Power Efficient Broadcast Facility Transmission Design

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Flexible Advanced Services for Television & Radio On All Devices

by

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FIGURES

EXECUTIVE SUMMARY

Cavell, Mertz & Associates, Inc. ("CMA") has researched and developed a short history of radio and television transmitters and their efficiency. This history has been combined with an understanding of current analog and digital transmission technology and methods to provide a primer on power-efficient broadcast facility transmission design for radio and television stations that are considering the alteration or construction of new RF transmission facilities for over-the-air broadcasting.

From data gathered, evolving transmitter technology has clearly improved transmitter efficiency between 1970 and today. New solid-state and tube designs have allowed efficiency improvements of as much as 30 percentage points.

There are a number of considerations that are involved in making a broadcast transmission system more efficient – transmitter design and choice, modulation scheme, combining technique, budget concerns, available real estate, and external climate are some of the many considerations.

Using data obtained from manufacturers, a *Transmitter Energy Efficiency Award (TEEA)* has been formulated to better assist broadcasters in deciding which transmitters to specify going forward. This Award would be available for the top 25 percent most efficient transmitters in each class, so that if a broadcaster were choosing a transmitter that has a TEEA "seal," they would know that it is one of the most efficient transmitters available.

This study forms the basis for a web-based tool designed by CMA that can assist a broadcast station engineer or manager, with the use of drop-down menus, to develop a "what if" study of various transmitter site topology decisions and their impact on facility long-term operational costs, as opposed to one-time capital costs.[1] As part of this analysis, the user can

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[1] This web site, http://te.cavellmertz.com, will become operational in the first quarter of 2011.

apply the measured efficiency of their current transmitter (if available), an actual efficiency procured from the manufacturer, or the manufacturer's published efficiency of the new transmitter that the station may be considering. Additionally, the tool can help specify the relative efficiency typical of the proposed transmission topology and, in the case of digital FM transmission, IBOC combining method.

PART 1 - POWER- EFFICIENT BROADCAST FACILITY TRANSMISSION DESIGN

Introduction

Cavell, Mertz & Associates, Inc. ("CMA") has researched and developed a short history of radio and television transmitters and their efficiency. This history has been combined with an understanding of current analog and digital transmission technology and methods to provide a primer on power-efficient broadcast facility transmission design for radio and television stations that are considering the alteration or construction of new RF transmission facilities for over-the-air broadcasting.

The study takes an objective look at transmitters that are currently in use across the country and, based on surveys of transmitter manufacturers, provides a range of power efficiencies for both new-technology and legacy analog, digital and hybrid transmitters for AM, FM and television.

Current transmission methods and technologies are explored for solutions to increase overall transmission facility efficiency for each type of radio and television transmission. Examples will include:

- Exploration of different modulation techniques in AM transmission that are intended to increase efficiency by use of carrier suppression;
- An outline of the various in-band/on-channel (IBOC) hybrid digital radio combining methods available to FM-band stations, considering individual station operational and financial needs;
- Understanding the differences in efficiency between tube-type transmitters and solid-state transmitters, and their impact on transmission facility efficiency as a whole;
- Consideration of how heat load and the cost of cooling of a transmitter, depending on factors such as insulation of the transmitter building, external climate conditions and many other factors that make a difference in choosing a new transmission system.

This study forms the basis for a web-based tool designed by CMA that can assist a broadcast station engineer or manager, with the use of drop-down menus, to develop a "what if" study of various transmitter site topology decisions and their impact on facility long-term operational costs, versus one-time capital costs.[2] As part of this analysis, the user can apply the measured efficiency of their current transmitter (if available), an actual efficiency procured from the manufacturer, or the manufacturer's published efficiency of the new transmitter that the station may be considering. Additionally, the tool can help specify the relative efficiency typical of the proposed transmission topology and, in the case of digital FM transmission, IBOC combining method.

The information contained in this paper makes it clear that there are a number of efficiency-related trade-offs with regard to the different transmission methods and modulation techniques available. Because there is no single "silver-bullet" solution, stations must choose carefully whether to spend capital funds on a one-time basis to purchase a completely new transmitter, HVAC unit or entire facility, or to spend operating cash to maintain an existing facility on a continual basis, or a combination of both.

