DTV Transmitter Installation and Proof of Performance

David A. Sparano
Harris Corporation Broadcast Division
Quincy, Illinois

Abstract

The advent of ATSC digital television (DTV) in the United States has created the need to install an entirely new terrestrial transmission infrastructure nationwide. A principal piece of equipment in any television transmission plant is the high power television transmitter. This paper considers the various challenges to the successful installation of high power DTV television transmitters and identifies the performance parameters that play an important role in transmitter adjustment and operation. Data excerpted from a recent DTV transmitter of performance are also included to provide an indication of performance levels to be expected.

This is an updated and revised version of an article that originally appeared in the July 1999 issue of the SMPTE Journal under the title of "DTV Transmitter Installation Experience and Planning."

Introduction

During the period of transition to DTV, the broadcast engineer will face a wide variety of challenges brought about by the requirement to install and maintain a second full-power television transmitter. There will be technical challenges, such as the need to adapt to a new transmission format, 8-VSB, with its unfamiliar performance parameters and measurement techniques. There will also be the physical challenge of installing a large, complex, transmitting system - often times at an NTSC site where space and electrical power were already at a premium before the advent of DTV. This paper examines some of these challenges, both physical and performance-related, that must be met and overcome to ensure a successful DTV transmitter installation. The stages of a DTV transmitter implementation are presented in chronological order, beginning with the task of specifying the correct transmitter type, proceeding through the stages of on-site installation, and concluding with the transmitter proof of performance.

I. Transmitter Specification: Choosing the right transmission technology

The first major task facing the broadcast engineer is that of selecting a transmitter with the appropriate transmission technology for their particular application. There are two major transmission technologies employed in high power DTV transmitters today: vacuum tube amplifiers and solid-state amplifiers. The determination as to which technology is appropriate will depend on the power level and frequency of operation required.

At VHF channels, because of the relatively low effective radiated power (ERP) levels required (less than 100 kW[1]), virtually all DTV transmitters are solid-state. These transmitters typically feature 250W - 500W solid-state MOSFET amplifier modules operating in parallel to achieve power levels of 1 - 2 kW per cabinet.

At UHF channels, however, ERP's ranging from 50 kW to 1000 kW create the need for both tube-type and solid-state DTV transmitters. The vacuum tube of choice is the Inductive Output Tube (IOT); the solid-state device of choice is the laterally diffused MOSFET or LDMOS FET.

Each transmission technology has its own particular benefits to offer. Table 1 offers a very brief comparison of the relative merits of each technology. An excellent, more extensive, comparison can be found in the DTV Express Training Manual [1] published by Harris. Additionally, articles dealing with this subject appear from time to time in the major trade publications.

[1] All power levels given in this section are based on *average* DTV power

Table 1 - Summary Comparison of IOT vs. Solid-state Transmitters

Parameter	UHF Tube Type (IOT)	UHF Solid-state (LDMOS)
Power per PA cabinet	21 kW avg.	7.25 kW avg.
Models available (avg. power)	15, 21, 30, 42, 63, 84 kW	1.8, 3.6, 5.5, 7.25, 10.5, 14, 20.5, 27.5, 34.5 kW
Configuration	single IOT per cabinet	16 x 500W modules per cabinet
Redundancy	requires additional cabinets	excellent
RMS efficiency	20% - 25%	18% - 20%
Peripheral equipment	RF system, heat exchanger, pump module, HV transformer, voltage regulator	RF system, air system
EVM Performance	3 - 5%	2 - 4%
Cooling	water / glycol	Forced air
Main power supply (per cabinet)	1 x 36 kV @ 3A	8 x 32V @ 125A
Installation time	2 weeks p/ PA cabinet *	1 week p/ PA cabinet *
Maintenance required	200 hours per year *	20 hours per year *
Maintenance skill level required	Engineer w/ 5 years experience *	Engineer w/ 1 year experience *
Purchase price per watt (approx.)	$20 - $25	$50 - $55
Target customer	200 - 1000 kW ERP	0 – 500 kW ERP

** estimated values*

Generally speaking, solid-state amplification becomes cost prohibitive beyond the 25 kW (average) transmitter power output (TPO) range. Therefore a solid-state transmitter may be a viable option for those stations with ERP's of 500 kW or less, depending on the antenna gain and transmission line being used. Required TPO can be determined from ERP by means of the familiar formula:

$$TPO = ERP / (\eta \, G_{ant})$$

Where,

TPO = transmitter power output in watts
ERP = effective radiated power in watts as assigned by FCC
G_{ant} = antenna gain in times (x)
η = transmission line efficiency for specified length ($0 < \eta < 1$)

Figure 1. Photo, IOT and solid-state transmitters.

II. Site Planning

Once the appropriate transmitter type and model has been identified, the next major task is that of assessing the suitability of the proposed site for a new transmitter installation. There is a myriad of potential site problems that may be encountered. These will vary from site to site, according to the local site conditions and the transmitter type selected (tube-type vs. solid-state). Representatives from the transmitter manufacturer are generally available to assist in this site assessment process.

IOT transmitter

First let us consider the site-related challenges posed by an IOT transmitter.

One of the major obstacles encountered with all new IOT-DTV installations is that of obtaining sufficient AC electrical power. The 36 kV beam supplies found in an IOT transmitter require a 480 VAC three-phase primary voltage. In the majority of cases, the installation of a new 480 VAC service is required to power the IOT-DTV transmitter. Many UHF-NTSC sites do not have sufficient AC current headroom with their existing service to accommodate a second full power transmitter; most VHF-NTSC sites have no 480 VAC service at all. The time and effort required to obtain a new 480 VAC service will vary according the local power utility and transmitter site location. In very remote locations, the timely installation of a new 480 VAC service may require a great deal of advance notification and planning. See Figure 7, contained in a later section of this article, for an indication of how many kilowatts of AC service will be required to power a new DTV transmitter.

The next major challenge is one of available space. Many existing NTSC sites present space difficulties in one of three areas: available floor space for transmitter cabinets, available ceiling space for the RF system, or available outdoor space for the cooling system and high voltage supplies.

