

Estimating the Loss of ATSC-8VSB Payload Due to a Single Echo

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I. Introduction

Strong and short-delayed echoes characterize indoor reception of television. In analog television, these echoes produce annoying ghost images on the television display screen but do not cause loss of service. In digital television, depending on the modulation, these same echoes could be constructive or destructive. Multicarrier digital television systems have the capability to add these echoes constructively with the primary signal and thus enhance the reception everywhere. The ATSC-8VSB modulation system does not have the capability to constructively use these echoes, resulting in loss of carrier-noise ratio (CNR), increase in inter-symbol interference (ISI) and ultimately the loss of signal-noise ratio (SNR) to below its threshold level, at which point reception fails.

This paper provides an estimate of how a single echo, especially short-delayed and strong, reduces the ATSC channel payload relative to that prescribed by Shannon's Law for Additive White Gaussian Noise (AWGN) channel^a.

II. Shannon's Payload for ATSC-8VSB

The theoretical threshold SNR for AWGN ATSC-8VSB channel is 15 dB^b. When the transmitter's SNR, typically 32 dB, is combined with the receiver's measured mean threshold SNR of 15.2 dB, the practical measured SNR of ATSC-8VSB AWGN channel is 15.1 dB, or ± 0.1 dB relative to the theoretical and measured values.

Shannon's net information capacity limit, exclusive of error correction, also known as payload, for AWGN channel W MHz wide and operating at $SNR=S/N$ is^c:

$$C(\text{Mbits/sec}) = W \log_2 \left(1 + \frac{S}{N} \right) \quad (1)$$

and changing the logarithm base from 2 to 10:

$$C(\text{Mbits/sec}) = \frac{1}{\log_{10} 2} W \log_{10} \left(1 + \frac{S}{N} \right) \quad (2)$$

The available channel width for ATSC-8VSB is 6 MHz. Thus, the maximum payload assuming $SNR=15.1$ dB according to Shannon is $C=30.4$ Mbits/sec.

This maximum payload is independent of the modulation and coding. The effective channel width with ATSC-8VSB modulation is 5.381 MHz and for that width, $C=27.3$ Mbits/sec.

Hartley¹, prior to Shannon, set the maximum data transmission rate, R , for errorless M -ary channel:

$$R(\text{Mbits/sec}) \leq \frac{2W}{\log_{10} 2} \log_{10} M \quad (3)$$

Hartley's errorless data transmission rate R , in contrast to Shannon's payload, depends on the modulation and coding, must be below C . If $R > C$, the Bit Error Rate (BER) increases without limit and decoding the message fails.

For the available 6 MHz channel and $M=8$ levels, $R= 36$ Mbits/sec and for the effective width of the ATSC channel, $R= 32.3$ Mbits/sec. To reach Hartley's limit of 36 Mbits/sec, Shannon's minimum SNR for AWGN channel is obtained by substituting R in equation (2) and solving for S/N :

$$SNR(\text{dB}) = 10 \log_{10} \left[10^{\frac{R \cdot \log_{10}(2)}{W}} - 1 \right] = 18 \quad (4)$$

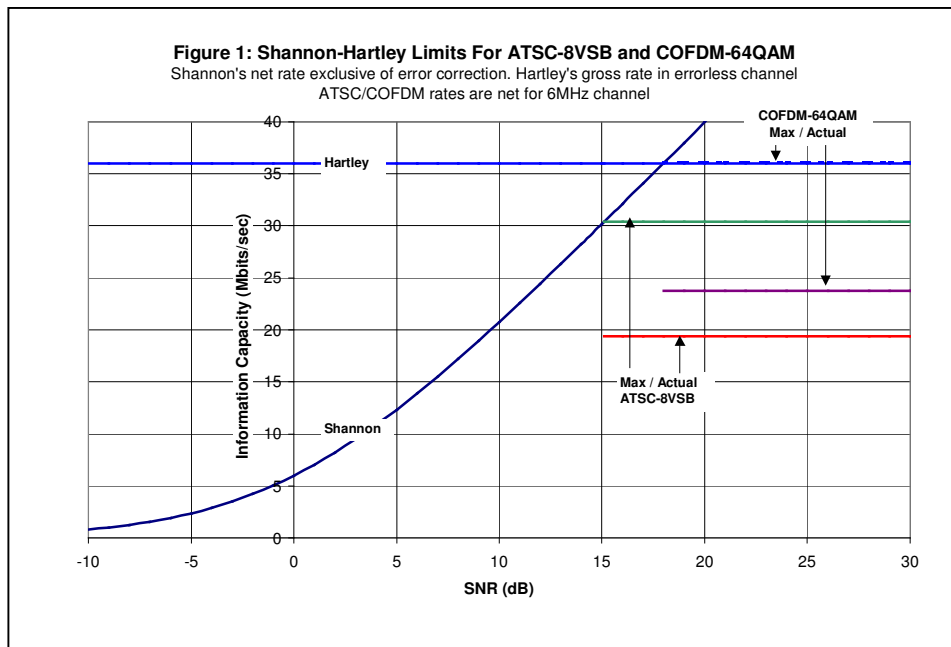
Theoretically, the net information capacity or payload for errorless AWGN channel could be raised with ideal modulation and coding to the Hartley rate of 36 Mbits/sec for a minimum operating SNR of 18 dB. That rate would be 100% of Shannon's capacity. Raising the capacity means raising the threshold SNR, which in turn reduces coverage, but not necessarily

