Analysis and Measurement of RF System Reflections and DTV Transmission

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***Abstract*---Terrestrial digital television (DTV) broadcast employs complex transmission facilities composed of filters, diplexers, transmission line components, and antennas. The reflections introduced by these components are minimized by broadband design methods, and the nature of the total reflection as these components are combined into a system is developed. The radio frequency (RF) transmission line, immitance, and network parameters used to characterize these systems (i.e., voltage standing wave ratio or VSWR) are related to key DTV performance parameters.**

***Index Terms*---Reflections, echoes, multi-path distortion, digital television (DTV) transmission, transmission lines, antennas.**

I. INTRODUCTION

The performance of the Advanced Television Systems Committee (ATSC) standard [1] eight-state vestigial sideband (8-VSB) modulation has been widely studied and measured [2]. In particular, the static multi-path correction by decision feedback equalization (DFE) played a major role in the adoption of 8-VSB as the DTV standard [3]. Digital tapped delay lines in the DFE efficiently correct echoes ranging from –3 to 40 μs [2], and receiver designs continue to improve [4]. Small reflections originating in the RF transmission system are within 5 μs and provide no challenge to the receiver.

II. BROADBAND DESIGN METHODS

Transmission components are designed for minimum reflection in the band of operation while maintaining the power handling. Most components designed for NTSC broadcast operate over a single-channel, 6 MHz bandwidth. The mandated DTV simulcast has increased the bandwidth requirement to 12 MHz and broader systems. Some facilities are being designed to operate over the entire core UHF band (470–698 Hz) to allow flexibility in future channel assignments. Other broadband systems consist of channels widely separated in the band. To compare the bandwidth of various configurations, the percent bandwidth is defined:

$$\%BW = 100\left(\frac{BW}{f_{mid}}\right) \tag{1}$$

The percent bandwidth of various TV broadcast bands is compared in Table 1.

TV Band	Entire Band	Channel
Low VHF	40	9
High VHF	20	3
UHF	50	1
UHF Core	40	1.1

Table 1. TV Band Percent Bandwidth

Generally, an RF design covering greater than 20% bandwidth is challenging. Therefore, any component and system designed to cover any TV band requires engineering effort. Two broadband design techniques are outlined.

A. *Distributed Systems and Heavyside's Condition*

Linear systems are modeled as either distributed or lumped systems. To describe the two using the jargon of linear systems, distributed systems have an infinite number of state variables while lumped systems have a finite number [5]. In other words, distributed systems are described in parameters per unit length, like resistance in ohms per foot, while lumped systems are described by discrete components like resistors and capacitors in a circuit model. Furthermore, distributed electrical systems are modeled using Maxwell's equations (a set of coupled integral or differential equations) while lumped systems are modeled using Kirchoff's voltage and current laws.

RF systems for TV broadcast are comprised of both distributed and lumped systems. Some components are modeled as lumped circuit components while some are modeled in terms of a distributed system. As the feature dimensions of components become significantly smaller than a wavelength, the component is considered as a lumped element.

The lumped model of a transmission line [6] illustrates the bandwidth enhancement possible using distributed techniques. Consider the circuit model shown in Figure 1.

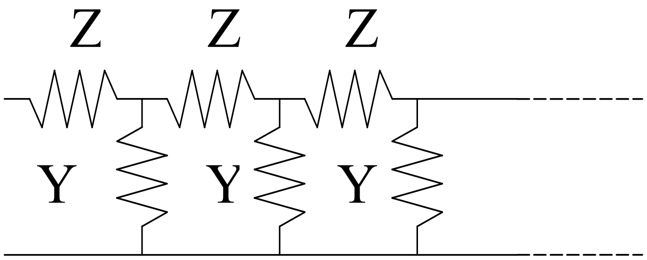

Figure 1: Lumped Element Model.

where

$$\begin{aligned} Z &= R + j\omega L \\ Y &= G + j\omega C \end{aligned} \tag{2}$$

are, respectively, the series impedance and the parallel admittance per unit length.

