Impact of Digital Signal Processing Systems on Coverage of Free Over the Air Digital Television

Osvaldo M. Torres Perez
Electrical Engineering
Luis M Vicente, PhD
Electrical Engineering Department
Polytechnic University of Puerto Rico

Abstract *— Digital Signal Processing (DSP) Systems are playing an important Role in today's communications systems. In June 12, 2009 all analog television Broadcasting stations were turned off in the United States, to remain on air with what we know today as: free over the air digital television (DTV), using a combination of technologies with data processing and signal processing that lead to a modulation scheme known as 8 levels of vestigial sideband (8VSB). This document will describe the steps in the implementation of 8VSB modulation and the impact on coverage of broadcast stations in Puerto Rico, using as a model real parameters of a local station WLII. The impact evaluation was based on establishing a difference between the transmitter coverage area before and after the DTV conversion and how DSP systems have supported this conversion.*

Key Terms *— ASI Asynchronous Serial Interface, ATSC Advanced Television System Committee, MPEG Motion Picture Experts Group, SMPTE Society of Motion Picture and Television Engineers*

8VSB MODULATION

8VSB is the basic standard of modulation process for free over the air television in the United States and Puerto Rico. This is the modulation process used to convert digital data into radio frequency (RF) signal to be transmitted to all television receivers [1]. This modulation scheme uses vestigial sideband amplitude modulation as part of the modulation process. The complete process will be explained using as reference, the block diagram in Figure 1.

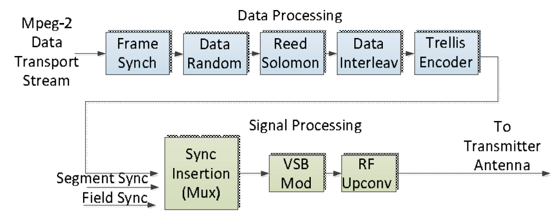

Figure 1
8VSB Block Diagram

The input signal to the modulator (*exciter*) is a digital Transport Stream (TS), which is received in ASI or SMPTE 310 standard formats.

The TS signal is received from an (MPEG-2) encoder that could be located at the studios or at the transmitter site. The transport stream is inserted in the exciter through a 75 ohm coaxial cable to begin the modulation process.

The following document will describe each section of the modulation process.

Frame Synchronizer

The frame synchronizer is responsible for identifying the first 8 bits (Byte) from the 188 bytes of data packets received from the MPEG 2 encoder as shown in Figure 2.

The first byte, which is known as the sync byte, is used by the exciter to synchronize the internal clock with the incoming data signal.

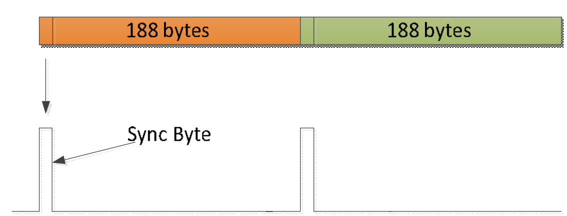

Figure 2
Sync Byte in Frame Synchronizer

Once the synchronization is completed by the exciter’s internal clock, the sync byte is removed, remaining 187 bytes clocked in the exciter as shown in Figure 3.

Figure 3
Clocked 187 Data Packets

Data Randomizer

The randomizer is responsible to randomize the incoming data, which is required to avoid repeating patterns of data that could cause peaks or valleys at the top portion of the RF spectrum.

Reed Solomon Encoder

The next step in the data process is completed by the Reed Solomon Encoder (RSE). RSE is a block type of forward error correction (FEC) for the 187 data bytes/packet. RSE is responsible of adding 20 additional bytes of data at the end of the 187 data packet, for redundancy error correction as in Figure 4. These 20 extra bytes are used in the receiver to identify errors up-to 10 missing or corrupted bytes within the packet.

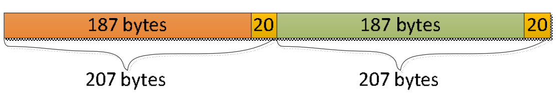

Figure 4
207 Data Packets

Data Interleave

The data inter-leaver is another method to prevent errors within the transport stream. The purpose is to interlace the data in each packet of the stream. The data will be re-distributed in each packet of the transport stream with the creation of 52 new data segments of interlaced data. As an example, suppose that we have all data packets distributed sequentially in block as in Figure 5.

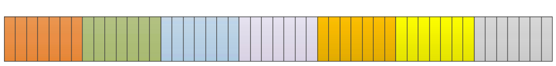

Figure 5
Sequential Data Packet

If the transport stream is submitted to a burst of noise, loss of data may occur as shown in Figure 6.

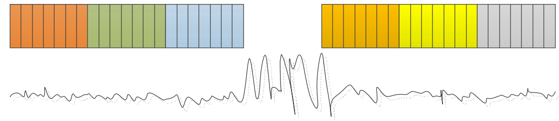

Figure 6
Burst of Noise Affecting Transport Stream

The loss of data can exceed the reed Solomon encoder limit of 10 bytes, causing the loss of a full related group of bytes from a segment.

Unrecoverable data on the receiving side will cause the loss or impairment of video and audio.

To prevent this from occurring, the data inter-leaver will interlace the data as shown in Figure 7.

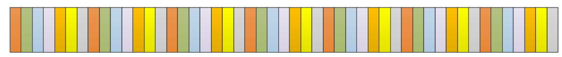

Figure 7
Interleaved Data

If burst of noise occurs, which is common with RF signals transmitted through air, these segments can be recovered since only small portions of each segment would be lost and reed Solomon correction could do the recovery job at the receiving side.