^a Characterized as a linear channel with flat spectral density without echoes and interference and with Gaussian noise distribution.

^b The measured value of practical receivers is 15.2 dB with a standard deviation of 0.2 dB. Threshold is defined by $BER = 3 \times 10^{-6}$. A signal generator with very high SNR was used to obtain these data. The SNR includes the power diverted to the pilot.

^c The limit applies to single-output and single-input channel. For multiple inputs/ multiple outputs (MIMO) channel the capacity is higher.

service^d within the coverage area. As shown in Figure 1, the ATSC-8VSB net information data rate, or payload, is 19.4 Mbits/sec, which is 64% of $C=30.4$ Mbits/sec with $SNR=15.1$ dB.



The ATSC-8VSB gross data rate, including error correction and overhead, is 32.3 Mbits/sec^e, almost 3 Mbits/sec below Hartley's limit.

For comparison, the information capacity of DVB-T, another standard for DTV with COFDM-64QAM modulation, can be as high as 23.8 Mbits/sec with threshold $SNR=18$ dB for a 6 MHz channel. For COFDM-64QAM in 6 MHz channel and a transmitter SNR of 32 dB, the 23.8 Mbits/sec payload at $SNR=18$ dB is 66% of $C=35.7$ Mbits/sec, very close to the 64% of ATSC-8VSB payload.

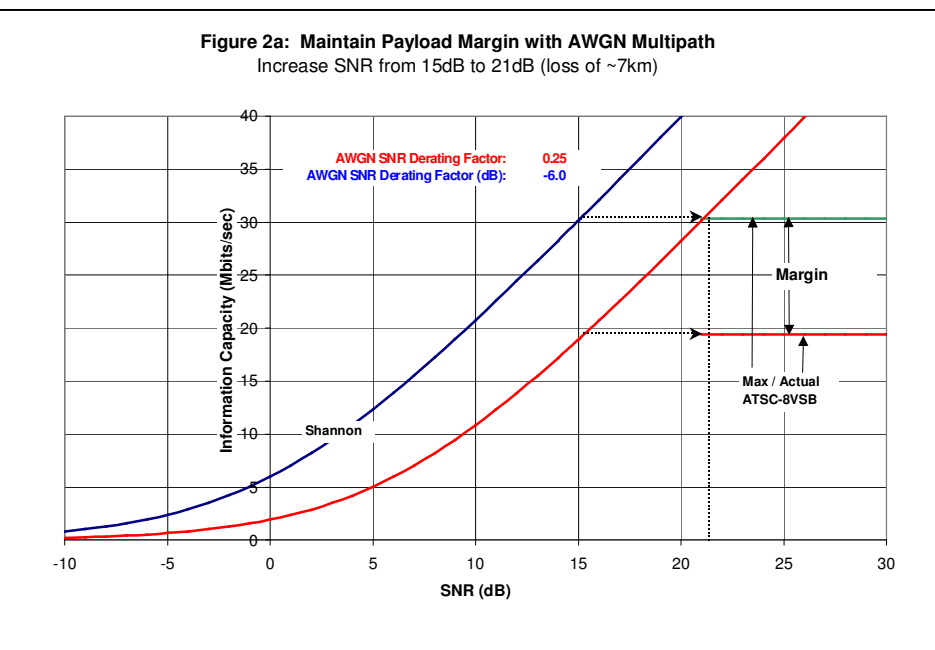
So for AWGN channel without echoes, ATSC-8VSB would have the advantage of wider area coverage over COFDM-64QAM due to the lower threshold

SNR (by 3 dB). The relative coverage loss of COFDM, about 3 km off the noise-limited contour radius in flat terrain, was one of the two main technical reasons used to reject it in favor of ATSC-8VSB modulation for DTV in North America. The second technical reason was the higher Peak-Average power ratio (PAR) of COFDM thus requiring higher transmitter peak power.