The input impedance is given by the following equation:

$$Z_o = \sqrt{\frac{Z}{Y}} = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \qquad (3)$$

If the transmission line is considered loss-less *(R=G=0)*, the frequency is considered very high *(ω→∞)*, or if Heavyside's condition *(RC=GL)* is applied, the input impedance reduces to

$$Z_o = \sqrt{\frac{L}{C}} \qquad (4)$$

The important consequence of applying these assumptions is that the parameter no longer depends on frequency and, therefore, no longer limits the bandwidth. The latter assumption, Heavyside's condition, is considered a broadband design equation and is valid if the quantities in Eq. (3) are lumped elements. Applying Heavyside's condition to the group delay of a lumped transmission line yields the following equation:

$$G.D. = -\frac{\partial}{\partial \omega}\left(-\omega x\sqrt{LC}\right) = x\sqrt{LC} \qquad (5)$$

which is also independent of frequency. Therefore, the addition of lumped inductance and capacitance causes no attendant bandwidth limitation with the application of Heavyside's condition. The benefits of a distributed system may be realized in a lumped system.

B. Open-Circuit Time Constants

The method of open-circuit time constants was developed at MIT in the 1960s as a technique to provide an estimate of the system bandwidth. In doing so, meaningful information about the band-limiting components in a circuit, typically troublesome capacitors, is provided. A system transfer function, representing the normalized reflections in a broadcast RF transmission system, is given by

$$\frac{V(s)}{V_i(s)} = \frac{a_o}{(\tau_1 s + 1)(\tau_2 s + 1)\cdots(\tau_n s + 1)} \qquad (6)$$

At the 3 dB bandwidth, it is assumed that the first-order term of the denominator dominates. With this approximation, Eq. (6) becomes

$$\frac{V(s)}{V_i(s)} \approx \frac{a_o}{(b_1 s + 1)} = \frac{a_o}{\left(\sum \tau_i\right)s + 1} \qquad (7)$$

and the system bandwidth is given by

$$\omega_h \approx \frac{1}{b_1} = \frac{1}{\left(\sum \tau_i\right)} = \frac{1}{\left(\sum R_{oi} C_i\right)} \qquad (8)$$

Computing the R_{oi} and C_i in Eq. (8) involves the following process [6]:

1) Compute the effective resistance, R_{oi}, facing each *ith* capacitor with all of the other capacitors removed (or open-circuited).
2) Form the product $\tau_i = R_{oi} C_i$ for each capacitor in the system.
3) Sum all of such "open-circuit" time constants.
4) Using Eq. (8) above, compute the upper limit on the bandwidth.

Valuable insight about what is causing the bandwidth limitation is given according to which components dominate the sum performed in step 3 above. This focuses the design effort on bandwidth enhancement. With the method of open-circuit time constants, the process requires remarkably less computational effort than full SPICE circuit analysis or full-wave electromagnetic simulation of the component or system.

III. SYSTEM DESIGN METHOD

Facilities for the transmission of TV broadcast are systems comprised of antennas, coaxial or waveguide transmission line, connectors, elbows, combiners, diplexers, and filters [15]. Coaxial transmission line contains support insulators and bullet interconnections as well. Modeling this assembly of components appeals first to two-port network theory.

The network description of two components separated by uniform transmission line is shown in Figure 2. The total reflection, Γ_t, is related to the reflection of component Γ_B, B, and the S-parameters of component S.

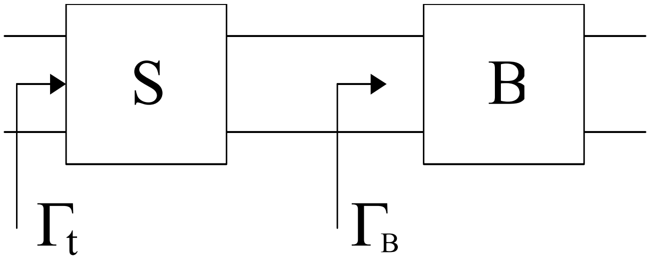

Figure 2: Network Model.

