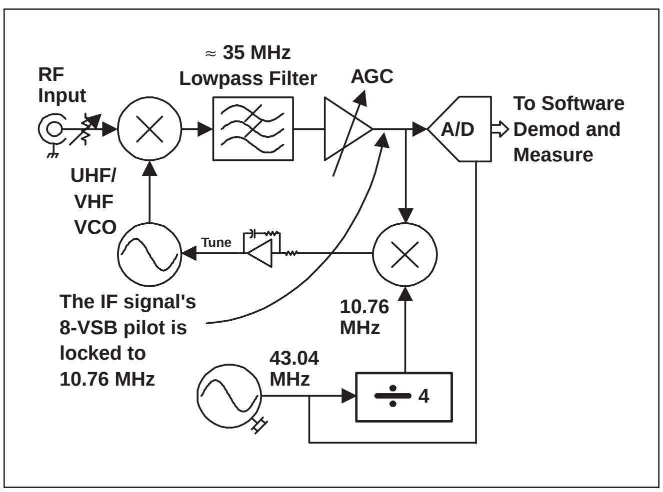

Figure 3. Very simplified block diagram of a 8-VSB measurement test set.

generated and inserted to develop the curves for frequency response error, group delay error, amplitude error and phase error given below. Direct phase modulation of the precision 8-VSB source's up-conversion oscillator with a shaped spectrum was used to determine the relationship of phase noise on S/N.

Frequency Response Error

Frequency Response Error is a frequency domain function. It is the difference between the spectral response of an ideal 8-VSB signal and that of the actual signal. The two types of unflatness errors modeled are shown in Figure 4. The linear model is a ramp function, across the TV channel, similar to what could be encountered in a broadband source. The square-law model approximates the crowned response one could encounter at the output of a transmitter's extra bandpass or channel filter typically used to help meet the FCC's emissions mask. Multiple versions of each type were generated, varying only in the number of dB_{p-p} of unflatness.

Note that frequency response error is a so-called linear function. That is, it does not cause intermodulation or spectral regrowth; e.g., it is not a source of-out-of-channel emissions.

The measured S/N as a function of frequency response error for the two different types of response errors are shown in Figure 5.

It appears that the S/N resulting from a relatively simple frequency response error can be estimated from its peak-to-peak in-channel variation. They lie closely together on the graph. The hatched band is an appropriate approximation of translating an amplitude error expressed in a peak-to-peak reading to a S/N value given that real sources will differ with the textbook approach used here.

Group Delay Error

Group delay error is also a frequency domain function. In this case, the ideal curve is a constant or flat response across the channel. Group delay can be thought of as the delay that a given portion of the spectrum experiences. Mathematically, group delay is:

$$\tau(f) = \frac{1}{360} * \frac{d\Phi°}{df} - T_0$$

where:

- $\tau(f)$ is the delay at frequency f.
- $\Phi°$ is the phase shift experienced by the signal in degrees
- f is in Hz.
- T_0 is the group delay offset constant. Typically taken as the absolute group delay value at either the channel center or the pilot frequency.

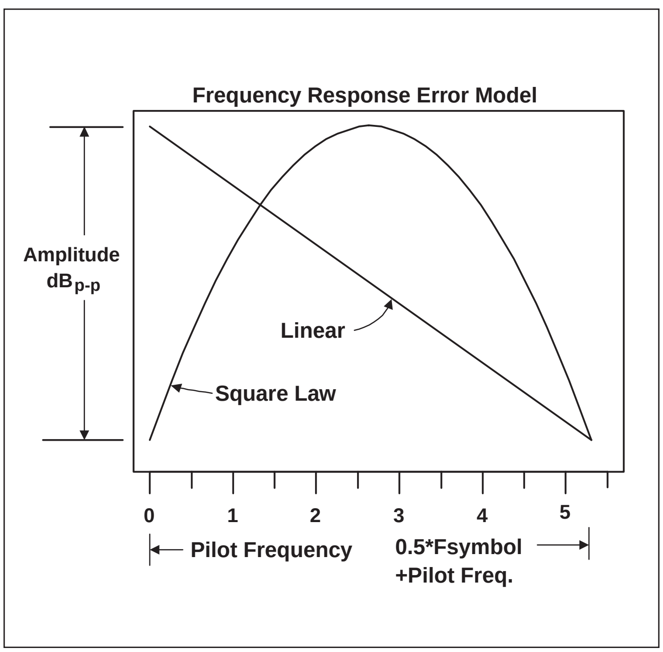

Figure 4. Flatness error models.