The ATSC channel can experience loss of SNR due to certain echoes and still be in compliance with Shannon's Law for AWGN channel. For a single, zero-delay echo, the channel spectrum remains undistorted and SNR is lost due to CNR loss, and not due to ISI, a consequence of delayed echo.

Figure 2a shows how the payload's margin is eliminated if the channel's SNR is lowered by loss of signal power due to a zero-delayed and out-of-phase single echo, which causes no change to the channel's AWGN characteristics.

Shannon's and the degraded SNR payloads are plotted in Figure 2a to show that the degraded payload is borderline to support ATSC-8VSB with threshold SNR of 15 dB because the original ATSC payload margin



(30.4 Mbits/sec relative to 19.4 Mbits/sec actual) would be gone. To regain the lost margin, the operating SNR must be at least 21 dB, approximately a 7 km loss to the radius of the noise-limited contour in flat terrain.

^d UHF Coverage, as defined by the FCC, is the noise limited contour of AWGN channel defined in terms of a fixed field strength at 30 feet above ground incident on a receive antenna, with gain of 10 dBd. Service within the coverage area is available if $SNR \geq$ Threshold SNR at the output of the demodulator.

^e Each symbol represents 3-bit number. The symbol rate is 10.76 Msym/sec and the gross data rate is 10.76×3 Mbits/sec.

The solution for robust DTV service over wide area would have to be based on multiresolution source and channel coding² using hierarchical modulation such that the decoded payload depends on the local SNR at the receiver as shown in

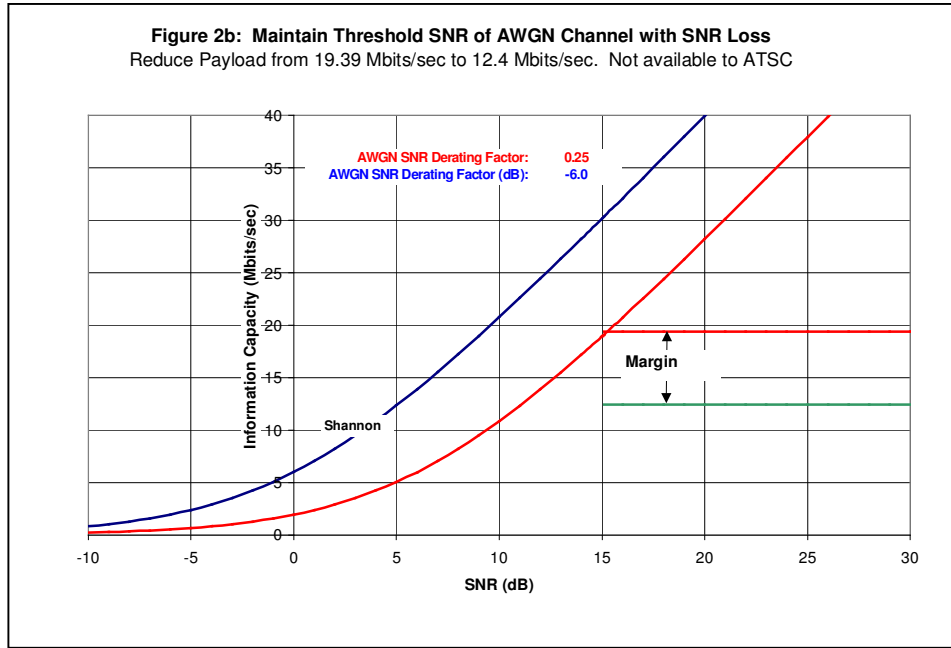


Figure 2b. The payload would be lowered to 12.4 Mbits/sec, or 64% of the maximum capacity of 19.4 Mbits/sec and the threshold SNR maintained at 15dB. Such multiresolution coding with hierarchical modulation would provide discrete if not entirely graceful degradation of video quality. Unfortunately, such capability requires multicarrier modulation. The ATSC-8VSB is a single-carrier modulation that cannot support multiresolution broadcasting and thus is depriving many would-be viewers from receiving watchable television.

III. Loss of Payload Due to Echoes

The real-world characteristics of the DTV channel

do not fit the AWGN channel model^f, and DTV coverage is not the only consideration to be made in regard to providing robust DTV service within the coverage area.