Determining if adequate space exists for the transmitter cabinets is a relatively straightforward task. In very cramped situations, some degree of flexibility is provided by the ability to remotely locate the transmitter system control cabinet (exciter cabinet); it may be located in a separate room, up to 50 feet away from the PA cabinets. Needless to say, if sufficient space cannot be found for the transmitter cabinets, or for any of the other transmitter components to be discussed shortly, the only remaining solutions are either to build an addition to the existing NTSC plant or to find an entirely new site all together.

The IOT RF system is comprised of several different major assemblies: magic tee(s), hybrid(s), a low pass harmonic filter, and a channel bandpass filter. The RF system is somewhat large and cumbersome, being constructed of WR1150 or WR1500 waveguide, and is typically ceiling-mounted in the interest of conserving floor space. This may create installation problems, especially at sites with a ceiling height of less than twelve feet or those with an existing NTSC waveguide RF system already in place. In cases where adequate ceiling space is not available, but floor space is plentiful, a floor-mounted unitized frame RF system may be employed.

Figure 2. Photo, IOT ceiling-mounted RF system
lower left: IOT amplifier cabinets and PIE racks
foreground: WR1500 waveguide magic tee combiner w/ water column coaxial RF loads
background: high power output bandpass filter (blue cavities)
background: cooling system pipes along back wall
lower background: line control cabinet against wall (just behind PC screen)

The IOT transmitter system has an assortment of peripheral equipment that is not mounted contiguous to the transmitter cabinets. These items include the HV beam supplies, pump modules, heat exchangers, line control cabinets (i.e. step-start contactors), a voltage regulator, and a surge suppressor. The quantity of these items required will vary according to transmitter power level and model. The line control cabinets, voltage regulator, and surge suppressor are always located indoors, preferably close to the main AC distribution panel. The beam supplies, pump modules, and heat exchangers are typically located outdoors in order to conserve indoor space and simplify cooling system operation. At most sites, the construction of a new outdoor concrete pad is required to accommodate these outdoor units. In many parts of the United States a protective ice bridge may also be required to shield against falling ice from the tower and/or guy wires.

Figure 3. Photo, IOT system outdoor components.
far left: bottled water for charging cooling system
left: 36 kV beam power supplies (2)
foreground: pump module (main / alt pumps, reservoir tank, auto switchover valves)
right: 3-fan heat exchangers (2)
note: no ice bridge shown

When sufficient outdoor space is not available, these peripheral units may be mounted indoors alongside the transmitter, indoors on a different level (such as the basement), or even on the roof. It should be noted, however, that an indoor heat exchanger requires the appropriate inlet and outlet ducting of outside cooling air. This represents additional project cost and complexity and should therefore be avoided, if at all possible.

Another space-related factor, which can play a crucial role in site planning, is the issue of expandability. Many stations may wish to initially purchase a basic transmitter and add additional PA cabinets for increased redundancy (or higher power operation) in the future - once DTV gains market acceptance. A popular trend recently has been the purchase of a single IOT transmitter with a physical site layout that leaves enough room for a second PA cabinet and a two-tube RF system (or even three cabinets with a three tube RF system). Some stations have even purchased two-tube RF and cooling systems to use with their single PA cabinet. This will reduce the amount of work (and off-air time) required when the second PA cabinet is eventually installed. The second RF input port, which corresponds to the missing PA cabinet, is simply terminated into an RF load.

Finally, one site-related difficulty not to be overlooked is that of site off-loading access. Good site accessibility is required for the tractor-trailers that will deliver the transmitter shipment. Sufficient maneuvering space must also be available for forklift and crane required to off-load, and place, the major transmitter assemblies, once they arrive. The HV beam supply for an IOT transmitter weighs approximately 3800 pounds, the PA cabinet 2400 pounds, the heat exchanger 700 -1300 pounds, and the pump module (unitized main/alt pumps with reservoir) 800 pounds.

Transmitter room cooling is generally not a problem, because almost all of the waste heat generated by the IOT itself is evacuated from the building by the liquid cooling system and vented outdoors. Some heat is lost to the room by radiation from the cooling system pipes, especially if they are not insulated. The transmitter control and solid-state driver circuits also generate some heat, along with the RF circuit losses in the output bandpass filter. As a rule of thumb, 2 - 3 tons of air conditioning capacity per PA cabinet is required to cool the transmitter room.

Solid-state Transmitter

From an installation standpoint, solid-state transmitters are generally easier to accommodate. Since solid-state transmitters do not require a large quantity of peripheral equipment, and use coaxial RF line instead of rectangular waveguide, they generally fit with little difficulty into most NTSC transmitter buildings. A wide variety of input voltage options are available (from 208 VAC to 480 VAC) which make interfacing to the existing power system quite easy.

The greatest difficulty posed by solid-state transmitters is typically the air-cooling system. There are two basic types of air systems: *open loop* and *closed loop*. In the *open loop* system, the transmitter room is positively pressurized with outside air by an external blower, the transmitter's internal blower pushes cooling air through the transmitter itself, and a third external blower removes the heated air from the transmitter room through an exhaust hood. In the *closed loop* system, the transmitter is allowed to vent freely into the transmitter room. A large air conditioning unit removes the waste heat load from the ambient room air - no outside air is allowed to enter the transmitter room.

The *open loop* air system has the advantage of being less expensive and mechanically simpler. It has the disadvantages of requiring frequent air-filter replacement and the possibility of allowing contaminated outside air into the transmitter room. From a site planning point of view, the main challenge in designing an open loop air system is that of ensuring that the required number of cubic feet per minute (cfm's) of air flow will pass through the transmitter. Solid-state transmitters require a much greater quantity of airflow than traditional air-cooled tube transmitters (typically 3500 cfm's per PA cabinet versus approximately 1500 cfm's per PA cabinet). Such a large quantity of air calls for large, straight ducts with no sharp turns. If exhaust air ducts are too constrictive, excessive backpressure will result, and airflow will be reduced. Additionally, the cfm flow rates among all three blowers must be balanced correctly (inlet vs. outlet) so that the air may flow smoothly throughout the entire system. Without adequate cooling airflow, transmitter reliability and longevity will be compromised.

In the *closed loop* system, balancing cfm's of airflow is no longer a concern since the transmitter exhaust vents freely into the surrounding room. With this arrangement, it is necessary to balance the air conditioner BTU capacity with the BTU heat load generated by the transmitter. As a rule of thumb, a solid-state transmitter requires about 7 - 10 tons of air conditioning capacity per PA cabinet when used in the closed loop configuration.