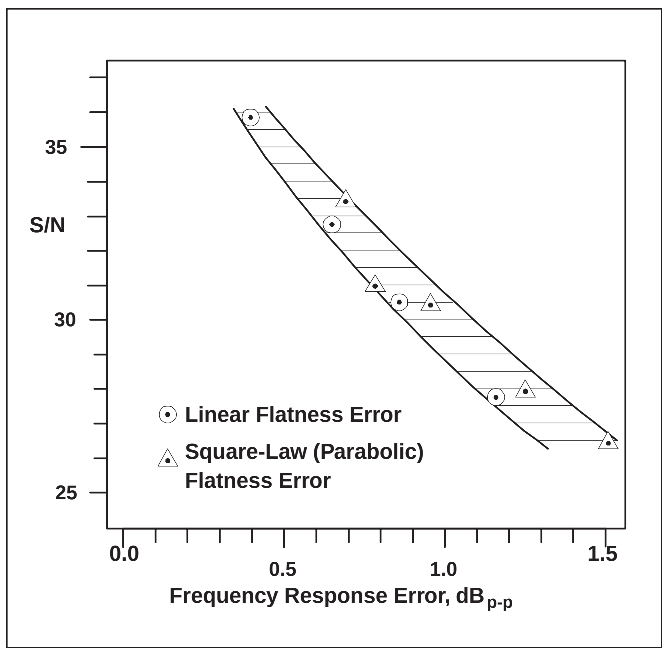

Figure 5. Measured S/N vs Frequency Response Error.

The group delay models are shown in Figure 6. Again, a simple ramp and a simple parabolic function were used. The ramp is an approximation of a mis-tuned broadband network and the parabolic function is approximately the shape that would be encountered when the signal is passed through a bandpass filter.

The resulting S/N vs peak-to-peak group delay curves are shown in Figure 7. Here, the type of group delay curve makes a large difference. The author's previous experience in simulating 8-VSB characteristics indicates that as the group delay curve becomes more complicated with high order curvature or ripple, more peak-to-peak delay variation can be tolerated for a given S/N. Therefore, it is difficult to establish a relationship between group delay and S/N if the shape of the curve is unknown.

Amplitude Error

Amplitude error can be visualized as gain change as a function of instantaneous variations in the signal's magnitude as shown in Figure 8. It is sometimes called AM to AM conversion. The models used assume that the 8-VSB source is essentially linear but experiences small negative gain changes with increasing signal magnitude with a second- or third-order curvature. The instantaneous gain variations as a function of signal magnitude are applied to the precision source's IF signal and then up-converted to the carrier frequency. Constellation Units (CU) and Magnitude are explained in Appendix A.

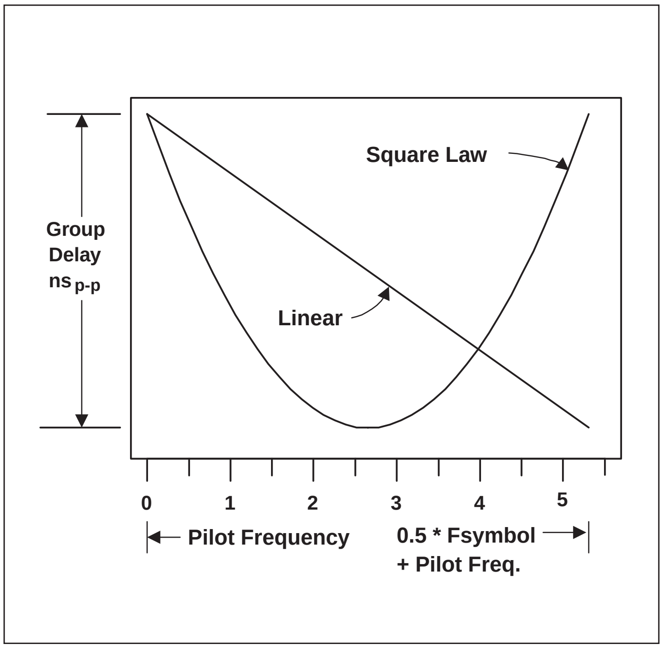

Figure 6. Group delay models.