The total reflection is given by

$$\Gamma_t = S_{11} + \frac{S_{12} S_{21} \Gamma_B}{1 - S_{22} \Gamma_B} \qquad (9)$$

Assuming that the through losses and level of reflections are much smaller than unity ($S_{22} << 1$, $S_{12}=1$, $S_{21}=1$), a reasonable assumption in the vast majority of system components, the total reflection becomes

$$\Gamma_t \approx S_{11} + \Gamma_B \qquad (10)$$

which is the addition of two complex numbers. As the two components are separated by a distance, d, the total is

$$\Gamma_t \approx S_{11} + \Gamma_B e^{-2j\beta d} \qquad (11)$$

where the phase constant $\beta=2\pi/\lambda$.

A depiction of this complex addition in terms of two vectors is shown in Figure 3. The magnitude of the total reflection varies according to the relative phase of the two component reflections. As Eq. (11) indicates, the relative phase of the two reflections depends on the distance between the two components and the frequency. At some frequencies, they add constructively (long red arrow, Figure 3), and at some frequencies, they add destructively (short, blue arrow).

Extending this to the total reflection of the entire RF system yields the summation of the complex voltage reflection coefficients of each component. With this model, the cardinal system design principle has been established: minimizing the component reflections reduces the total system reflection.

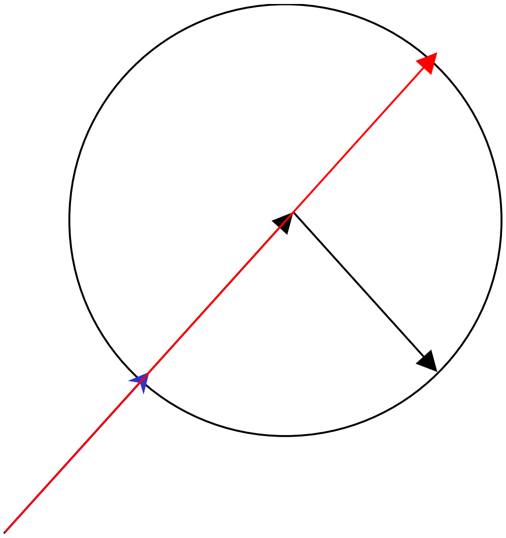

Figure 3: Vector Addition of Reflections.

Considering only the magnitude of each component, the maximum total reflection may be computed. Component values adding to a system VSWR of 1.10 are tabulated below. The excessive number of decimal places is included to allow the computations to be verified.

# Components	Reflection Coef.	VSWR	Return Loss
2	0.0238	1.0488	32.46
5	0.0095	1.0192	40.42
10	0.0048	1.0096	46.44
20	0.0024	1.0048	52.46
30	0.0016	1.0032	55.99
50	0.0010	1.0019	60.42

Table 2. Component VSWR for 1.10 System

Component reflections are complex quantities. A design criteria relating to the magnitude has been developed above, and one concerning the phase will now be developed. Because the magnitude of the total reflection given in Eq. (11) depends on the distance between components, the spacing of components may be designed to minimize the total reflection. In a transmission line system, this requires that the section lengths be varied along the total length of the line according to the patented method used in ERI WIDELine$^{\text{TM}}$ transmission line [7]. Essentially the spacing of support insulators and bullet interconnects is varied by a half-wavelength along the full transmission line length, making the last stick a half-wavelength shorter than the first.

Many 6 and 12 MHz TV broadcast systems are successfully designed with the application of a "fine-tuner" section. These sections are a short length of coaxial transmission line with a number of capacitive probes spaced along its length. The addition of these tuner sections allows the narrowband optimization of the total system reflection. Similar narrowband tuning is accomplished by the addition of capacitive rings or "slugs" at select locations along the line. Neither of these methods will result in a broadband minimization of reflection because the reactance of a shunt capacitor is directly proportional to frequency, which was painstakingly avoided in the design principles developed in Section II above.

IV. MEASUREMENT METHOD AND RESULTS

The design principles established in the previous sections have highlighted the important contribution of small reflections to the total system reflection. Designing components with Return Loss performance better than 60 dB presents a challenge to conventional laboratory techniques. Through the use of a vector network analyzer (VNA) and time-domain transform (TDT) analysis, the components may be accurately characterized.