AM Transmitters and Transmission Systems

Efficiency data for current and legacy AM transmitters were solicited and gathered from several different transmitter manufacturers. Two manufacturers responded with data for legacy transmitters only, and data for current-model transmitters were obtained from published specifications listed on the various company websites. Other manufacturers responded with specifications for their current product line specifications as well as some historical information on their legacy transmitters.

Information was obtained on AM transmitter models dating back to the late 1970s. Not surprisingly, many of these transmitters are still in use by stations of various sizes all over the

[2] This web site, http://te.cavellmertz.com, will become operational in the first quarter of 2011.

country. The transmitters that were considered in this study range from 500 watts (W) to 50,000 W. While several companies also build and sell AM transmitters at power levels greater than 50 kilowatts (kW), these transmitters are primarily intended for use in the shortwave or overseas medium-wave broadcasting services, and will not be addressed here. There is a mix of tube-type and solid-state technology both in the legacy transmitters and current-model transmitters.

The development of more efficient tube-type and solid-state devices over time is evident in the data gathered across the history of the AM transmitters. Over the range of transmitter models that one manufacturer provided, the efficiency of current equipment clearly improves over the older models, from 55% efficiency for a late 1970s model to 86% for current technology, manufactured first in 2008.[3] Among that particular company's products, legacy transmitters utilize both solid-state and tube technology, whereas their current-edition digital-capable transmitters utilize solid-state components exclusively. Another manufacturer's solid-state AM transmitter products (which were first manufactured in 1991) prove to be 75% efficient for all products and model years.

A third manufacturer provided information for equipment that dates from 1982 to 2002, with efficiency information for the current-model transmitters acquired from their website literature. These transmitters also follow the general pattern of overall or "AC-to-RF" efficiency improvements. As technology has advanced, this company has improved AM transmitter efficiency from 74% (built in 1982) to upwards of 90% efficiency (for current solid-state products).

Given the data that was obtained, there is no conclusive evidence that legacy tube-type transmitters are any more or less efficient than the comparable solid-state models. Using manufacturer historical data, the older tube transmitters have an efficiency of 60%, while the legacy solid-state equipment was 65% efficient. Most of the manufacturers have no tube-type AM transmitters available in their current lineup of equipment operating at 50 kW or less.

[3] In this context "efficiency" refers to the ratio of output RF power to input prime AC electrical power. For example, if a transmitter requires 90 kW of prime AC electrical power to generate a 50 kW RF signal, then that transmitter has an efficiency of (50/90) x 100 = 55.5%.

Across all manufacturers surveyed, it is noted that adding a digital exciter to an existing AM transmitter to generate an in-band/on channel (IBOC) hybrid digital signal does not materially affect the efficiency of that transmitter. Current solid-state transmitters, as mentioned previously, are more efficient in general than older models.

The cooling of an AM transmitter is integral to the overall efficiency of a radio station transmission facility. According to the various transmitter specification documents, some of the 50 kW solid-state units, which can support up to 62 solid-state amplifier modules, (depending on the efficiency rating) requires as much as 57,000 BTU/hour of cooling.

Air-conditioning units are rated in SEER.[4] Given that a typical air-conditioning unit has a SEER of approximately 12, the power necessary to cool that particular transmitter is 57,000/12, or 4750 Watts per hour. It is vital to consider the cooling needs of a new transmitter or transmitter combination as carefully as the actual efficiency of the transmitter itself. Otherwise, increased cooling needs may completely negate any efficiency gains, depending on the model, type and power output of the transmitter.

Modulation type and level play a significant part in AM transmitter efficiency. In conventional double sideband (DSB) full-carrier AM modulation, the amount of sideband power varies with modulation level. Typically, only one-third of the power in a 100% modulated signal is associated with the sidebands; the remaining two-thirds of the power is expended in generating the carrier signal, which in some sense is wasted since the carrier itself contains no modulation information. There are a number of technologies that utilize partial or total carrier and/or (single) sideband suppression which results in more signal power to the modulation signal and increased transmission efficiency.