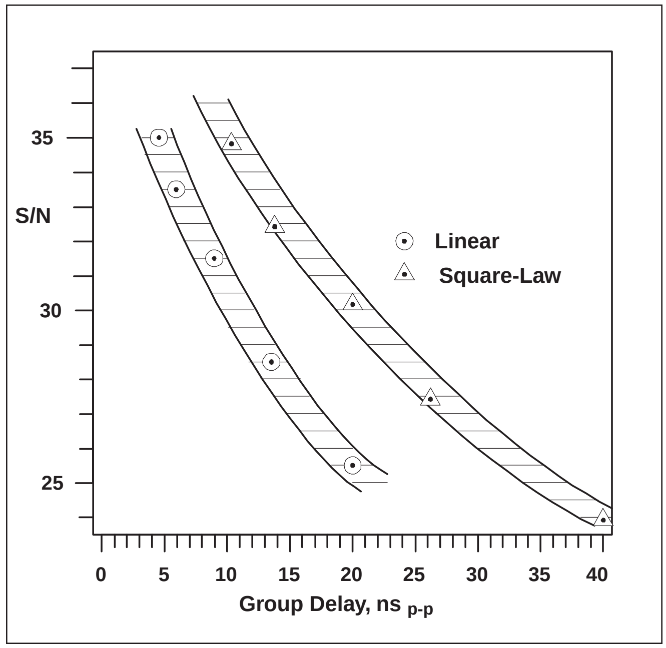

Figure 7. Measured S/N as a function of group-delay error.

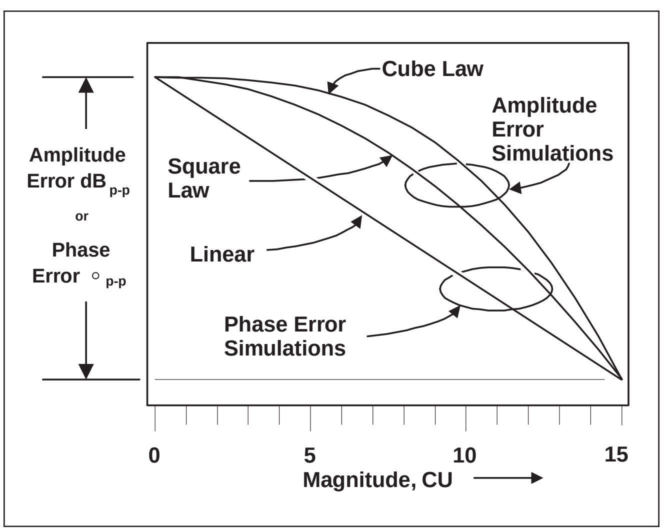

Figure 8. Amplitude and phase error models.

The measured results are shown in Figure 9. To a good approximation, the S/N impairment caused by amplitude error is dependent only upon the peak-to-peak gain variation and not the type of curvature.

Amplitude error is a nonlinear process which causes intermodulation terms that fall outside the assigned channel; sometimes called spectral regrowth. Therefore, Figure 10 answers a second, very important question about the relationship between the amplitude of the spectral regrowth vs the S/N impairment caused by amplitude nonlinearity. Definition of shoulder amplitude is given in Appendix B. This effect is discussed further in ***Combined Errors*** below.

Phase Error

A second type of nonlinear behavior is called phase error. This is phase variation imparted on a signal passing through a system as a function of the signal's magnitude. This is also called AM to PM conversion or, in the case of analog TV transmitters, ICPM. The models used for this simulation are also shown in Figure 8. They are similar to the amplitude error model used above.

The resulting relationship between S/N and phase error is shown in Figure 11. The two different curvatures cause approximately the same S/N degradation. Again, because this is a nonlinear process, the second issue is the relationship between S/N and shoulder amplitude. This is shown in Figure 12.