A. TDT Technique

Components in a TV broadcast transmission system require transitions from large coaxial transmission lines to small standard connectors on the VNA (typically type-N or 7 mm connectors). Such transitions are often narrowband components tuned by using narrowband techniques discussed in Section III above. As such, the reflections caused by the transitions are typically much higher than the 60 dB reflections demanded from the broadband components. Overcoming this limitation requires the use of TDT analysis.

The reflection measurements of the VNA are performed in the frequency domain. The VNA contains vector voltage detectors and a synthesized, swept frequency source. Frequency domain data are transformed to the time domain using a Chirp-Z transform, a numerically efficient generalization of the discrete time Fourier transform (DTFT). The data may be digitally filtered in the time domain by using "gating" and inverse-transformed back to the frequency domain. Such gates may be positioned in the time domain to remove the troublesome reflections from the test adaptors. Gating may also be applied to filter the TDT data to eliminate all reflections in a system but those of interest, focusing the measurement on a particular component.

BW, MHz	Np	Range, ft	Resolution, ft
6	1601	131136	157
6	801	65568	157
12	1601	65568	79
25	1601	31473	38
100	1601	7868	9
300	1601	2623	3
1000	1601	787	1

Table 3. TDT Range and Resolution

The swept bandwidth, or frequency span, affects the range and resolution in the time domain. The range (in seconds), being the largest value of time computed in the transform, is related to the number of data points and the swept bandwidth by the following equation:

$$range = \frac{N_p - 1}{BW} \qquad (12)$$

where BW is the swept bandwidth in Hz, and N_p is the number of points. The time range may be converted to distance by multiplying by the speed of light (approx. 1 ft/ns). This range is the round-trip time of the reflected wave and must be halved to relate to the physical distance.

The resolution, in seconds, of the TDT data is given by

$$resolution = \frac{1.92}{BW} \qquad (13)$$

where the 1.92 constant represents a band-pass transform by using a normal window and ranges from 0.45 to 2.88, depending on the VNA window and transform settings. Note that the resolution is not dependent on the number of points and may be converted to distance in the same manner as the range.

In the laboratory, the range is typically not a problem and the bandwidth is set solely based on the desired resolution. The range may become a factor in field measurements of transmission systems mounted atop tall towers. Measuring the reflections from an antenna atop a 2000 ft tower requires a range of 4 μs, which requires a bandwidth of 196.7 MHz with 801 points. Sweeping greater than this bandwidth will reduce the range and not allow TDT data manipulation of items outside the range of the transform. The corresponding resolution at this bandwidth is 4.8 ft, which can only be improved by increasing the bandwidth. By increasing the number of points to 1601 (at the expense of measurement time), the range may be doubled to 4000 ft. Alternatively, the bandwidth may be doubled, maintaining the 2000 ft range and improving the resolution to 2.4 ft. Table 3 contains a number of useful range and resolution relations.

B. Measured System Performance

Broadband DTV systems have been designed for minimal reflections by using the methods in Section II and III above, installed and measured according to Section IVa. The VSWR performance of several systems is presented in Figures 4a–e below. The data are presented across the entire UHF TV band and include traces of transmission line only and (in most cases) the transmission line and the antenna. Also, a 6 MHz running average RSS reflection coefficient converted to VSWR is also plotted for each trace. In the following section, this statistic will be shown to be directly related to the amount of echo energy overcome by the 8-VSB receiver.