A non-AWGN channel can be divided into K Parallel subchannels, each subchannel of equal width Δf , and each sufficiently narrow to be essentially AWGN. Then the capacity of the kth subchannel is:

$$C(f_k) = \Delta f * \text{Log}_2 \left(1 + \frac{|Y(f_k)|^2 |H(f_k)|^2}{N(f_k)} \right) \quad (5)$$

where $|Y(f_k)|^2$ is the average signal power at the center of the kth subchannel and $|H(f_k)|^2$ is the normalized transfer function at the center of the kth subchannel.

The capacity of non-AWGN can be estimated by letting $\Delta f \rightarrow 0$ and integrating over the available bandwidth³:

$$C = \int \text{Log}_2 \left(1 + \frac{|Y(f)|^2 |H(f)|^2}{N(f)} \right) df \quad (6)$$

IV. Loss of Channel SNR due to a Single Static ATSC Echo

Assuming a single rectangular pulse bandwidth of 5.381 MHz combined with an undesired single echo of amplitude $r \leq 1$, delayed by τ and with arbitrary phase ϕ , the resultant baseband carrier at the receiver is:

$$|Y(f)|^2 |H(f)|^2 = P_{in} \left[1 + r^2 + 2r \cos(2\pi[f - f_0]\tau + \phi) \right] \quad (7)$$

where f_0 is the baseband center frequency and P_{in} is the input power without echoes.

With no added noise other than that contributed by receiver's noise floor N_{Rx} and the transmitter's noise N_{Tx} , the total noise power is $(1+r^2)N_{Tx} + N_{Rx}$ and the instantaneous input CNR at baseband is:

$$\text{CNR}_{in} = \frac{1 + r^2 + 2r \cos(2\pi[f - f_0]\tau + \phi)}{\frac{1 + r^2}{\text{SNR}_{Tx}} + \frac{1}{\text{SNR}_{Rx}}} \quad (8)$$

When $r=0$, (8) reduces to $P_{in}/(N_{Rx} + N_{Tx})$ per Section II. A close approximation for the average CNR can be obtained by integrating (8) over the channel width of the rectangular pulse².

^f Unfortunately, the FCC's link budget for DTV is based on AWGN channel model thus making it useless for service planning and inefficient for channel allotment table.

When the equalization fails, for example if the echo delay τ is too short or too long, or its amplitude is too weak or too strong ($r=0$ dB and $r<20$ dB cannot be equalized), equation (8) describes the output SNR.

The ATSC equalizer topology requires a tapped-delay filter and the first tap delay would typically be one symbol period. Therefore, echo delays within $\pm T_s$ will not be equalized. Instead, such short-delayed echoes cause significant reduction of the primary signal's power at the input to the receiver⁴. The loss of carrier power occurs during the autocorrelation period between identical symbols of the signal and its short-delayed echo. During that period, part or the entire carrier's power would be reflected back into the antenna to be reradiated (or be absorbed at the generator). For example, if the echo arrives at the input to the receiver with no delay and with equal amplitude but out of phase relative to the primary signal, the power into the receiver would be zero.

If the equalization succeeds for delays outside $\pm T_s$, the channel's spectrum into the demodulator would be flat but the SNR would be degraded because the equalizer would amplify the channel's noise power uniformly across the channel.

In summary, the echo will raise the noise floor level by its inherent transmitter noise and by the equalizer noise gain and also reduce the carrier power for echo delays within the autocorrelation period. Beyond the correlation period[§] there is effectively no loss of carrier power regardless of the spectral distortion given by (7).

The resulting degradation of SNR can be expressed as:

$$SNR = \frac{L_C}{\left[\frac{1+r^2}{SNR_{Tx}} + \frac{1}{SNR_{Rx}} \right]} \quad |\tau| < T_s \quad (9)$$

$$SNR = \frac{1}{\left[\frac{1+r^2}{SNR_{Tx}} + \frac{1}{SNR_{Rx}} \right]} G_{EQ} \quad |\tau| \geq T_s \quad (10)$$

where G_{EQ} is the noise gain contributed by the equalizer and L_C represents the loss of carrier power at the input to the tuner.