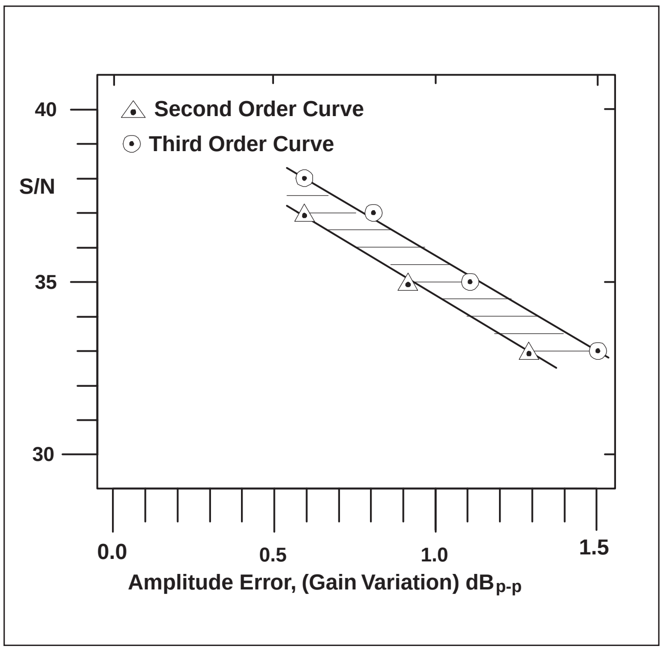

Figure 9. S/N impairment caused by amplitude error.

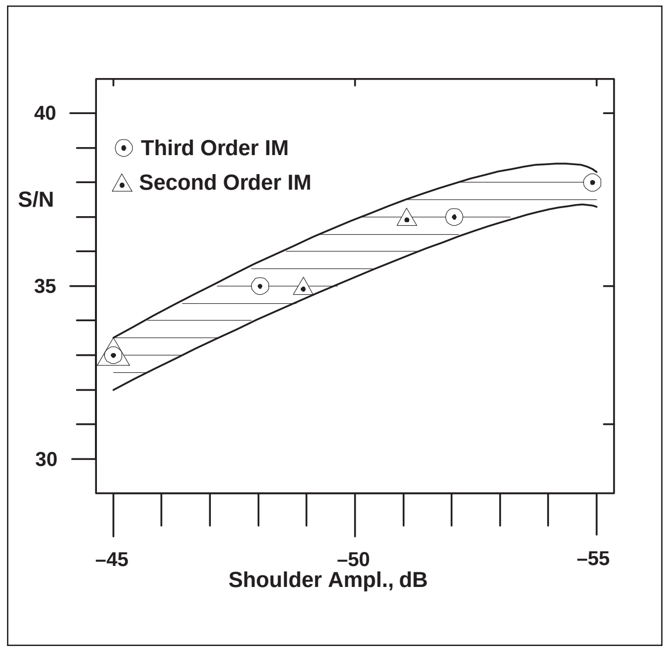

Figure 10. Shoulder amplitude caused by amplitude error.

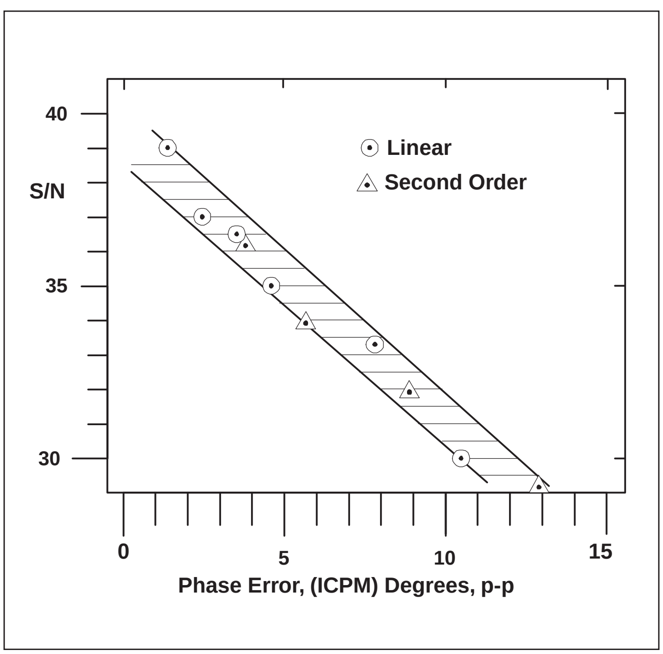

Figure 11. S/N vs phase error.