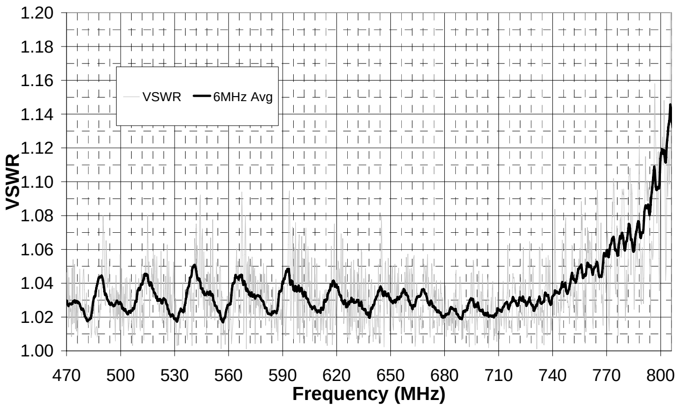

Figure 4a. Site #1

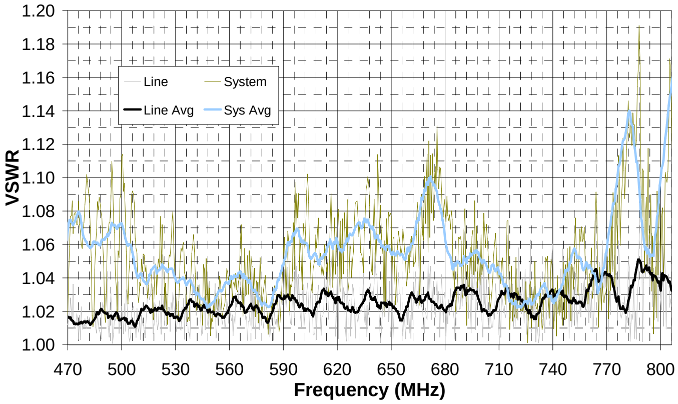

Figure 4b. Site #2

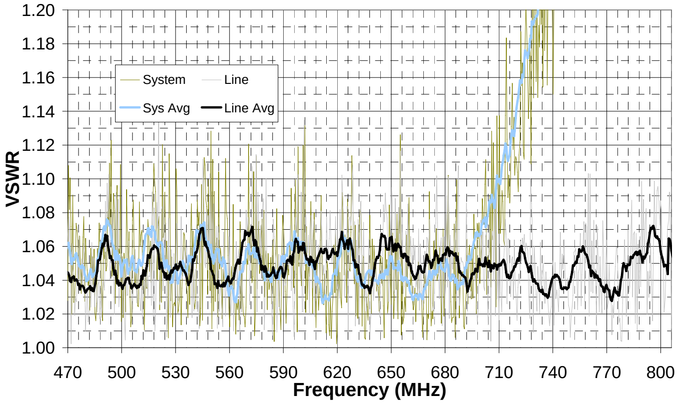

Figure 4c. Site #3

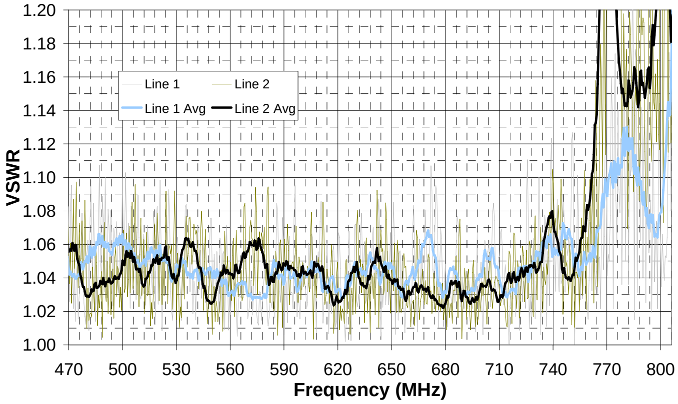

Figure 4d. Site #4

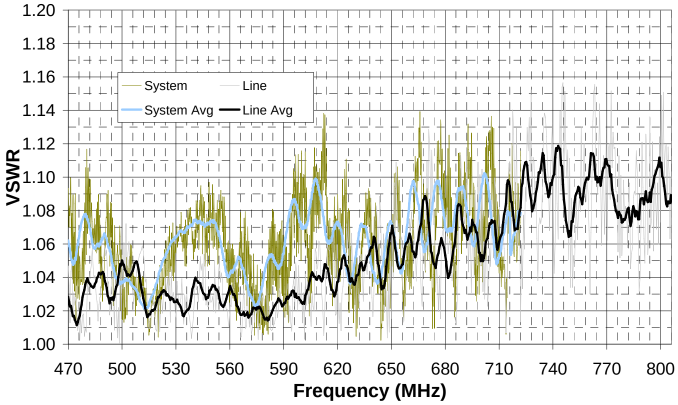

Figure 4e. Site #5

V. ANALYSIS OF DTV PARAMETERS

Reflections originating in the RF transmission system are modeled as static multipath interference [8], [9]. The key DTV system parameter indicating the state of the received signal is the error vector magnitude (EVM) [10] and signal to noise ratio (SNR). The relationship between RF measurements of system reflections and the SNR degradation is developed as follows.

Site #	Line Type*	Length	# Sticks	# Elbows
1	7-75	1447	82	1
2	7-75	900	49	1
3	7-75	860	48	1
4	6-50	320	17	9
5	6-50	635	41	1

Site #	Avg VSWR	CRE/TE(dB)	WNE(dB)	△SNR(dB)
1	1.055	-31.45	0.00311	0.05497
2	1.060	-30.71	0.00369	0.06503
3	1.070	-29.42	0.00497	0.08743
4	1.070	-29.42	0.00497	0.08743
5	1.100	-26.44	0.00986	0.17169

Table 4. Summary of Site Data in Figure 4

*Site #4 is ERI MACXLine® transmission line product, all other sites are ERI WIDELine™ products.

A. *DTV System Parameters*

Interfering noise combines with the original transmitted signal as

$$S_r \approx S_0 + EV \qquad (13)$$

where S_o and S_r are, respectively, the original and received signals, and EV is the interfering noise vector, the magnitude of which is the EVM. At the symbol sampling time, the EVM closes the data eyes as in Figure 5.

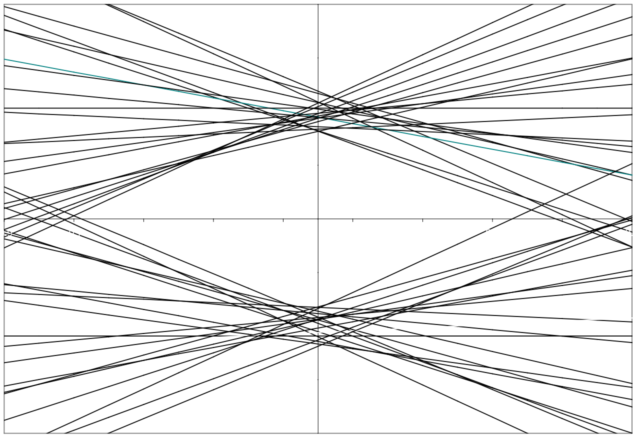

Figure 5. EVM as Eye Closure