III. Transmitter Mechanical Installation

Once an order is placed for a new DTV transmitter, there is usually a 3 - 5 month waiting period while the transmitter itself is being built. During this time, the customer performs all necessary building modifications / expansions and installs any new AC services that may be required. Once the transmitter is completed, it is delivered to the customer site and the transmitter installation begins. Transmitter manufacturers typically offer a variety of installation options, from (one-man) on-site supervision to a complete turnkey installation.

An IOT transmitter installation typically lasts four to five weeks and is divided into two major phases: the transmitter *mechanical installation* and the *check out and proof*. Table 2 contains a sequential list of all of the steps involved in an IOT-DTV transmitter installation.

During the *mechanical installation*, a work crew of typically two or three persons installs the transmitter cabinets, RF system, and cooling system. An installation crew typically consists of a lead installation engineer, an assistant engineer, and a mechanical installer/plumber.

The customer typically supplies a local electrician for the electrical hookup portion of the installation. This is often required by local labor regulations and a local electrician is generally more aware of the prevailing building, fire, and electrical codes in their area. A work crew of four or five electricians is generally required to complete the electrical phase of the installation in a timely manner. The electricians work from drawings supplied by the manufacturer and should complete their portion of the installation within the first ten days after the transmitter shipment arrives in order to avoid costly project delays.

Figure 4a. Photo, IOT system outdoor components: workers move 36 kV beam supply into final position.

Figure 4b. Photo, IOT system outdoor components: workers move pump module into final position.

Table 2 - Sequential List of Tasks Involved in an IOT-DTV Transmitter Installation

Sales contact
Applications site survey by Harris (if required)
- determine transmitter model required
- approximate system layout determined

Site specific system drawings made (if required)
Order placed with Harris
Harris places order with vendors (beam supplies, heat exchanger, RF system, tubes)
Customer contacts electricians / general contractors
Implementation site survey by Harris
- meet with electrician, architect, general contractor
- discuss scope of work, review installation drawings

Electrician / general contractor submit bids to customer
Customer completes building preparation work (concrete pads, ice bridge, new AC service)
Customer lines up off-loading rentals if necessary
Harris field engineers arrive
Transmitter shipment arrives
Transmitter cabinets off loaded & assembled
Transmitter cabinets positioned & leveled
Tubes unpacked and assembled
Tubes installed in cabinets
Crowbar installed in cabinets
Driver module installed in cabinets

Beam supplies placed	Channel strut frame installed in ceiling	Cooling system layout determined
Spark gap installed in HVPS	4-port switch hung & leveled	Heat exchanger bled off and un-capped
	Bandpass filter hung & leveled	
Line control cabinets placed (Electrician)	Magic tee(s) hung & leveled	Heat exchanger placed
480V conduit installed (Electrician)	Entire RF system level re-checked	Pump module placed
Interconnect conduit installed (Electrician)	RF loads hung	Small plumbing assemblies made
480V wiring installed (Electrician)	RF system braces installed	Strut supports & hangers installed for plumbing
120V wiring installed (Electrician)	RF lines from cabinets cut, soldered	
	Saddle couplers and fine matchers installed	Flow meter hung & indoor plumbing interconnected
Interconnect wiring installed (Electrician)		
Interconnect wiring terminated	RF lines from cabinets installed	Flexible hose installed
		Tube collectors temporarily by-passed
		Outdoor plumbing interconnected
		480 VAC hooked up to cooling system
		Cooling system loaded with water
		Phase rotation checked for pumps and heat exchanger fans
		Soap added & circulated
		Cooling system drained
		System re-loaded with water, rinsed, and drained 2-3 times
		System re-loaded with water and 50% glycol
AC turned on to cabinets	Water and glycol circulating in loads	
Safety interlocks checked	RF system matching verified with network analyzer	
Test equipment shipped to site		
Test equipment set up		Tube collectors connected to water system
Exciter signal checked		
Driver signal checked		
Tube low voltage parameters adjusted		
High voltage turned on		
Crowbar tested		
Tube high voltage parameters set		
Tube(s) tuned		
Tube(s) driven to 100% power		
Power meters calibrated		
Exciter & transmitter adjusted to meet specifications		
Transmitter operated 24 hours		
Exciter & transmitter adjusted again		
Proof measurements taken		
(Remote control installed if required)		

A *solid-state* transmitter installation typically lasts one to two weeks and involves 1 - 2 engineers, a customer-supplied electrician, and a customer-supplied HVAC installation crew. Figure 5 shows a typical VHF solid-state transmitter installation. The main tasks in the installation of a solid-state transmitter are the piece-by-piece build up of the multi-cabinet RF combining system and the air-cooling duct system, when used (open air system). Unlike IOT transmitters, for which almost all stations purchase a professional installation from the manufacturer, a significant percentage of solid-state transmitter buyers choose to install the transmitter themselves. In many such cases, the manufacturer is still contracted to perform the final transmitter check out & proof. This is an economical alternative that has the added benefit of giving station personnel valuable hands-on experience with the new transmitter, while still allowing the final installation result to be certified by the manufacturer.

Figure 5. Photo, solid-state VHF transmitter installation
right: rear view of three PA cabinets showing air intake filters
right top: air exhaust manifold above transmitter cabinets (silver duct)
center top: RF system with 3 1/8 inch rigid coaxial line
background: reject loads for 3 dB power combiners on floor
note: output bandpass filter not shown in picture
note: room air input plenum not shown in picture

IV. Transmitter Checkout and Adjustment: Performance Issues

Once the transmitter is physically installed, the AC mains power is applied, and the correct operation of all safety interlock circuits is verified. The transmitter is then adjusted for operation at full power. During this commissioning phase, there are three major performance parameters that are carefully monitored to ensure proper transmitter operation: efficiency, error vector magnitude (EVM), and RF mask compliance. These are listed in Table 3. This section features a brief discussion of these parameters and what secondary factors influence them.