Without echoes, the channel's SNR is:

$$SNR_0 = \frac{1}{\frac{1}{SNR_{Tx}} + \frac{1}{SNR_{Rx}}} \quad (11)$$

Therefore, the relative loss of SNR due to the echo is:

$$\frac{SNR}{SNR_0} = L_C \left[\frac{SNR_{Rx} + SNR_{Tx}}{(1+r^2)SNR_{Rx} + SNR_{Tx}} \right] \quad |\tau| \leq T_s \quad (12a)$$

$$\frac{SNR}{SNR_0} = \frac{1}{G_{EQ}} \left[\frac{SNR_{Rx} + SNR_{Tx}}{(1+r^2)SNR_{Rx} + SNR_{Tx}} \right] \quad |\tau| > T_s \quad (12b)$$

The noise enhancement by the equalizer depends on the combination of filters (FIR and IIR) used, the number of filter taps, the sampling rate and the combination of time domain and frequency domain processing used to speed the convergence of the distorted spectrum into a flat spectrum. Thus, the equalizer design requires a tradeoff between noise enhancement and convergence speed to restore the channel's unit impulse response by removing all ISI. Since the unit impulse has a flat frequency spectrum the noise enhancement would be white⁵.

For a single echo, the worst-case noise power enhancement when the tap delay equals the echo delay is⁶:

$$G_{EQ} = \frac{1-r^{2M}}{1-r^2} \quad \text{FIR}$$

$$G_{EQ} = \frac{1}{1-r^2} \quad \text{IIR} \quad (13)$$

where M is the number of equally delayed taps. The IIR filter requires only a single tap to cancel the single stationary echo. For $r = -.25$ dB echo, $G_{EQ} = -12.5$ dB.

[§] The correlation duration ends when $\Delta F \tau = 1$. It is twice the symbol period between $\pm \tau = T_{SYM} = 10^{-6} / (2 * 5.381 \text{ MHz}) = .093 \mu\text{sec}$.

Figure 3 shows the noise G_{EQ} enhancement due to a single echo. Clearly, the FIR with $M=1212$ taps provides less noise enhancement than the IIR with one tap but only for near a 0 dB echo. The IIR provides faster convergence but neither can eliminate the noise amplification by a 0 dB echo.

Since the worst-case loss of carrier power of the signal is $(1-r)^2$, the carrier loss during the autocorrelation interval when the equalizer is not functional, can be estimated using the quadratic $a+b\tau^2$:

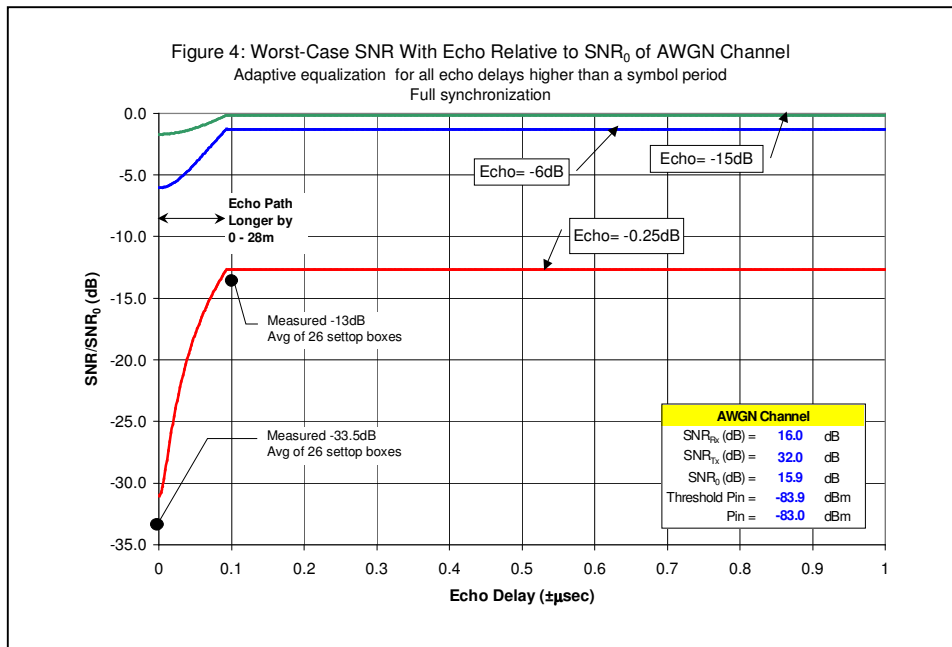
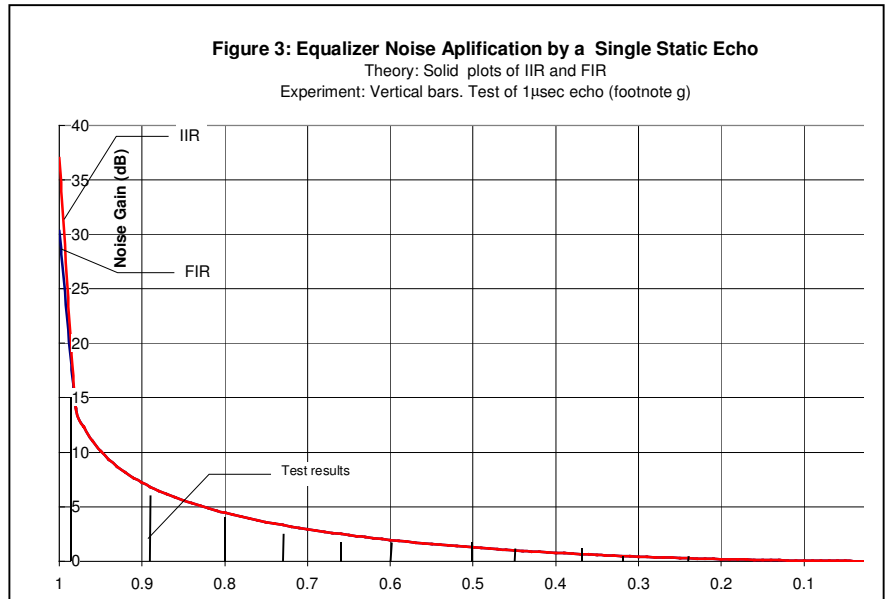
$$L_C = (1-r)^2 + [(1-r^2)Z - (1-r)^2] \left(\frac{|\tau|}{T_S} \right)^2 \quad (14)$$