The SNR prior to the inverse channel filter (ICF) in the receiver is given by the following equation:

$$SNR = 10\log\left(\frac{\sum (S_{ri})^2}{(EV_i)^2}\right) \qquad (14)$$

where S_{ri} and EV_i are the received signal and the error vector voltages from Eq. (13) sampled at each symbol time. Using decision feedback equalization (DFE) [3], also understood as a tapped delay line, static multipath echoes are corrected. This correction of linear distortion is essential for DTV reception and was the major distinction of the 8-VSB system [3]. In the correction of correlated multipath echoes, a number of equalizer taps are activated that also amplify the white noise present at the receiver. This channel degradation is called white noise enhancement (WNE) and is defined as

(15)

where C_i is the *ith* tap voltage and C_o is the main tap voltage. The summation in the numerator is carried out over all the taps (typically 15 or 30 in the literature), including the main tap [11]. The tap energy (TE) is computed much like WNE with the exception that the summation in the numerator excludes the main tap (I=0),

$$TE = 10\log\left(\frac{\sum (C_i)^2}{(C_o)^2}\right) \qquad (16)$$

and is a measure of the energy expended in canceling the energy of the echo. The energy present in multipath echoes, in particular the RF reflections under consideration, has been computed by the 6 MHz channel average introduced in Section IV. The square magnitude of voltage reflection coefficient is the spectral energy density of the echo and may be summed and averaged over the channel bandwidth. Consequently, the channel reflected energy (CRE) may be defined as