Table 3 - Important DTV Transmitter Performance Parameters

Performance Parameter	Affected by...
Efficiency	Tube tuning
	Peak-average ratio (in turn limited by RF mask compliance)
Error Vector Magnitude	Group delay
	Frequency response
	Amplifier non-linearities
RF Mask Compliance	Tube tuning and bandpass filter response
	Amplifier non-linearities

Efficiency

Since both IOT and solid-state transmitters utilize class AB amplification, they have a maximum theoretical DC to RF efficiency of 79%. This maximum efficiency would occur only at the highest peak power levels. Real world DTV operating efficiency is somewhat lower because the DTV signal spends most of its time at lower power levels, where class AB amplifiers are less efficient.[2] This effect is demonstrated by Figure 6 and by the following formula:

The expected efficiency of the transmitter PA stage is *signal dependent* and given by:

$$\eta = \frac{RF\ Average\ Power}{Total\ AC\ Consumption} = \frac{\int_0^\infty P(p)\, p\, dp}{\int_0^\infty P(p) \frac{p}{\eta(p)}\, dp}$$

Where,

η = overall amplifier stage efficiency
p = the instantaneous RF power level
P(p) = the probability density function of the signal to have a certain power level
η(p) = the DC-RF efficiency of the amplifier at a certain power level
∫ dp = integral summation of all possible RF power levels from zero to infinity

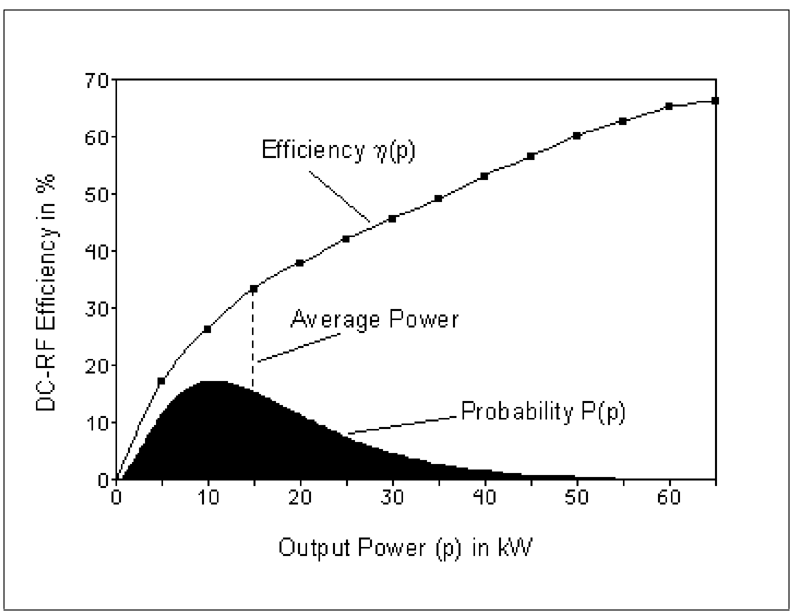


Figure 6. Efficiency and DTV signal probability vs. output power level for an IOT operating at 15 kW average power. [2]. The DTV

[2] There are also a variety of unavoidable real-world losses that prevent the theoretical maximum efficiency from ever being achieved.

signal spends most of its time at lower levels where amplifier efficiency is lower.[3]

However, Harris engineer Bob Plonka, in his 1997 NAB paper [3], showed that a given transmitter will have the same AC consumption and efficiency when transmitting the dissimilar signals of NTSC and DTV, provided that both signals have the same average power and peak to average ratio. The 6.5 dB transmitter peak to average ratio[4] for a DTV signal roughly corresponds to a gray (50% APL) NTSC picture. Therefore, an NTSC visual transmitter transmitting a 50% APL picture will consume roughly the same current as an equivalent peak-rated DTV transmitter.[5]

It can be seen in Figure 6 that transmitter efficiency could be improved by shifting the average power level upwards to the more efficient, higher power regions of the efficiency curve (i.e. decrease amplifier back-off). The ability to do this, however, is limited by the absolute peak power saturation level of the amplifier and how low a transmitter peak to average ratio can be tolerated in terms of signal EVM and RF mask performance. This phenomenon is discussed in a subsequent section on RF mask compliance.

The total AC current draw of the entire transmitter system is determined by the *transmitter plant efficiency* which also takes into account the power 'overhead' consumed in power supplies, cooling systems, and other peripheral devices. An IOT transmitter typically has a plant efficiency of 20% - 25% RMS when operating at the full, specified RF output power. Solid-state transmitter plant efficiencies generally average about 18% - 20% RMS. Although both technologies have similar DC-RF efficiencies in their PA stages, the solid-state transmitter suffers from losses in its multiple RF combining stages and from a lower AC-DC conversion efficiency in its power supplies due to the lower voltages and larger currents involved.

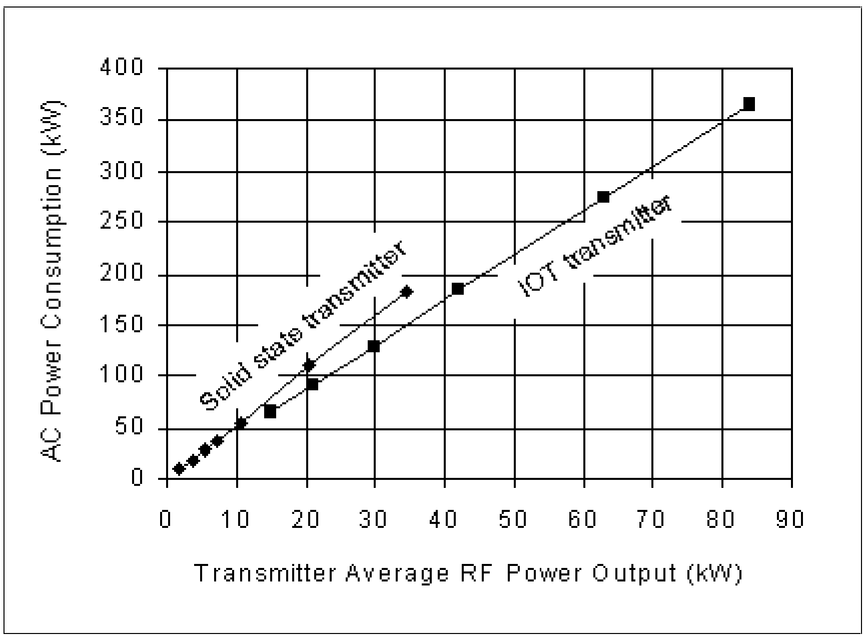


Figure 7. AC power consumption vs. RF power output for IOT tube-type and LDMOS UHF solid-state transmitters.