Where

$$Z = \left[\frac{SNR_{Rx} + SNR_{Tx}}{(1+r^2)SNR_{Rx} + SNR_{Tx}} \right]$$

The experimental result^h for 1 μ sec post-delayed echo was added to Figure 3 for comparison with the theoretical result of equation (13). The choice of 1 μ sec delayed test echo, just above the symbol period, avoids the expected additional deterioration cause by longer delays in practical equalizers.

Figure 4 shows how the channel's SNR, relative to that of AWGN channel, degrades with a single echo. Full equalization was assumed for all echo delays and amplitudes except for an exactly 0 dB echo and for delays less than a symbol's period. In reality, practical adaptive equalizers cannot attenuate long delayed echoes regardless of the echo's amplitude. The receiver's floor noise was set at -99 dBm and the threshold SNR set at 15.1 dB.



There are two distinct echo delay regions. For delays less than the ATSC symbol period ($\pm 0.093 \mu$ sec or ± 28 meters) there is no echo equalization and the worst-case loss of SNR is proportional to the peak power or $(1-r)^2$. For longer delays, the relative SNR is proportional to $(1-r^2)$ where r is the echo's amplitude.

The loss of SNR can be viewed as a penalty on the transmitter power, which must be increased by the penalty amount to maintain the AWGN SNR margin above threshold. The effect of a single echo on the average receiver's threshold amplitude was measuredⁱ for echoes at 180° and at 0 and 0.1 μ sec delays and the results are shown in Figures 4 and 5. At 0 delay the calculated increase in power is 31 dB and the measured 33.5 dB. At 0.1 μ sec delay the

^h "Test of Digital Television Systems", performed at Brazil's Mackenzie University. Submitted to the Brazilian Telecommunication agency (ANATEL), 05/02/2000. In those laboratories tests, $L_C \cong 0$ and $N_{Tx} \cong 0$. Test results for delays below 1 μ sec are not available, presumably because the equalizer failed.

ⁱ Data taken by Charles Rhodes and Linley Gumm on August 25, 2011. A bank of 26 receivers was used to determine the average required increase in power to attain threshold visibility.

calculated increase in power is 12.7dB and the measured increased in power was 13.5 dB. Figure 5 shows the required increase in signal power at the receiver to compensate for the SNR degradation shown in Figure 4.