Trellis Encoder

Trellis encoder is another type of error correction. Different from the reed Solomon encoder that treats data as blocks; Trellis encoder uses convolution coding and manages data as a stream of bits that changes with time. Trellis encoder separates each byte in four 2 bit words. Each two bit word is compared to the previous history of the previous two bit words. This code generation is done using shift registers and modulo 2 adders.

A 3 bit binary code is mathematically generated to create an 8 voltage level of modulation process, $2^3 = 8$.

An example of a Trellis encoder with a stream of 8 bits = 1 Byte is, 10110001. Four 2 bit words are 10 11 00 01. At the output, 4 sections of 3 bit words are generated to form 4 new symbols that represent the original 8 bit word. These 4 new symbols have 3 bits each: 101 111 011 001. These 3 bits will give 8 possibilities of patterns or levels of 3 bits for encoding which are: Level 0 = 000, Level 1 = 001, Level 2 = 010, Level 3 = 011, Level 4 = 100, Level 5 = 101, Level 6 = 110, Level 7 = 111.

These patterns for each symbol will be used and distributed into 8 different voltage levels. This is done by rescaling the symbols on a voltage scale of 2 voltage steps from -7 to 7 as shown in Figure 10.

Presenting a simple mathematical formulation we have the following Equation 1:

Original stream data packet = 188 Bytes		(1)
-1 sync byte	187 Byte	
+ Reed Solomon FEC	+ 20 Bytes	
	207 Bytes	

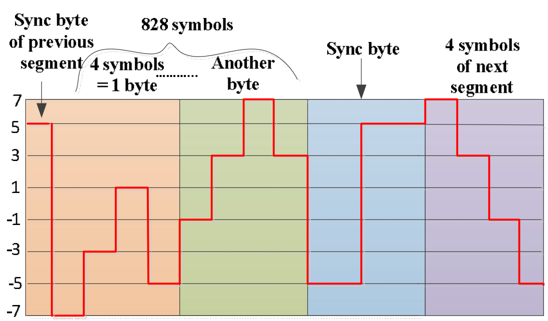

Figure 10
Symbols and Bytes after Trellis Encoder

Additional calculations for the total amount of symbols per segment are shown in Equation 2.

207 Bytes X 4 symbol/Byte = 828 (2)

The segment sync will repeat every 832 symbols, including the 4 sync symbols. Figure 11 shows a full graph of a segment. One field is 313 data segments and two fields is one data frame.

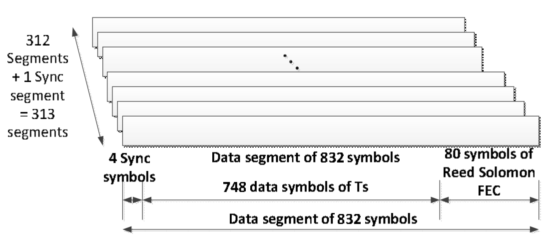

Figure 11
Data Segment

The Mpeg-2 stream received by the exciter is of 19Mbps, which is modified by the 2/3 rate concatenated Trellis coder. This means that 90% of the data is processed at a 2/3 rate and will give an output rate of 187/207*2/3 = .6022.

With this coding rate, we can process the 19.44 Mbps/.6022 stream and obtain an output of 32.3 Mbps stream. The symbol rate is 32.3Mb/3 = 10.76 Msymbol/sec.

The channel assigned bandwidth is 6 MHz, and half the symbol rate is 10.76/2= 5.38Mhz, which is the used bandwidth. The difference is 6Mhz-5.38Mhz = 0.62. The roll off will use .62Mhz/2 = .31Mhz for each side of the edge or roll-off portion of the bandwidth.

Vestigial Sideband Modulation

The modulation process is an essential part of the digital signal processing section. One of the most important parts of this modulation process is the filter which will eliminate the portion of the excessive bandwidth to stay inside the 6MHz portion assigned per channel.

As we could recall from a modulator of amplitude as in Figure 12, we can arrange several equations as follows below.

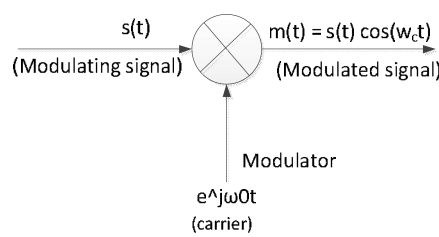

Figure 12
Amplitude Modulator

Equation 3 is the product of the modulating stream s(t) with the carrier, which is in this case, an intermediate frequency to get the modulated signal.

$$m(t) = s(t)e^{jw_0 t} \quad (3)$$

If we calculate the Fourier Transform of this modulated signal to analyze the behavior of the signals spectrum, as in Equation 4

$$m(t) = \mathcal{F}\{m(t)e^{jw_0 t}\} = \int_{-\infty}^{\infty} s(t)e^{jw_0 t}\, e^{-j\omega t} \quad (4)$$

Equation 5 below is the results of Fourier transform which represents the spectrum of m(t).

$\frac{1}{2}$ $A[m(w - w_c) + m(w + w_c)]$ (5)

The graphical representation of the spectrum is presented in Figure 13.