Error Vector Magnitude (EVM)

Since both IOT's and MOSFET's are real world devices, they do not amplify the DTV signal with perfect fidelity, but rather impart to it a variety of subtle distortions. These distortions fall into two major categories: *linear* and *nonlinear* distortions.

Linear distortions are further divided into poor amplitude vs. frequency response (or simply, *frequency response*) and poor phase vs. frequency response (*group delay*). In the 8-VSB modulation format

[3] DTV signal probability distribution has no vertical scale. It has been included to show the relative probability of the various power levels.

[4] See Figure 9 and section on RF mask compliance.

[5] That is, when NTSC peak sync power is equivalent to DTV peak power (DTV avg. + 6.5 dB).

employed by DTV, the prevention of intersymbol interference depends on a carefully synthesized orthogonal symbol impulse response with a very specific frequency and phase content. When an amplifier stage with imperfect frequency response and group delay alters this information, pulse orthogonality is lost and intersymbol interference results. At each symbol sampling point, the demodulated RF waveform deviates from the eight theoretical amplitude levels of 8-VSB because of these distortions.[6] The difference between the actual recovered level and the assumed theoretical level of the demodulated waveform (at each sampling point) is considered noise and is recorded as an error vector. The average of the magnitudes of these error vectors is given as the error vector magnitude (EVM).[7] Figure 8 shows the effect of linear distortions on the level of observed EVM.

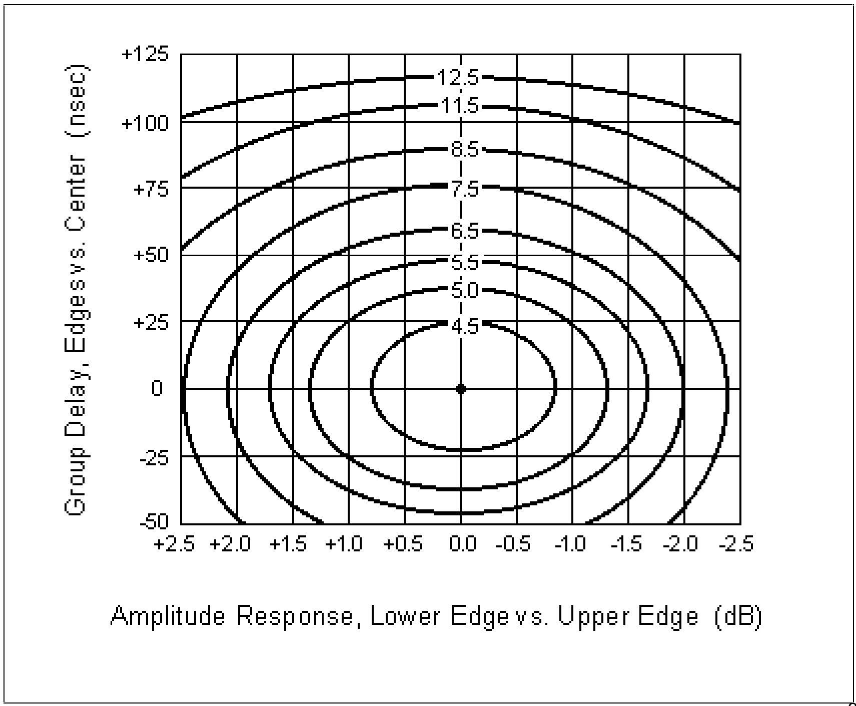


Figure 8. Measured EVM (%) vs. group delay and frequency response.[8]

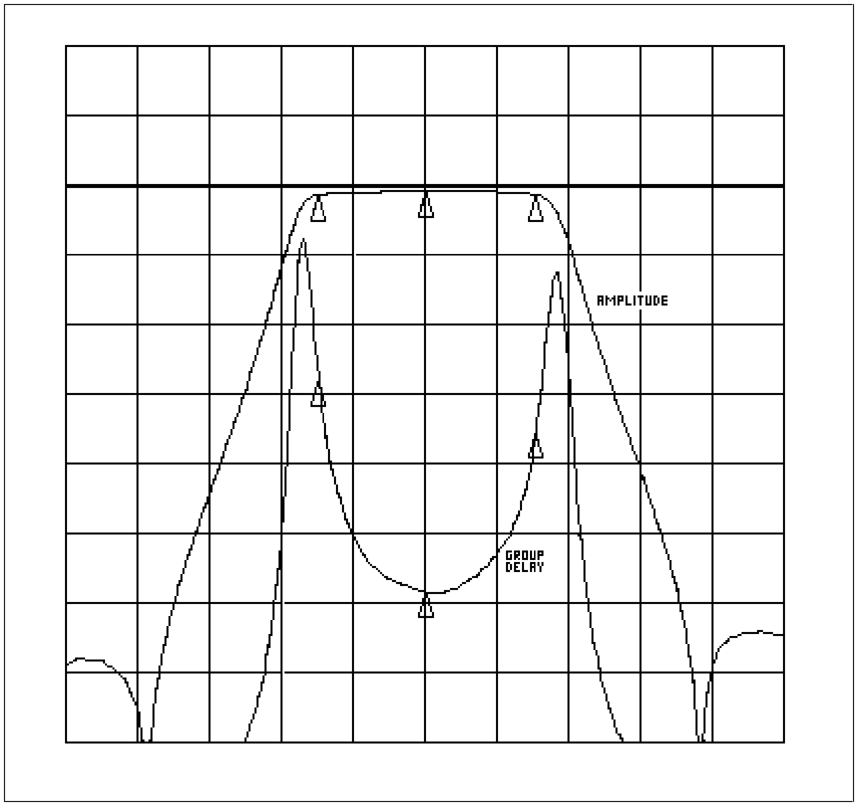
Transmitter frequency response problems may be caused by the misalignment of the DTV exciter, damage to the bandpass filter at the transmitter output, or the mistuning of the IOT itself in an IOT transmitter.