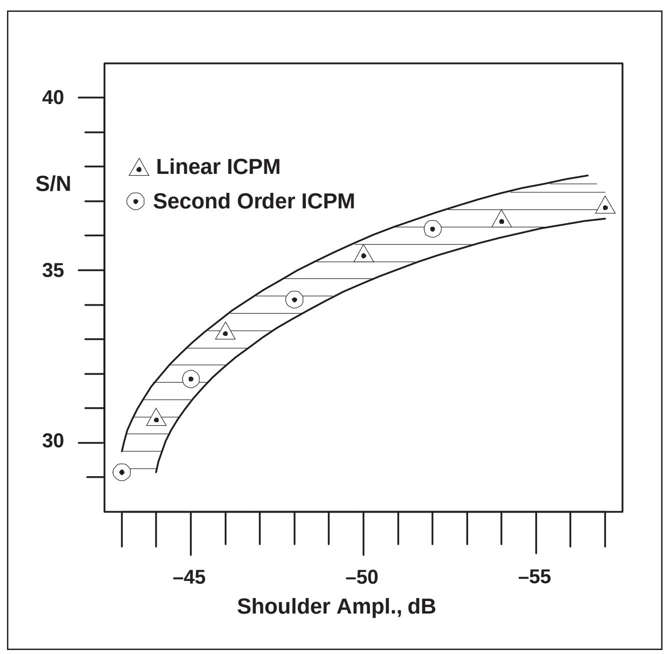

Figure 12. Shoulder amplitude vs s/n caused by phase error.

Phase Noise

Simulation and measurements have determined that the effect of phase noise on the S/N as measured at the receiver is primarily determined not by its amplitude at any given offset from the carrier but by the integral of the carrier's phase jitter. That is, the carrier's phase jitter integrated from the cutoff frequency of the receiver's pilot tracking loop to some high frequency. There is very little information available about what tracking bandwidths will be used in 8-VSB receivers. Virtually the only data point available is the 2 kHz value given in the ATSC documents [REF 5]; therefore this value was used in the design of the test receiver. In UHF sources, the spectral shape of the jitter is such that low-frequency effects dominate. Therefore, the upper frequency bound of the integral is relatively immaterial and was arbitrarily set at 300 kHz.

To make sure that any effects caused by the measurement receiver's tracking loop do not effect the result, it's necessary for the testing waveform to have noise-like components to frequencies well below 2 kHz. Given the 86 MHz clock frequency of the D/A converter, this requires very long record lengths which were beyond the scope of the simple computational engine used for this project.

Instead, a shaped audio noise spectrum was used to phase modulate the generator's up-conversion oscillator. The generator had the spectral shape shown in Figure 13. This shape is similar to many RF sources in this frequency range. The overall amplitude of this signal was varied to produce the information shown in Figure 14.

Combined Errors

As was mentioned above, simulation and experiment indicate that, at least to a good approximation, the various sources of S/N impairments do not interact with each other; they add like noise power. That is:

$$S/N_{Total} = -10\log\left[10^{-\frac{S/N_a}{10}} + 10^{-\frac{S/N_b}{10}} + 10^{-\frac{S/N_c}{10}} + \ldots\right]$$

As mentioned above, the two requirements for an operational transmitter are that the transmitted S/N ≥ 27 dB and that the transmitter stay within its emissions mask (see the Appendix for details of the mask). The mask allows a shoulder 500 kHz wide to extend into the adjacent channel at the –47 dB_{FCC2} level. From there, the mask slopes sharply down to a –110 dB_{FCC} value at the far edge of the adjacent channel, 6 MHz from the channel edge.