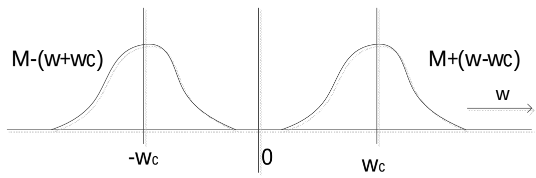

Figure 13
Spectral Characteristics Amplitude Modulation

Now we will develop a specific transfer function as in Equation 6, with requirement equal to 1 and spectral characteristics as seen in Figure 14.

$H(w - wc) + H(w + wc) = 1$ (6)

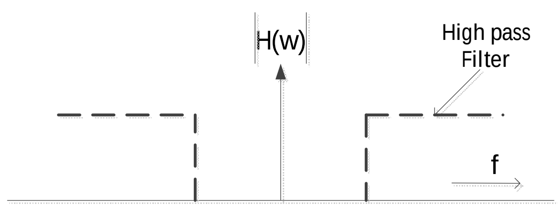

Figure 14
Spectrum Graph of the Filters Transfer Function

We need spectral requirements for vestigial symmetry, with a gradual roll-off, after the cutoff frequency to eliminate the portion of the sideband in a correctly vestigial shape as in Figure 15.

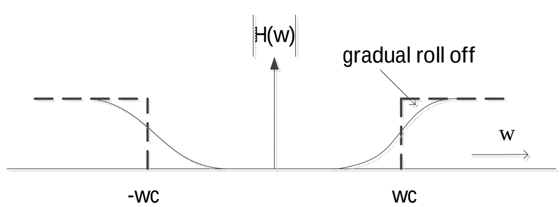

Figure 15
Vestigial Filter Spectral Requirements

Vestigial symmetry means that the lower portion of the roll-off must be perfectly symmetric with the upper portion in order to make a difference equal to the constant value of one and comply with the mathematical requirements of Equation 6 as shown in Figure 16.

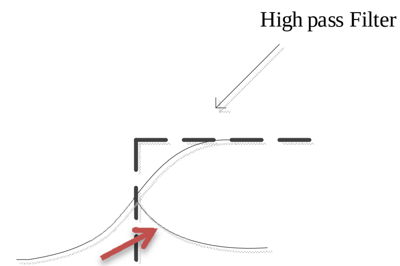

Figure 16
Roll Off Portion Fold Back for Symmetry Comparison

The importance of vestigial symmetry is that the filtering method will eliminate only a portion of the lower sideband, to maintain enough bandwidth for the 6 Mhz channel and the roll off factor.

In a VSB signal, the in-phase portion $s_I(t)$ of the signal remains the same, while the quadrature portion $s_Q(t)$ does not when the signal is passed through the filter with vestigial characteristics.

Signal s(t) is represented by the Equation 7, and each component, $s_I(t)$ and $s_Q(t)$, will be analyzed independently when passed through the VSB filter.

$s(t) = s_I(t) \cos 2\pi f_c t + s_Q(t) \sin 2\pi f_c t$, and (7)

Using the in-phase component and assuming a coherent detection to relate $s_I(t)$ with s(t). Multiplying s(t) with $\cos(wt)$ will give the same spectrum as in Equation 3. Passing the signal through the VSB filter will give us Equation 8 for s(t) < bandwidth, and Equation 9.

$s_I(w) = \frac{1}{2} A[s(w - w_c) + s(w + w_c)] * H(w)$ (8)

$s_I(w) = 0 \qquad |f| > BW$ (9)

The result of the multiplication in frequency domain, which is convolution in time domain, is shown in Equation 10.

$s_I(w) = \frac{1}{2} Am[H(w - w_c) + H(w + w_c)]$ (10)

The filters requirement from Equation 6 indicates that the filter's transfer function must equal to 1. The results of $s_I(w)$ is in Equation 11.

$s_I(w) = \frac{1}{2} Am(w)$ (11)

The same procedure will be applied with $s_Q(t)$, which is the quadrature time domain signal in Equation 10. The Fourier transform of $s_Q(t)$ Equation 12 will lead us to $s_Q(w)$ in Equation 13.

$$s_Q(t) = \sin 2\pi f_c t, \quad (12)$$

$$s_Q(w) = j[s(w - w_c) - s(w + w_c)] \quad (13)$$

The quadrature signal, $s_Q(w)$, is passed through the VSB filter as in Equations 14 and 15.

$$s_Q(w) = \frac{j}{2} A[m(w - w_c) - m(w + w_c)] * H(w) \quad (14)$$

$$s_Q(w) = \frac{j}{2} Am[H(w - w_c) - H(w + w_c)] \quad (15)$$

We can observe from Equation 15, that $s_Q(w)$ does not remain the same when filtered. Then, If we give another variable to the Equation 15, which could be (ḿ); we can restructure the original signal input s(t) as shown in Equation 16, and its corresponding circuit representation in Figure 17.

$$8_{VSB} = \frac{1}{2} Am(t)\cos 2\pi f_c t + \frac{1}{2} A\acute{m}(t) \sin 2\pi f_c t \quad (16)$$

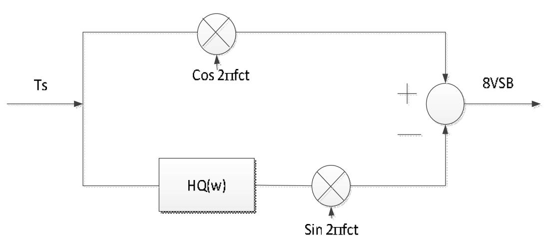

Figure 17
8VSB Modulator

COVERAGE BEFORE AND AFTER DTV CONVERSION

Plenty of changes have been made due to this new modulation scheme. One of them has been the power output from transmitters used to reach a specific population with free over the air television signal. With former analog modulation systems, high power was necessary because there were no error corrections methods as part of the modulation process to stand against noise encountered through air, since baseband signals were modulated directly and not a data transport stream as today.