Group delay problems typically arise from the sharp skirts of the channel bandpass filter used at the transmitter output to control out-of-band emissions. This filter exhibits a steep roll-off close to the DTV channel band edges and can cause in-band group delay distortions of up to 120 - 160 nsec. The group delay exhibits a 'U' shape with the maximum delay being located just outside of both channel edges. This effect is shown in Figure 9. The output cavities of the IOT also contribute to the observed group delay, although this contribution is usually a more modest 20 - 30 nsec. Precorrection circuits in the DTV exciter correct for both frequency response and group delay distortions, thereby reducing the measured EVM of the transmitted signal to a level of 4% or less.

[6] For more information on the properties of the 8-VSB RF signal, see the technical white paper "What Exactly is 8-VSB?"

[7] This measurement is sometimes also given as digital signal to noise (SNR). 4.5% EVM is approximately equal to 27 dB digital SNR.

[8] Provided mainly for illustration purposes. Contours are extrapolated from limited measurement data.



Amplitude: 10 dB / div. Span: 2 MHz/div.
Group Delay: 30 ns / div.

Figure 9. Amplitude and group delay response of RF mask compliant output bandpass filter. Source: R. Plonka.

Nonlinear distortions are created by a nonlinear transfer curve in an amplifying stage of a transmitter and may be either of two types: poor input amplitude vs. output amplitude response (known simply as AM-AM or "linearity") or poor input amplitude vs. output phase response (AM-PM or "ICPM"). These non-linear distortions may occur at any point in the amplifier transfer curve. At the highest peak power levels, increasingly severe signal compression results from device saturation. At the lowest power levels, the exponential turn-on characteristic of the amplifying device may also create signal compression. These low level "turn-on" distortions were of little importance with NTSC; the NTSC waveform contains very little useful information above 100 IRE (i.e. the lowest RF envelope power levels). The DTV RF envelope, however, has frequent zero crossings and contains important information right down to the zero carrier level.

These nonlinear distortions will also affect the EVM performance of the transmitter, although generally to a lesser extent than the linear distortions of frequency response and group delay. This phenomenon is discussed further in the following section on RF mask compliance.

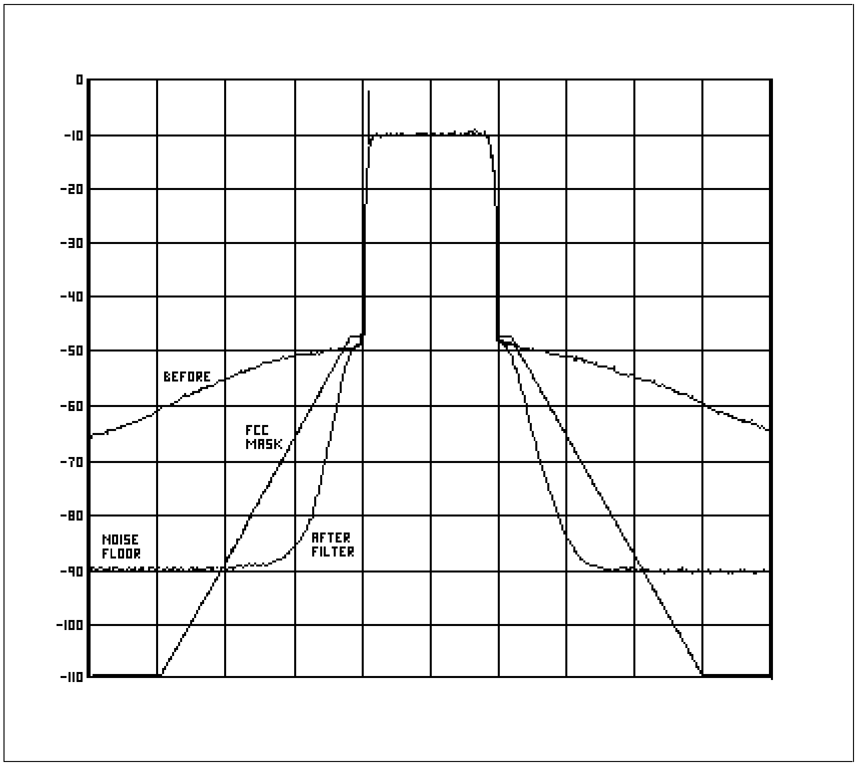
RF Mask Compliance

Nonlinear distortions will also manifest themselves as signal intermodulation and the creation of spurious spectral products. With the DTV RF signal, third-order distortions in the PA or IPA transfer curves produce a triple bandwidth spectrum of intermodulation noise centered on the desired DTV channel.[9] A 5x bandwidth fifth-order and 7x bandwidth seventh-order noise spectrum are also present, but to a much lesser degree.

The portion of these spurious spectral products that falls outside the assigned six megahertz channel must be filtered away in order to avoid interference to adjacent channels. The FCC has established a permissible RF spectral mask to limit out-of-band emissions. A high power, external bandpass filter is

[9] Mathematically, this is result of the double convolution of the DTV spectrum with itself, the result of the cubic term in the familiar power series expansion of a non-linear transfer curve.

used at the transmitter output to eliminate spurious sideband energy at frequencies greater than 0.5 MHz away from the channel edges. The amplitude response of this filter is shown in Figure 9. This filter cannot be used at frequencies closer to the channel edge because it would create excessive in-band group delay. Spurious sideband energy immediately adjacent to the channel edges must be prevented by applying linearity precorrection techniques to the DTV signal, upstream in the exciter. The spectral performance of a solid-state transmitter both before and after the external mask compliant bandpass filter is shown in Figure 10.



Amplitude: 10 dB / div. Span: 3 MHz / div.

Figure 10. Solid-state transmitter output before and after RF bandpass filter. Out of band emissions must be attenuated at least 36.6 dB at the channel edges relative to the observed in-band signal. Note how noise floor limitation of the spectrum analyzer does not permit certification of mask compliance below -90 dB. A method for performing this measurement is discussed in the Proof of Performance: Measurements section of this paper. The 0 dB top line is referenced to the total channel average power (as measured with a 6 MHz resolution bandwidth).