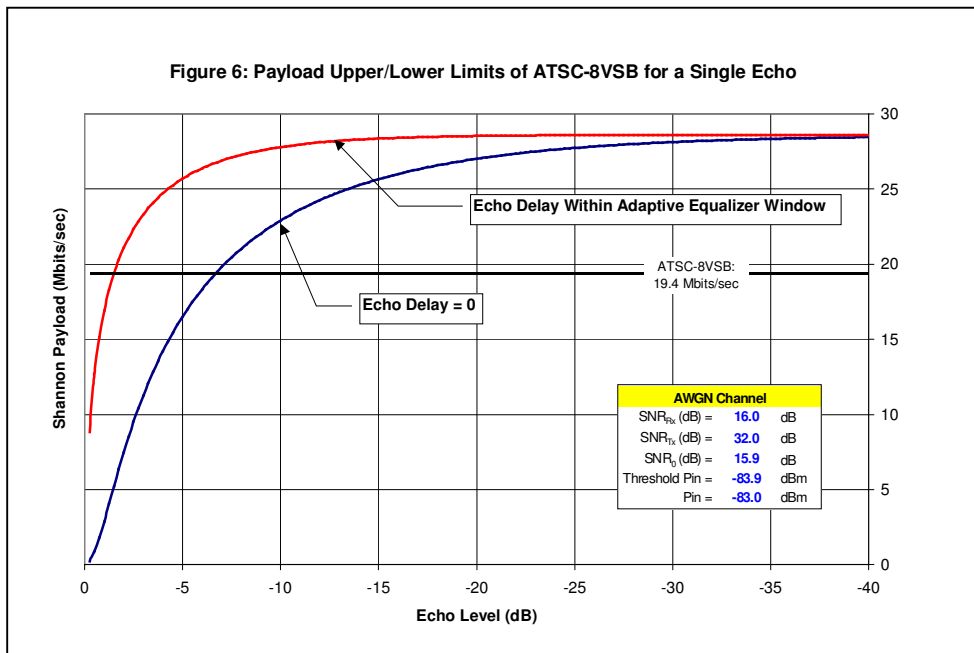
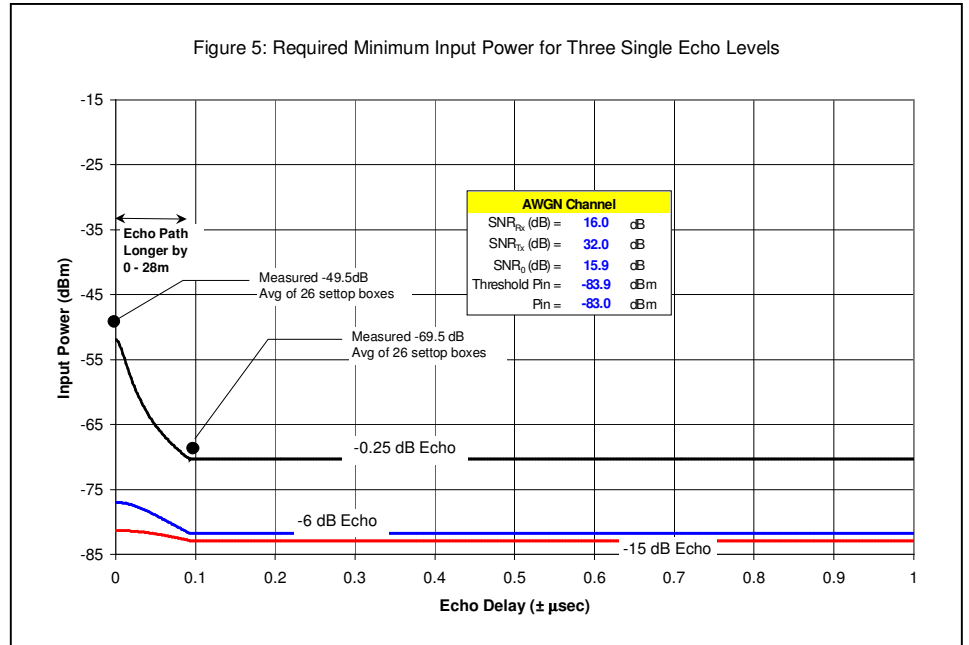
V. Loss of Payload for ATSC-8VSB Receiver due to a Single Static ATSC Echo

From Section IV it is clear that the loss of channel capacity should be defined in two separate regions of echo delay. One region for echo delays too short to be equalized and a second region where all delays are equalized. The first region is characterized by loss of carrier power due to the autocorrelation of the symbol and its identical echo. In that region, the worst loss of payload occurs without spectral distortion at zero delay. Spectral distortion requires that the echo delay not be zero. For zero delay with no spectral distortion, the worst-case payload of the ATSC-8VSB channel with rectangular pulse (effective bandwidth of $\Delta F = 5.381$ MHz) and for all echo amplitudes $r < 1$ is:

$$C_{MIN}(\tau = 0) \approx \Delta F * \text{Log}_2 \left[1 + SNR_0(1-r)^2 \left[\frac{SNR_{Rx} + SNR_{Tx}}{(1+r^2)SNR_{Rx} + SNR_{Tx}} \right] \right] \quad (16)$$

In the second region, where the echo delay is within the adaptive equalizer window, the best-case payload expression for the fully equalized ATSC-8VSB channel with rectangular pulse (effective bandwidth of $\Delta F = 5.381$ MHz) and for all echo delays and $r < 1$ is:

$$C_{MAX} \approx \Delta F * \text{Log}_2 \left[1 + SNR_0(1-r^2) \left[\frac{SNR_{Rx} + SNR_{Tx}}{(1+r^2)SNR_{Rx} + SNR_{Tx}} \right] \right] \quad (17)$$



Equation (16) provides the lower limit and equation (17) provides the upper limit of the payload for ATSC-8VSB receivers. They are independent of the echo delay. These payloads depend only on the echo amplitude and the AWGN channel's parameters.