$$CRE = \frac{\sum \Gamma_i^2 \Delta f}{6MHz} = \frac{\sum \Gamma_i^2}{N_{pc}} \qquad (17)$$

where Γ_i is the system voltage reflection coefficient, Δf is the frequency step used in the reflection measurement, and N_{pc} is the number of data points in the 6 MHz channel. The equivalent VSWR computed from this statistic is

$$VSWR = \frac{1+\sqrt{CRE}}{1-\sqrt{CRE}} \qquad (18)$$

and is plotted in Figure 4 and reported in Table 4 for the various measured sites. From these site measurements, the peak-to-average reflected energy is 10 dB. The narrow peaks and deep nulls of a typical system reflection measurement generate this high peak-to-average ratio. Therefore, the RF performance parameter of importance is the CRE not the peak VSWR typically specified, measured, and reported. The relationship between CRE, equivalent VSWR, and peak VSWR is shown in Figure 6.

B. CRE and SNR Threshold Degradation

Considering the energy of reflections originating in the RF transmission system, the CRE, as static multipath echo distortion, the TE and WNE may be computed. At values of CNE less than –20 dB, representing an equivalent VSWR of 1.22 and peak VSWR of 1.92, the TE (using 31 taps) is within 0.1 dB of the CRE. Therefore, the TE may be considered equivalent to the CRE for TV broadcast facilities. The 8-VSB DTV receiver threshold of 15 dB [11] represents the SNR needed for tolerably error-free demodulation. The presence and correction of static multi-path distortion requires the threshold SNR to be improved by the WNE to maintain error-free demodulation. Therefore the WNE represents the SNR degradation that the CRE has on the DTV system. Figure 7 shows the relationship between WNE and CRE.

The SNR degradation has been considered (roughly) equivalent to the reduction of coverage in miles [12]. Figure 7 clearly indicates that at a CRE of –20 dB, the coverage reduction is less than 0.05 mi. Therefore, as the small reflection energy typical in TV broadcast transmission systems is easily corrected by the DFE, it degrades the SNR by a negligible amount.

The performance of various 8-VSB receivers and mathematical models subjected to various ensembles has been routinely published [3], [13]-[15]. These ensembles contain echoes with significantly greater amplitude and delay than those generated in the RF transmission facility. The ATTC ensembles contain echoes with energy totaling –7.5 dB and the typical measured and modeled SNR degradation is 2.5 dB [3], [16]. The WNE for a –7.5 dB echo is 0.85 dB, 1.65 dB less than the typical performance.