The greater the amount of nonlinear distortion created by the transmitter, the higher the spurious sidebands will appear in relation to the desired in-band DTV signal. In the interest of maximizing transmitter power output and efficiency, the highest possible average power is transmitted while the peak power is limited by PA stage saturation. (i.e. the peak to average ratio is compressed). This strategy is employed until such a point is reached that the resulting spurious sidebands cannot be pre-corrected to below the FCC required -36.6 dB at the channel edges. Since the DTV signal spends relatively little time at highest peak power levels (see Figure 6), large amounts of peak clipping are possible before the level of spurious sideband energy becomes objectionable. The resulting peak reduction is dramatic, transforming the 10+ dB peak to average ratio of the original DTV signal to a more modest 6.5 dB. This relationship is shown in Figure 11.

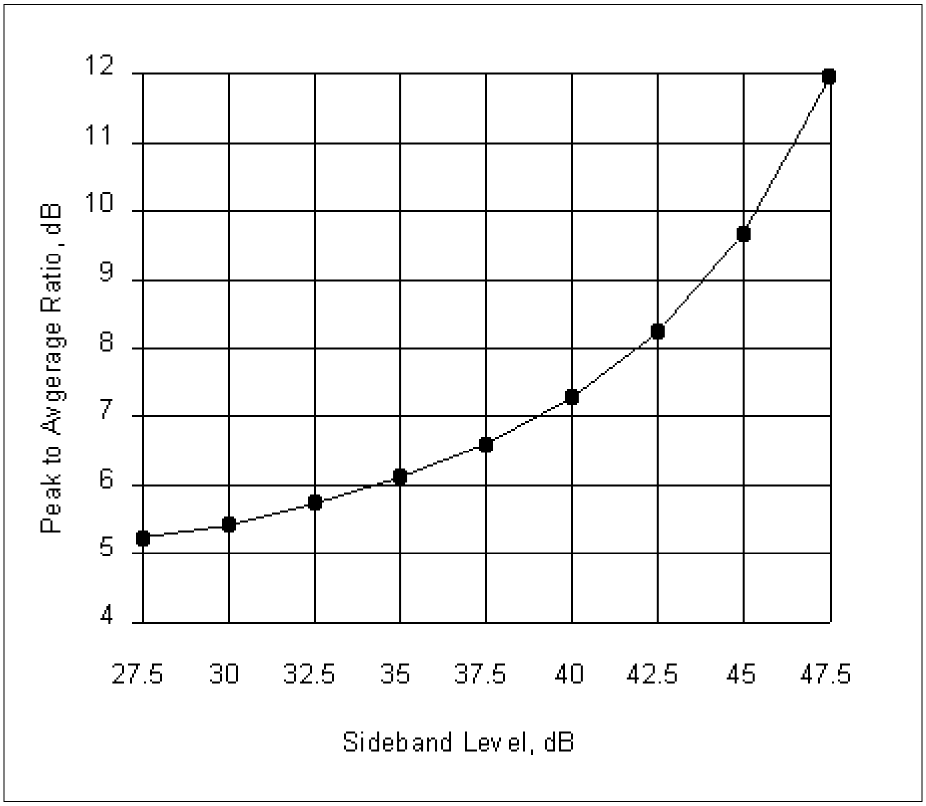


Figure 11. Transmitter peak to average ratio vs. spurious sideband energy at channel edges. Source: R. Plonka.

As mentioned previously, nonlinear distortions also have an effect on measured EVM. However, once properly controlled to comply with the FCC -36.6 dB sideband specification, nonlinear distortions contribute relatively little to the final EVM number. This is shown in Figure 12. During the transmitter adjustment process, the EVM contributions due to nonlinear distortions are largely masked by those due to linear distortions (frequency response and group delay).

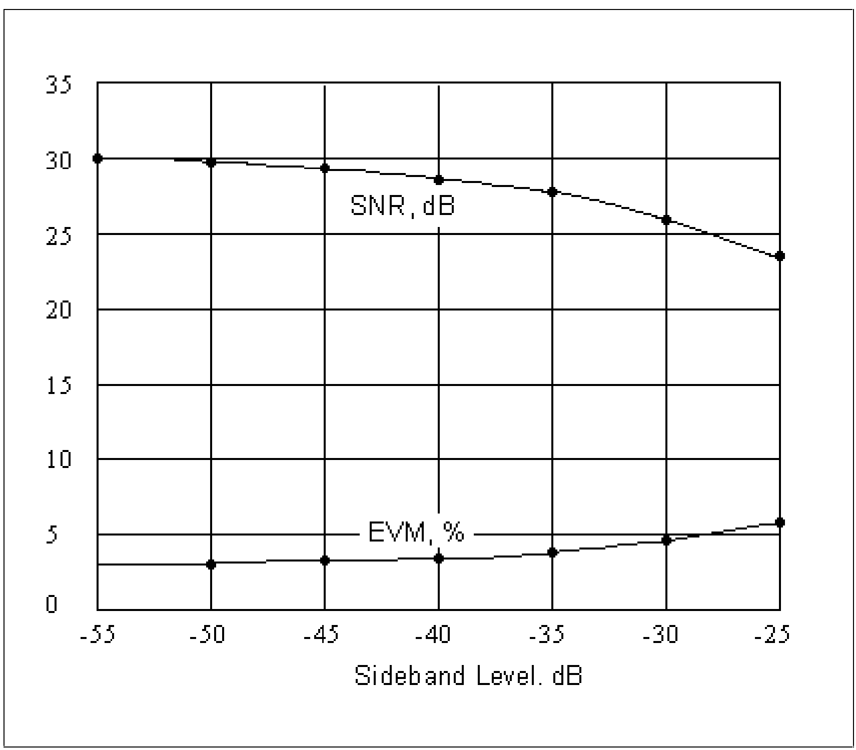


Figure 12. EVM (and digital SNR) vs. spurious sideband level at channel edge, IOT transmitter. Source: R. Plonka.