This narrow emissions requirement is thought to be beyond the ability of today's transmitters. This means that a bandpass filter, sometimes called a channel filter is typically required between the transmitter and its antenna to remove the unwanted out-of-channel emissions. However, to obtain reasonable in-channel response, this filter must have a bandwidth that substantially includes the entire channel. This leaves the close-in emissions largely unattenuated. Therefore, the transmitter's power amplifier must be operated in such a way that the total shoulder amplitude caused by non--linear distortions must be at

2 DB_{FCC} is an invented term, taken here to mean dB on the FCC's out-of-channel emissions scales as shown in Appendix C.

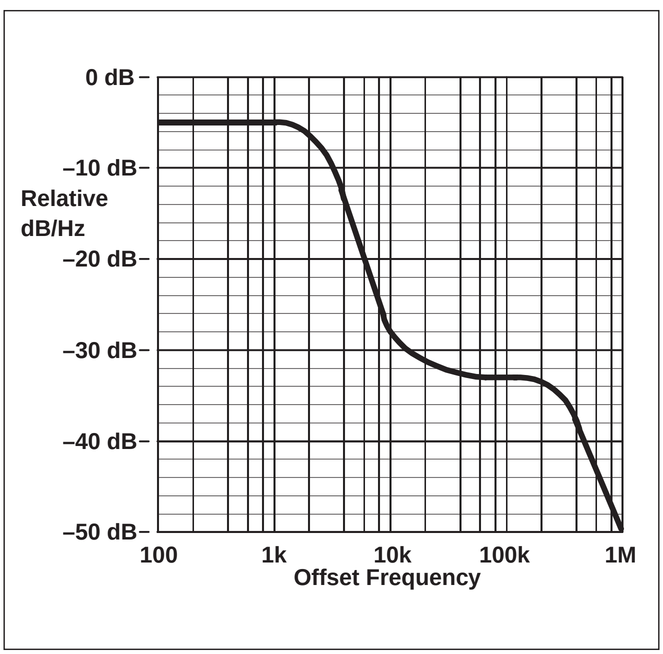

Figure 13. Phase noise spectral model.

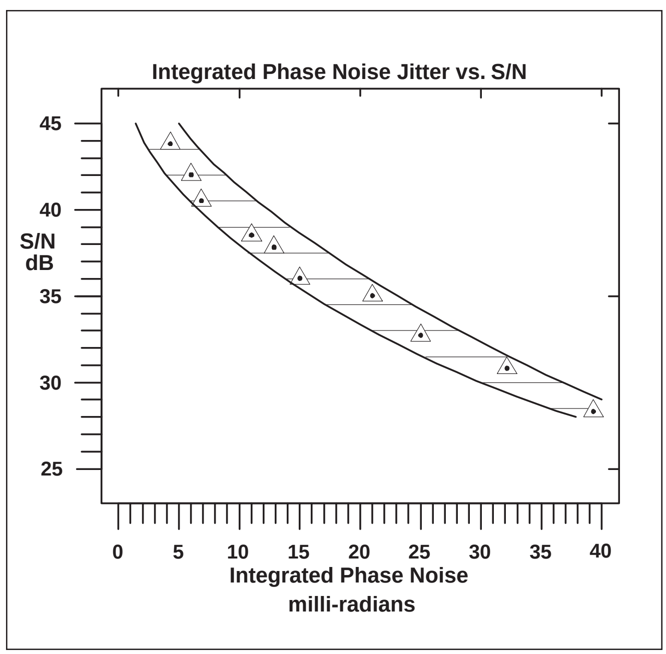

Figure 14. S/N as a function of integrated phase jitter.

Table 1

S/N Impairment Cause	S/N Impairment	Specification
Amplitude Unflatness	32 dB	0.7 dB p-p
Group Delay	32 dB	10 nS p-p
Phase Noise	40 dB	10 milli-radians
Amplitude Error	36 dB	0.7 dB p-p, 50 dB shoulder
Phase Error	35 dB	6.5° p-p, 50 dB shoulder
Broad-Band Noise	60 dB	
Software Noise	50 dB	
Total S/N	27.1 dB	
Total Shoulder Amplitude		–47 dB

least –47 dB_{FCC}. This fact provides a starting place to apportion the S/N impairments.