To analyze this in detail, prediction coverage maps will be used as part of the analysis before and after the DTV conversion using as base, Longley Rice computer model, which is the standard model adopted by the FCC, rule 73.683(d) [2] for evaluation of Irregular Terrain.

Field Strength

Determining the field strength is one of the most important parts of predicting coverage since it is the base of the effective power to be radiated (ERP) to reach the area to be served with over the air DTV signal. Table 1 represents the reference field strength levels which were obtained from section 73.625 [3] of FCC rules to establish a DTV transmitter location.

Table 1
F(50,90) Field Strength

Channels 2–6	35 dBu
Channels 7-13	43 dBu
Channels 14–69.................................	48 dBu

These field strength values represent the minimum median values that should receive an antenna at 30 feet high, above ground level, at a specified distance from the transmitter. These values are known as the threshold of visibility (TOV). With these values, the FCC has constructed the contour charts of F (50,90) for DTV systems. The F(50,90) curves are a determined upon calculations of statistical mean and standard deviation, and are used in predicting the distance to the field strength contours. The contour charts are meant to establish that, 50 percent of locations within a specified transmitter distance should have minimum mean signal strength, at least 90% of the time. These charts are calculated using as reference an ERP of 1 KW radiated from a half wave dipole at a 1 mile distance.

The levels at a receiver site does not only depend on field strength of signal but also on line of sight, receiver figure noise, orientation of receiving antenna, gain of receiving antenna, cable and connector loss, as well as random noise, among other interference.

For the purpose of a prediction analysis tool, we will assume ideal conditions and will include only the losses permitted by software Mobile Radio.

The electric field intensity in dbu units does not depend on receiving antenna gain, impedance, line loss or frequency. Therefore, the measure is completely used as a representation of service area from a transmitter point of view. When the path has line of sight and there are no obstruction within 0.55 of the first Fresnel zone [4], which would then add attenuation, the received electric field intensity for free space propagation could be calculated using the Equation 17.

$$E\frac{\text{dBuV}}{\text{m}} = 106.92 + \text{ERP(dBk)} - 20\log(\text{d km}) \quad (17)$$

This means a signal levels in dB units above 1 microvolt per meter. With Equation 18, we can confirm that the prediction charts are based on an effective radiated power of 1 KW obtained from a half wave dipole in free space, assuming no loss, from 1 mile distance transmitter.

$$E = 106.92 + 60\text{ db} - 64.13\text{ db} = 103\ \frac{\text{dBuV}}{\text{m}} \quad (18)$$

Longley Rice Modeling and Coverage Comparison

The facilities used for this analysis is a real DTV transmitter located at Aguas Buenas, La Mesa that belongs to Univison Puerto Rico, Ch-11, 198-204 Mhz. All values as lines loss, antenna gain and transmitter power output are actual values.

The methodology used will be based on FCC regulations for prediction DTV coverage using Longley Rice Model [5] to establish a theoretical comparison between the transmission coverage before and after DTV conversion. The only difference between both systems was the power output and modulation scheme. The antenna patterns are the same, as well as line loss, transmitter site location and municipalities to be served.

Figure 18 shows a clear line of sight path profile between transmitter site at Cerro Marqueza and a receiving site in San Juan. With a transmitter power output of 3.98 KW, an ERP of 34.76KW was calculated for that specific azimuth by the software.