V. Transmitter Proof of Performance: Measurements

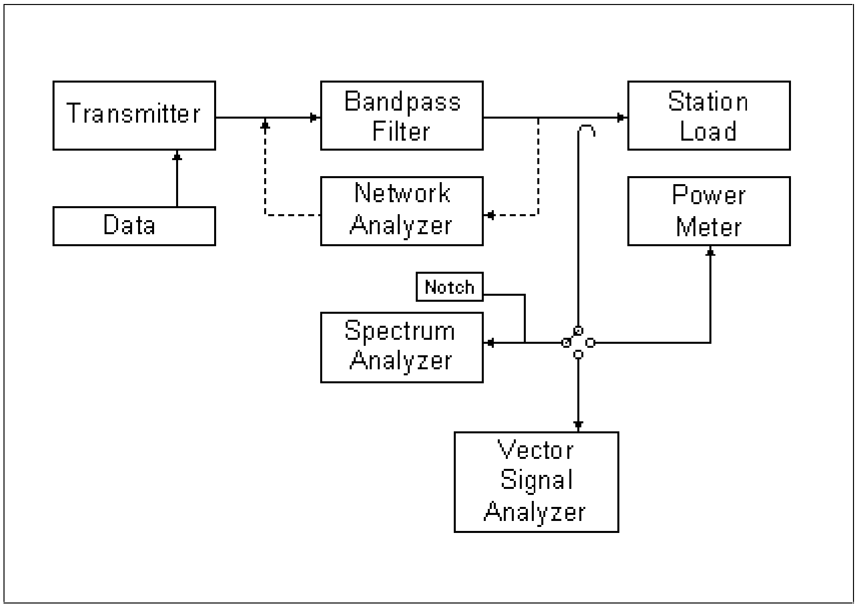


Figure 13. Block diagram, test equipment set-up for DTV proof of performance.

Once the transmitter has been adjusted to give satisfactory performance at full power, the transmitter proof of performance data is taken. This is the final phase of the transmitter installation process. The determination as to which measurements are to be included in a DTV proof of performance, and how they are to be presented, is somewhat open to interpretation since no FCC-mandated guidelines have been given in this area. The following data are excerpted from an actual DTV proof performed at station WXIA-HD by Don Manion of Manion and Associates. [4]

Table 4 - Proof of Performance Specifications

Specification	Required Level	Measured Level	Measurement Technique
Average output power	Required TPO	3.14 kW (100%)	RF average power meter and precision directional coupler
Pilot frequency	192.309441 Hz +/-1000 Hz (channel 10 VHF)	192.309444 Hz (+0003 Hz)	Vector signal analyzer
Error Vector Magnitude EVM	4%	3.95%	Vector signal analyzer
RF mask compliance	FCC Mask	see Table 5.	Output spectrum of transmitter measured before channel filter with spectrum analyzer. Filter attenuation response measured with network analyzer. Transmitter output spectrum added to filter attenuation response to calculate final system performance
RF mask compliance - wideband harmonic suppression	FCC Mask	-110 dB relative to total channel average power. Total channel power reference measured with 6 MHz resolution bandwidth.	Output spectrum of transmitter measured after channel filter with spectrum analyzer. Eagle TNF-2 notch filter tuned to DTV channel used to prevent analyzer overload for certain sensitive measurements. 6 dB per octave correction factor applied.

Of special interest is how the transmitter's compliance with the FCC emissions mask was determined. Since the FCC-mandated emissions floor is beyond the measurement capability of the common field spectrum analyzer, it was necessary to separately measure the transmitter output spectrum (before the bandpass filter) and the bandpass filter attenuation characteristics. These two numbers were then added together to determine the final system response. This is shown in Table 5.

Table 5 - Additive System Response Showing Compliance with FCC Emissions Mask[10]

Frequency (MHz)	Filter Attenuation Response (dB)	Transmitter Output Response (dB)	Final Net Response (dB)	Required FCC Mask Response (dB)	Compliance Margin (dB)
186.00	79.214	61.27	140.48	99.80	-40.68
187.00	70.141	61.30	131.44	88.30	-43.14
188.00	59.638	60.46	120.10	76.80	-43.30
189.00	47.178	59.05	106.23	65.30	-40.93
190.00	31.331	54.83	86.16	53.80	-32.36
190.50	21.276	50.64	71.92	48.10	-23.82
191.00	9.094	49.39	52.48	42.30	-10.18
191.50	0.527	37.27	37.80	36.60	-1.20
191.70	0.137	36.95	37.09	36.40	-0.69
198.30	0.128	39.34	39.47	36.40	-3.07
198.50	0.456	39.72	40.18	36.60	-3.58
199.00	8.088	45.68	53.77	42.30	-11.47
199.50	19.872	52.92	72.79	48.10	-24.69
200.00	29.775	56.01	85.79	53.80	-31.99
201.00	45.377	58.88	104.26	65.30	-38.96
202.00	57.624	60.83	118.45	76.80	-41.65
203.00	67.816	61.33	129.15	88.30	-40.85
204.00	76.532	61.59	138.12	99.80	-38.32

Conclusion

During the next ten to fifteen years, there will be an enormous quantity of DTV transmitters installed. The implementation of a DTV transmitter is greatly facilitated when the broadcast engineer has an appreciation of the installation process and the potential problems that may arise. This paper has sought to expose some of these items to the general broadcast engineering public. It hoped that this paper, along with other sources of DTV installation information, might help the reader to avoid potential transmitter installation problems and smooth the ongoing transition to the world of digital television.

References

1. "DTV Express Training Manual on Terrestrial DTV Broadcasting," *Harris Corporation Broadcast Division,* 1998, Ch. 8

2. Robert S. Symons, "The Constant Efficiency Amplifier," *Litton Electron Devices*, 1998

3. Robert J. Plonka, "Planning Your Digital Television Station," *Harris Corporation Broadcast Division*, 1997, pg. 6

4. Donald Manion, "Engineering Report of Television Transmitter: Performance Characteristics for WXIA HD," *Harris Corporation Broadcast Division,* 1998

About the Author

David Sparano received a Bachelor of Science degree from Siena College and a Master of Science degree from Rensselaer Polytechnic Institute. He is currently TV Installations Manager for Harris Corporation Broadcast Division in Quincy, IL. Mr. Sparano is fluent in four languages and has given presentations on DTV throughout North and South America.

[10] The measurements in this table are referenced to the average in-band channel energy as seen on a spectrum analyzer with a resolution bandwidth of 500 kHz. Add 10.3 dB to convert these readings to the total channel power top-line reference (6 MHz resolution bandwidth) shown for the FCC mask in Figure 10.