One version of a budget leading to an overall S/N of 27 dB is shown in Table 1.

A waveform with this set of impairments was synthesized (excluding software and broadband noise) and measured as having a 29 dB S/N with –49 dB shoulders. The 2 dB difference in S/N and shoulder amplitude are ascribed to small interactions between the different impairments that are not included in the calculation process and to the uncertainty in the measurement process. (Including the software and broadband noise would only account for 0.04 dB of the difference.) The default measurement masks in the measurement receiver were selected using this budget of S/N impairments.

III. Conclusions

Measurements have determined the relationship between cause and measured S/N impairment for five of the seven sources in 8-VSB systems. It is found that once the source's nonlinear behavior is controlled enough to meet the FCC's emissions mask requirements, the S/N impairment from these sources are not the dominant issue in achieving a 27 dB overall S/N. With good design, the rest of the specifications should be reasonably easy to meet. Note that the linear amplitude unflatness and group delay errors can be very easily removed by some form of closed-loop correction.

References

Reference 1. Advanced Television Systems Committee, ***ATSC Digital Television Transmission Measurement and Compliance, (Document T3/272)***, August 27, 1997.

Reference 2. Gary Sgrignoli, ***VSB Tutorial***, Zenith Electronics Corporation. Tutorial presented by Mr. Sgrignoli at Tektronix, Inc., November 12, 1997.

Reference 3. Advanced Television Systems Committee, ***ATSC Digital Television Standard, (Document A/53)***, Advanced Televisions Systems Committee, James C. McKinney, Chairman, Sept. 16, 1995.

Reference 4. Advanced Television Systems Committee, ***Guide To The Use Of The ATSC Digital Television Standard, (Document A/54)***, Advanced Televisions Systems Committee, James C. McKinney, Chairman, October 4, 1995.

Reference 5. Advanced Television Systems Committee, ***ibid., (A/53)***, page 48.

Advanced Television Systems Committee, ***ibid., (A/54)***, page 107.

Reference 6. FCC Regulation 947CFR73.622(h).

Acknowledgement

Many thanks to John Cousins for making the difficult and onerous phase-noise measurements.

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Appendices

Appendix A. Constellation Units and Signal Magnitude

Figure 15 shows the idealized constellation of an 8-VSB signal (i.e., the signal has passed through the transmitter's and the receiver's raised-root-cos filter). The data falls into one of eight states along the real axis. Data may fall at any point along the imaginary axis. The unit of measurement used here to describe the positions of the constellation lines is the constellation unit or CU. Each of the states is separated by 2 CU. As transmitted, the baseband constellation of –7 CU to +7 CU is offset by 1.25 CU to create the constellation pattern shown in Figure 15. The magnitude of the Nth sample is the distance from the origin to that sample as measured in CU.

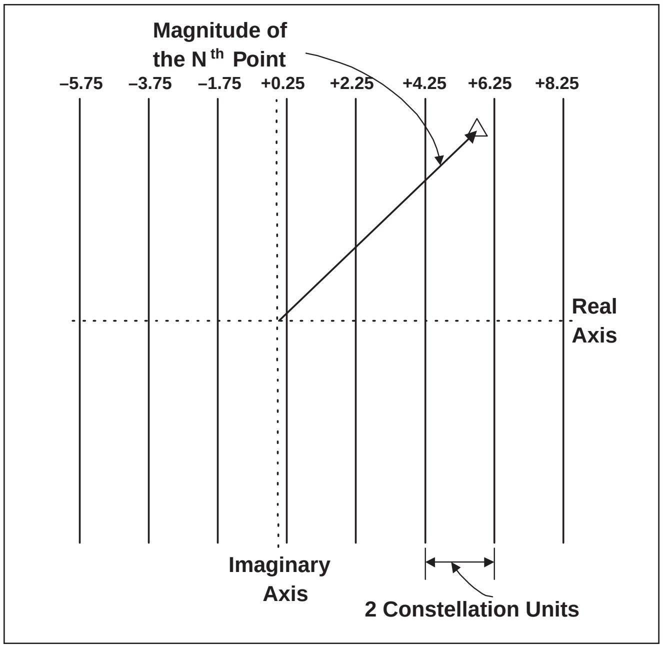

Figure 15. 8-VSB constellation with illustration of Signal magnitude.