Figure 6 shows how the upper and lower limits of the payload vary with the echo amplitude. The payload could be increased if the SNR at the receiver is increased,

Appendix: Derivation of the Payload Equation for Unequalized and Spectrally Distorted ATSC-8VSB Channel

Substituting (8) in (6) yields the capacity of the unequalized channel:

$$C_U = \int_{\Delta F} \text{Log}_2 \left(1 + \text{SNR}_0 \left[\frac{1 + r^2 + 2r \cos(2\pi[f - f_0]\tau + \phi)}{(1+r)^2} \right] * \left[\frac{\text{SNR}_{R_x} + \text{SNR}_{T_x}}{(1+r^2)\text{SNR}_{R_x} + \text{SNR}_{T_x}} \right] \right) df \quad (18)$$

To facilitate the integration of equation (18), define:

$$K = \frac{\text{SNR}_0}{(1+r)^2} \left[\frac{\text{SNR}_{R_x} + \text{SNR}_{T_x}}{(1+r^2)\text{SNR}_{R_x} + \text{SNR}_{T_x}} \right] \quad A = \frac{2rK}{1 + K(1+r^2)}$$

Then

$$C_U \approx \Delta F * \text{Log}_2[1 + K(1+r^2)] + \int_{\Delta F} \text{Log}_2\{1 + A \cos[2\pi(f - f_0)\tau + \phi]\} df$$

With the following approximation:

$$\text{Log}_2(1+x) \cong \left(x - \frac{x^2}{2} + \frac{x^3}{3} \dots \right) / \text{Ln}2 \quad 0 \leq |x| \leq 1$$

and integrating the first two terms of the series yields:

$$C_U \approx \Delta F * \text{Log}_2[1 + K(1+r^2)] + \frac{A * \Delta F}{\text{Ln}2} \frac{\text{Sin}(\pi\tau \Delta F)}{(\pi\tau \Delta F)} \text{Cos}\phi - \frac{(A/2)^2 * \Delta F}{\text{Ln}2} \left\{ 1 + \frac{\text{Sin}(2\pi\tau \Delta F)}{(2\pi\tau \Delta F)} \text{Cos}2\phi \right\} \quad (19)$$

Without echoes, $r=0$, $A=0$ and $K=\text{SNR}_0$ and (19) reduces to:

$$C_U(r=0) = \Delta F * \text{Log}_2[1 + \text{SNR}_0] \quad (20)$$

which is equivalent to Shannon's equation (1)

VI. Conclusions

There are two distinct regions in which the loss of payload for the ATSC-8VSB channel must be separately defined. One region is for echo delays outside the window of the adaptive equalizer and a second region is for delays within the window of the adaptive equalizer. These regions serve to define the upper and lower limits of the payload.

The worst-case loss of payload occurs for zero delay echoes. This loss is expressed by equation (16) and is plotted in Figure 6. The minimum loss of payload, which occurs for delays inside the window of the adaptive equalizer, is expressed by equation (17) and is plotted in Figure 6. These expressions can be easily expanded for multiple echoes but the result would be cumbersome without adding new insight.

The inability of the ATSC receiver to attenuate (equalize) short-delayed (by less than one symbol period or ± 28 meters) echoes, especially indoors where the echo's amplitude could equal to the signal's is a major handicap in applying ATSC-8VSB modulation for wireless video links.

The future DTV system must be designed for real-world service in a noisy channel with echoes and interference rather than designed to maximize the noise-limited contour of AWGN channel. That means discrete and reasonably graceful video degradation compatible with the local SNR at the receiver. To maximize to SNR, the receive antenna could be designed to be reasonably small and configured to act as a smart adaptive array that directs a null in its pattern toward the worst echo.

Acknowledgement

I am grateful to Charles W. Rhodes for suggesting this topic and also for the tests, performed with Linley Gumm, that helped me correct a mistake in my initial formulation of the SNR loss.

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