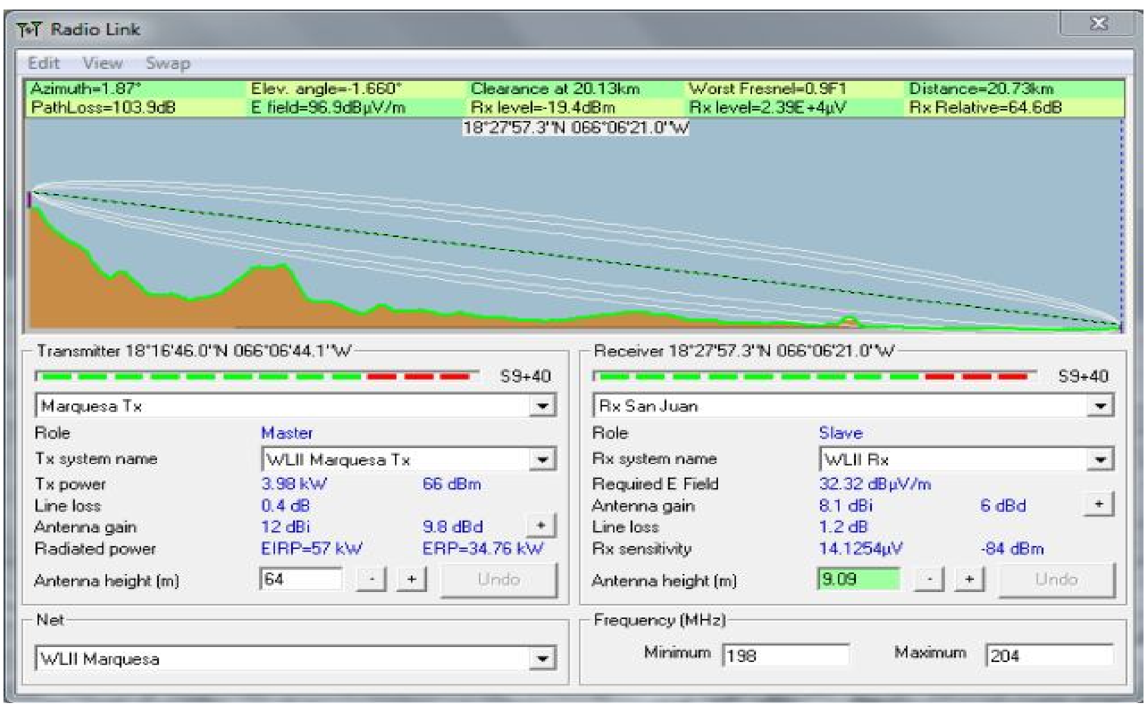

Figure 18
Marqueza-San Juan Path Profile

As could be observed from the profile Figure 18, we have field strength in dbu which can be confirmed using the previous Equation 19.

$$E = 106.92+15.41-26.33 = 96\,\frac{dBuV}{m} \qquad (19)$$

With this field strength we can calculate the power level received in dbm [6], as shown in Equations 20 and 21 .

$$P(dbm) = E\left(\frac{dBuV}{m}\right) + \mathrm{Gr(dbi)} - 20\log F(Mhz) - 77.2 \qquad (20)$$

$$Pdbm = 96 + 8.1 - 46.06 - 77.2 = -19.16 \qquad (21)$$

As could be observed -19.16 dbm is the received power calculated in San Juan and is confirmed on the profile path of Figure 18.

With -84 dbm established as the minimum required receiver sensitivity threshold, we have a receiver in San Juan to operate at a level of -19.4 dbm which is a good level.

This is the methodology used for the software algorithm to establish the receiving level with clear line of sight. When signal level is over 60% Fresnel zones level 1, the signal level is considered as in clear line of sight.

When the signal level is below 60% of Fresnel level 1, then it is considered to have diffractions, and additional loss is required in the calculation. In that case the algorithm used to calculate that additional diffraction loss is based on Longley Rice model.

In the San Juan path profile Figure 18, the Fresnel zone is 0.9F1 or 90% of Fresnel level 1, which means a clear line of sight path. This could also be observed visually in the Figure 18 by the contour elevation data between Marqueza transmitter and San Juan city. There are no visual obstructions in the path.

Using this methodology, all sites served by Marqueza transmitters will be evaluated with the Longley Rice model software, Mobile Radio. Using as reference 38KW ERP after DTV conversion and the former power when analog 316KW ERP, to establish a base for analysis.

Figure 19 is a screen shot of Mobile Radio with some main municipalities served by the Marqueza transmitter and others that could not be served by Marqueza Transmitter. This transmitter has call sign WLII and is located at Cerro La Mesa Marqueza, Aguas Buenas Municipality.

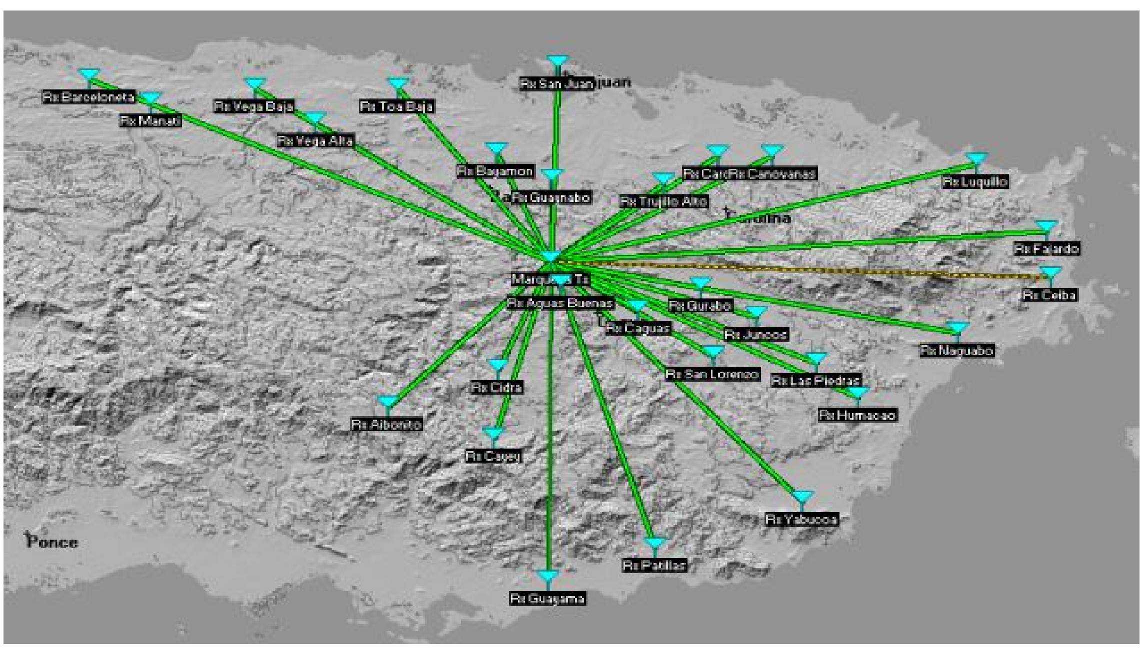

Figure 19
WLII Transmitter Coverage Sites with Mobile Radio

Figure 20 is the predicted coverage map of the -43dbu strength service level referenced to Table 1 for DTV transmitter Marqueza site WLII.