Appendix B. Spectral Regrowth and Shoulder Amplitude

Figure 16 shows the relationship between the spectrum of the 8-VSB in-channel transmission and the out-of-channel spectral response caused by amplitude error (i.e., AM to AM) or phase error (i.e., AM to PM or ICPM). This effect is sometimes called spectral regrowth. Shoulder Amplitude, as used in this technical brief, is the difference between the amplitude of the spectral regrowth spectrum at the channel's edge and the total power of the 8-VSB source. Note that the measurement is made in a 500 kHz bandwidth (i.e., the same as used in the FCC definition). Since the signal is noise-like, the 500 kHz bandwidth measurement shows the in-channel amplitude 10.6 dB below the line representing the total power of the 8-VSB source.

Appendix C. FCC Mask

The Emission mask required by the FCC [REF 6] is shown in Figure 17. All emissions must be below the mask.

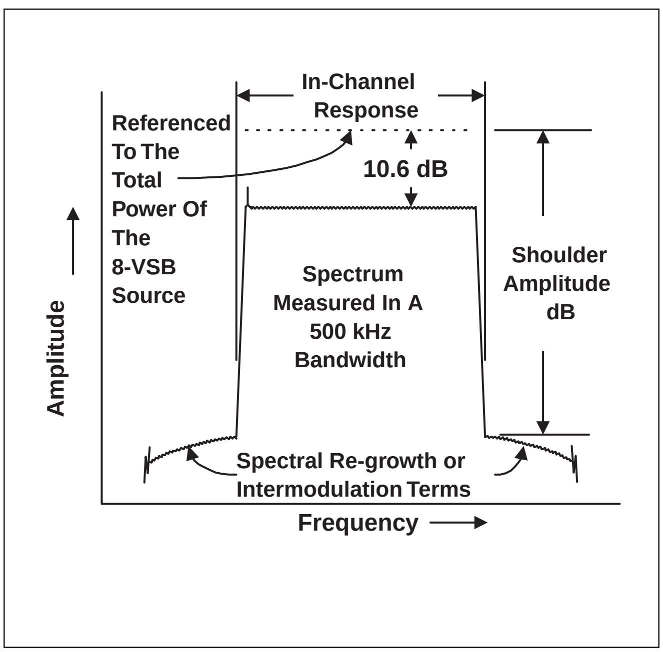

Figure 16. Spectral content of DTV transmission showing definition of shoulder amplitude.

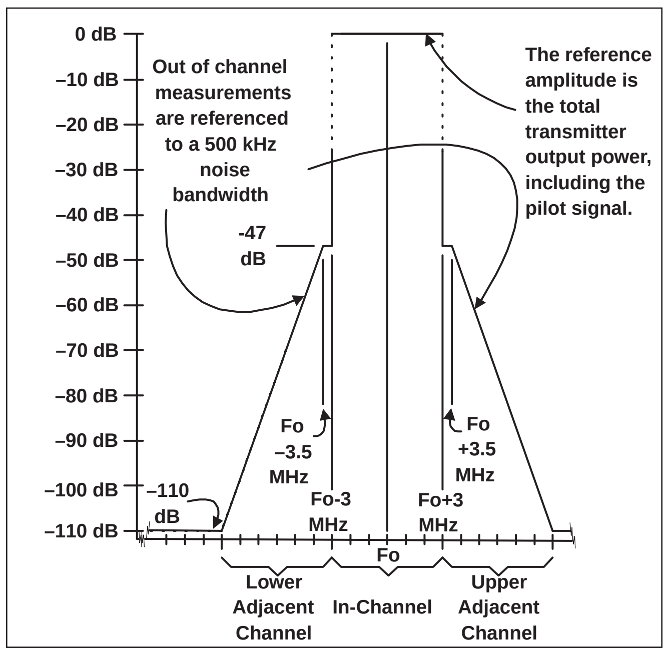

Figure 17. FCC emissions mask.

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