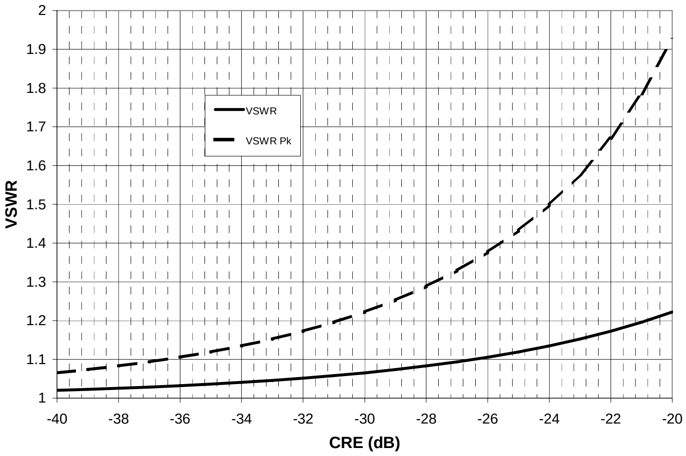

Figure 6. VSWR and CRE

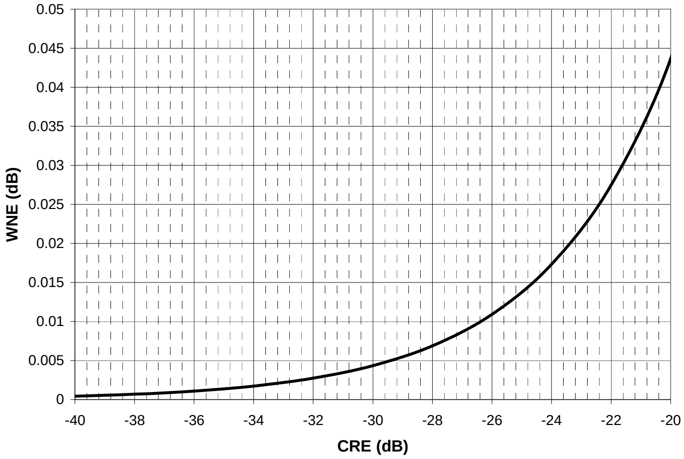

Figure 7. WNE and CRE

If the 8-VSB receiver completely corrects an echo, the WNE represents the smallest degradation to the SNR. If the receiver provides no correction, the total ghost energy degrades the SNR. Therefore the upper and lower bound on SNR degradation are the WNE and CRE, respectively. Let the degradation to the SNR be defined as

$$\Delta SNR = 10\log\left(\eta \frac{CRE}{TOV} + 1\right) \qquad (19)$$

where TOV is the power-ratio expression of the 8-VSB receiver threshold of –15 dB and η is an efficiency factor at which the DFE corrects the echo distortion, ranging from the TOV to unity. From Eq. (15) and (16) above, the WNE may be expressed as

$$WNE = 10\log\left(10^{\frac{TE}{10}} + 1\right) \qquad (20)$$

Also, the TE may be considered equivalent to the CRE at levels below –20 dB. With $\eta = TOV$, $\Delta SNR = WNE$, Figure 8 shows the relationship of SNR degradation and CRE.

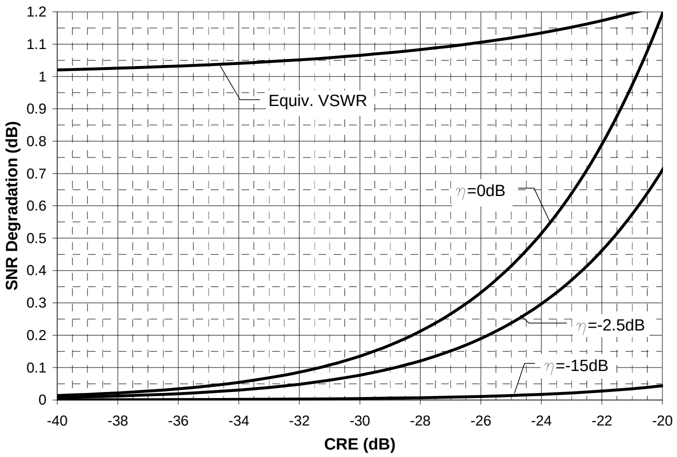

Figure 8. SNR Degradation and CRE

The ATTC ensemble echoes are significantly different than the echoes from the RF transmission facility. However, –27 dB linear distortions in amplifiers have been reported to degrade the SNR by 0.1 dB [12] that uncorrected would have caused 0.3 dB degradation. These data are representative of the echoes under consideration and are similar to the ATTC ensemble data in that the receiver corrects the echoes with $\eta = -2.5$ dB. Therefore, the SNR degradation due to the reflections originating in the RF system are computed by using the $\eta = -2.5$ dB curve plotted in Figure 8. The SNR degradation of the measured site data is reported in Table 4. Analytic and laboratory studies may be performed to confirm this performance.

VI. CONCLUSION

Broadband design equations for RF components and systems have been presented. Measurement techniques have been outlined and applied to several broadband UHF TV broadcast installations. Measured data indicates the successful application of the broadband design principles to the many RF components and operating broadcast stations.

The nature of reflections originating from the RF system was investigated. The Channel Reflected Energy (CRE) was defined from measured reflection data (i.e., VSWR data) and was related to SNR degradation in the DTV receiver. The CRE is the RF system performance parameter relating directly to DTV reception and should be measured and reported in the qualification of such systems [17].

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