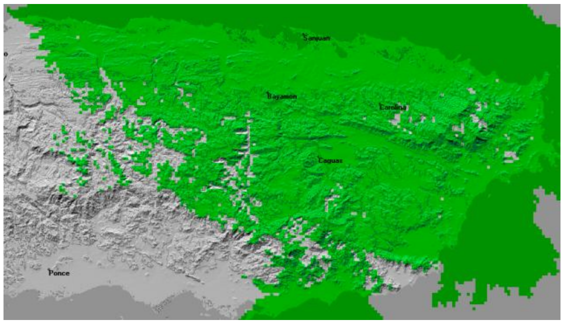

Figure 20
WLII Marqueza DTV Coverage

The green area is the area of signal level and the gray area has no signal. As could be observed, there is an area of the southeast part of the Island that has shades of gray. This is the Municipality of Guayama and this service area is not impacted with this transmitter due to line of sight and obstructions between Guayama and Marqueza as shown in the profile Figure 21. The predicted signal receiving level (Rx Level) reading in the profile is -79.7dbm.

Recall that the sensitivity at receiver is -84dbm, which means that this receiver located at Guayama is near what is called the cliff effect, or threshold of visibility (TOV), which is the level established by the curves F(50,90).

In the next analysis, the data from F(50,50) [7], will be used as reference to analyze the former analog transmitter prediction coverage, with 316KW ERP. Table 2 shows the grade B minimum level to receive service from the curves F(50,50) when in analog NTSC systems [8].

Table 2
Service Grade B Levels

Channels 2–6 .... 47 dBu
Channels 7-13 .... 56 dBu
Channels 14–69.................................. 64 dBu

These signal levels from Table 2 are directly compared to Table 1. It is to be observed how the signal strength levels were higher with NTSC analog modulation systems and with higher power transmission output as compared with the digital modulation schemes.

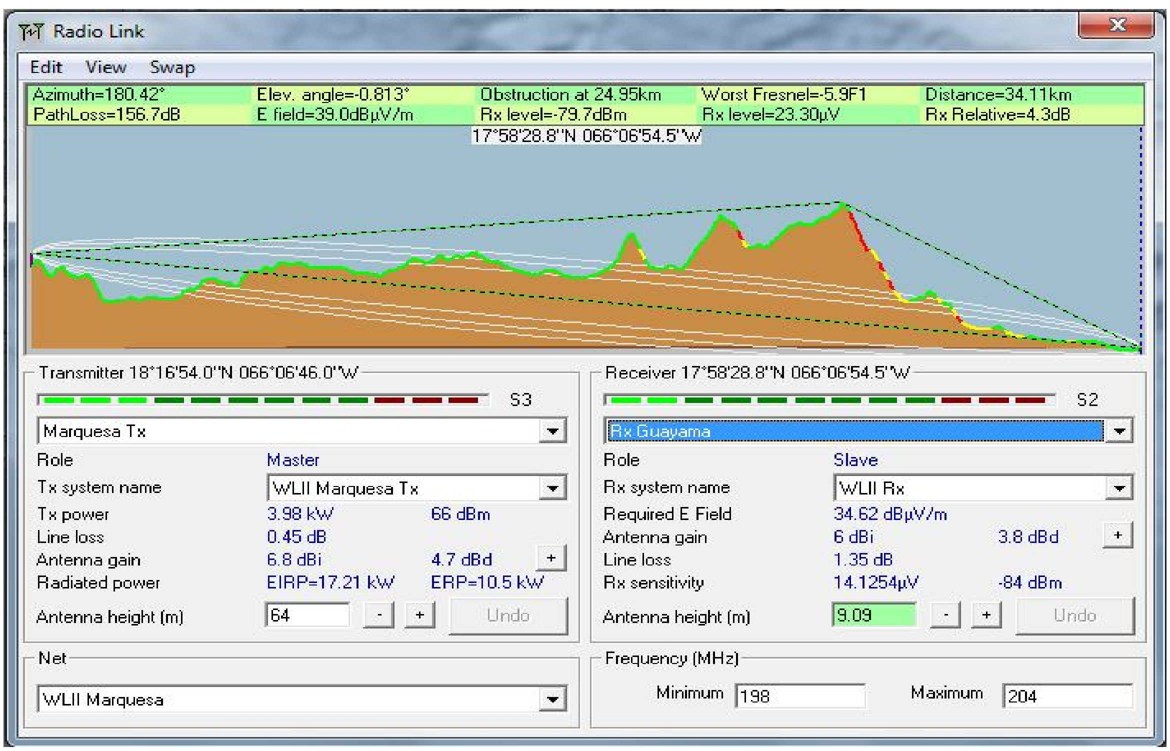

Figure 21
Marqueza-Guayama Profile With DTV Power

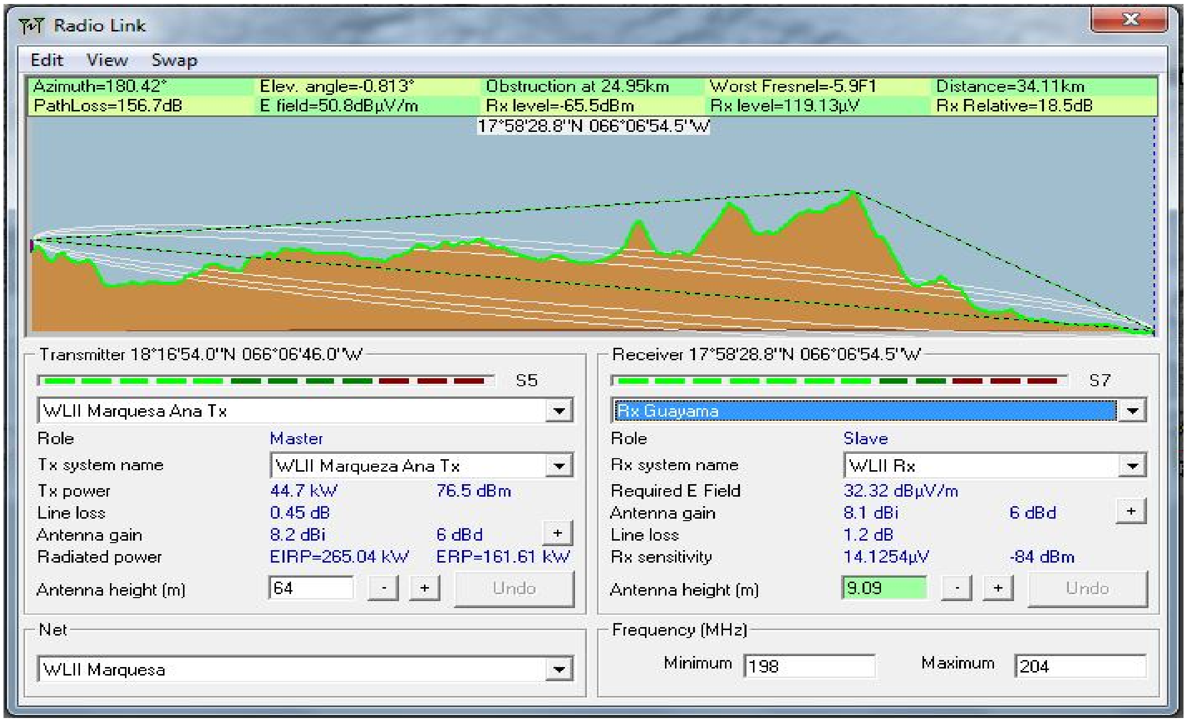

Figure 22
Marqueza -Guayama Profile Analog Power

Figure 22 shows the same analysis profile path of Marqueza-Guayama with former analog power transmitter output. It is to be observed that when analog, this area reflected a higher signal strength of 50 dbu compared to 39 dbu with actual DTV system.

Figure 23 shows coverage maps of Marqueza using former analog transmitter power output. It is to be observed that the difference between Figure 20 and Figure 23 is the ERP output .

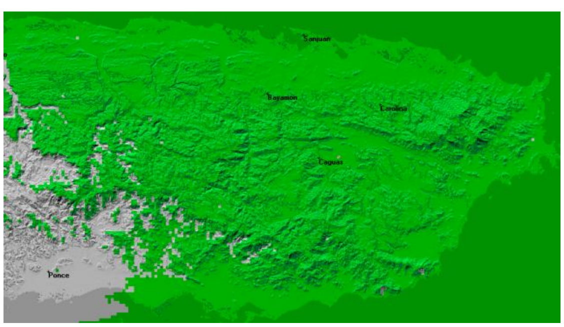

Figure 23
Former Marqueza Transmitter Predicted Analog Coverage

However, when the 50 dbu were compared with the former analog NTSC contour parameters, F[50,50], it was observed that the receiving level was also near threshold of grade B service which was 56dbu referenced to Table 2 with a significant increase in transmitter power output from 3.98 KW to 44.7 KW.

More power was required in analog system since these systems were more sensitive to noise because no error correction factors were included in the modulation schemes as with digital modulation, which has the advantage of including several methods of forward correction parameters.

8VSB SIMULATION WITH MATLAB SIMULINK

8VSB modulators are designed with DSP systems. The following methodology has been implemented on a basic 8VSB simulation.

An MPEG 2 stream has been replaced by a dual Bernoulli random generator as in Figure 24.

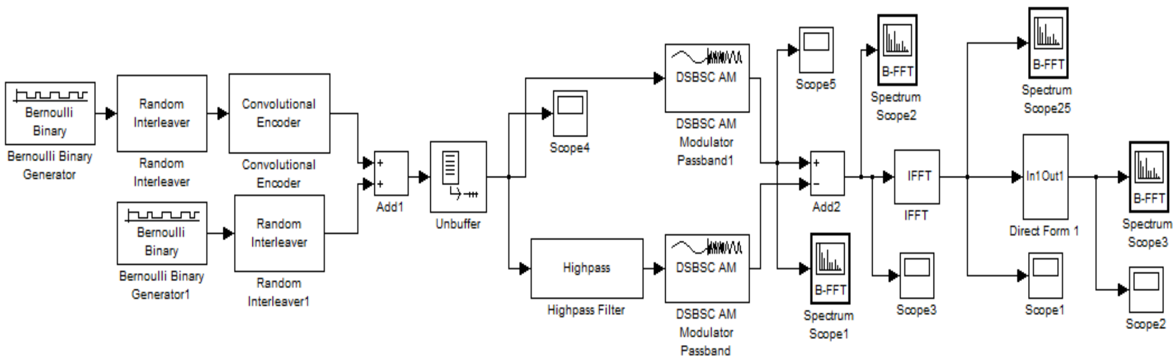

Figure 24
8VSB Modulator

The data interleaver followed by convolution encoder are combined to deliver a 2/3 rate Trellis encoded data to the modulator.

Next is the VSB modulator that will work on the stream to generate a 44 Mhz IF signal as shown in Figure 25. The output of the modulator is a double sideband suppressed carrier signal DSB-SC, and as expected from Equation 5, there is a replica of the spectrum. This theory could also be proved by the application of the modulation property to the Fourier Transform of a sinusoidal signal.

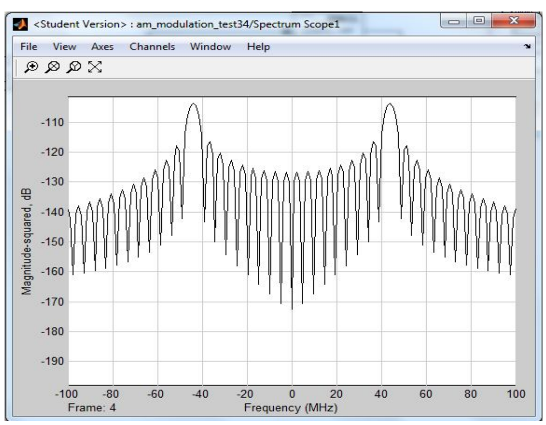

Figure 25
Modulator Output, DSB-SC

The next step in the process is to obtain the impulse response of the modulator output. This is done by taking the IFFT of the spectrum of the signal which is known as the interpolator function or sync function. This signal will be used to input the Direct Form Realization filter [9], as shown in Figure 26. This system will convolve the impulse response obtained from the Inverse Fourier Transform with each of the 8 voltage levels of the system to generate the IF signal of 8VSB. It is to be observed that + 1.25 is added to each level to generate the pilot.

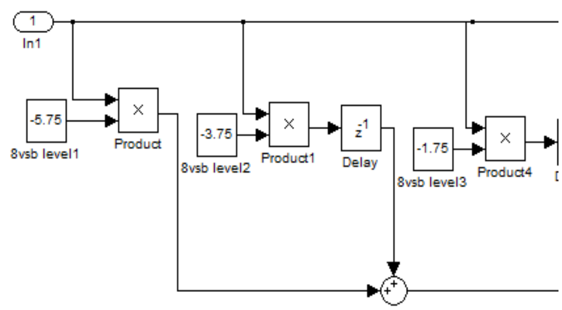

Figure 26
Direct Form I Realization Subsystem

The output of this system is the IF signal with the data modulated as shown in Figure 27 which is a time signal.

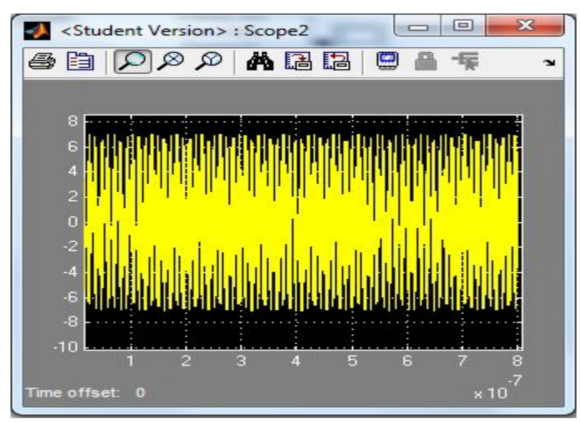

Figure 27
44Mhz IF, 8VSB Signal

Figure 28 shows the same IF signal zoomed in to observe the data and the 8 voltage levels.

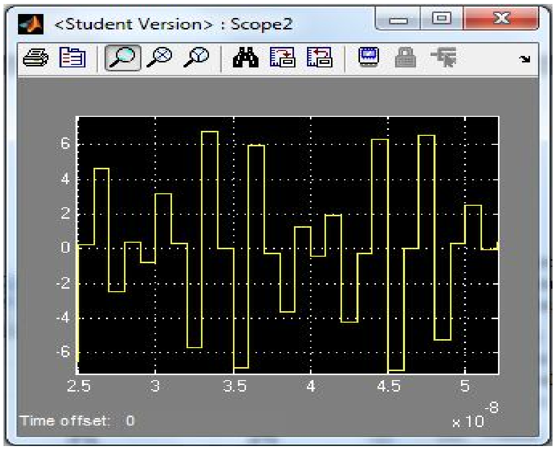

Figure 28
Spectrum of VSB Modulator Output

CONCLUSION

DSP has played an important role in the design and deployment of 8VSB modulation system for terrestrial broadcast systems. One of the impacts was the reduction of power in transmission system due to the introduction of FEC techniques in the modulation schemes.

With this reduction in power in DTV transmission systems, signal to noise ratio (SNR) at receiver level has decreased to 15db in DTV systems as compared to former analog systems which had a SNR of 34db with the worst quality signal annoying to viewers. When power was incremented to a SNR of 51db the signal gradually had a less annoying effect until reaching a considerable snow free view. In digital systems there is not such a wide threshold range, if level decreases by 1db below SNR of 15db, signal is lost or impairments start to appear in video and audio which is known as the cliff effect.

Other important impacts that DSP technology has offered is the better utilization of bandwidth due to advanced MPEG compression techniques. Due to this, it has been possible to have combinations of several Standard Definition (SD) and High Definition (HD) channels in one same stream on air simultaneously on one same 19.4 Mbps stream [10]. This distribution and compression process is completely transparent to the modulation process. The modulator just requires 19.4 Mbps or less within the standards. The way the user wants to distribute that stream of data is an individual decision for each station based on stations objectives and standards.

With the findings and concepts learned in this project, further steps to measure the actual power in these referenced areas, and compare with theoretical data is to be made. If results are according to theory, the next step is to identify possible locations to perform further evaluations and addition of low power transmitters to cover the small areas.

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