Single sideband and fully-suppressed carrier modulation methods are not considered suitable for the current AM radio broadcast environment because they are incompatible with

[4] Seasonal Energy Efficiency Ratio, or BTU per hour per watt input power.

hundreds of millions of existing analog AM receivers. Thus, employing them would require the re-development and manufacture of appropriately capable AM radio receivers, and completely replacing every analog AM receiver that is currently in use. These technologies require a more sophisticated receiver than the simple diode-detection AM receivers currently in use all across the country. The narrow-band properties of these two modulation methods would not likely be suitable for digital AM operations, either, since hybrid analog-digital radio requires more bandwidth than the existing analog modulation, not less.

Power-efficient AM modulation techniques

Other types of AM modulation, currently used in Europe and South America, are able to make transmission more efficient without the need to replace the simple receivers that are in use everywhere. These modulation schemes include *Dynamic Amplitude Modulation ("DAM"),* developed by AEG Telefunken, *Dynamic Carrier Control ("DCC"),* developed by Asea Brown Boveri, and *Amplitude Modulation Companding ("AMC"),* developed by the BBC. All of these technologies were developed in the early 1980s in response to steep energy cost increases during the first Gulf Oil Crisis, and are still in use today. A number of white papers, equipment sales brochures and engineer testimonials in several countries cite 20% or greater reduction in electrical cost due to greater AC-to-RF efficiency over conventional AM modulation techniques.[5] Based on published international results, it is believed that employing any of these technologies would be compatible with the inventory of AM receivers currently in use all over the US.

In the DAM method, the carrier is suppressed in relation to the modulation level. Both carrier and amplitude voltage are reduced linearly when the percentage of modulation is more moderate, and increases at higher modulation indices.

In a similar fashion, DCC causes the carrier level to be automatically reduced when the modulation level is small or non-existent. For example, during periods of silence (0%

[5] See www.rveritas-asia.org/index.php?option+com_content&view=article&id=96. Also: Implementation of Amplitude Modulation Companding in the BBC MF National Networks, C.P. Bell, 12/1988.

modulation), the carrier is reduced by half, so that, in those instants, a 50 kW radio station is using only 25 kW. The amount of carrier power suppression utilized is a variable and can be set for either 50% or 75% power reduction so that power savings can be balanced against any possible undesirable artifacts generated due to the carrier being suppressed.

There are trade-offs in the *DAM* and *DCC* carrier power suppression schemes. 50% dynamic power reduction is recommended for optimal power saving with minimal artifacts. Some facilities, due to long-term funding issues, prefer to use 75% dynamic power reduction for greater energy savings. When operating with 75% suppression, however, poorer performance is possible in the fringe areas of the coverage footprint than would have been achieved with less carrier suppression. Although it is not currently permitted for AM broadcasting in the U.S., some transmitter manufacturers offer DCC technology in their current line of transmitters being sold in the U.S.

The AMC method is completely the opposite of the other two schemes. The carrier is suppressed as modulation increases, and then rises to 100% of signal during quiet or low modulation periods. The theory is that even though the signal-to-noise ratio is compromised with lower carrier levels during modulation, the "loudness" of the modulation itself will mask the increased noise floor so that listeners will not notice an appreciable difference.[6] One stated advantage of AMC over DAM and DCC is that the receiver stays locked to the carrier at all times. All of the above efficiency enhancement algorithms are currently available from several AM transmitter manufacturers.

If these modulation schemes can be developed for use in conventional domestic AM broadcast stations, many AM stations may benefit from the use of these modulation schemes, especially high-power stations that are currently operating older, less efficient transmitters. So far, these methods have not been permitted for use in the U.S., although there is significant interest in doing so.

[6] See Amplitude Modulation Broadcasting: Application of Companding Techniques to the Radiated Signal, W.I. Manson, B.Sc., November, 1985

The suitability of these modulation schemes in the U.S. or with AM digital hybrid IBOC signals may need to be demonstrated with further testing to determine public acceptance and actual receiver compatibility, as well as spectrum occupancy and interference mechanisms.

Present FCC Rules were written to define specifications for AM broadcasting based on technology in use in the 1930s. Fortunately, they do not specifically exclude any evaluation of new technology. For Part 73 AM broadcast licensees, an internal letter request can be employed to request experimental authority for the purpose of testing the power-efficient technologies described above at an existing radio station.[7]

Further, interested manufacturers and others can enlist a capable engineering consultant to work with the FCC to seek temporary authorization to operate a new experimental broadcast facility for the purpose of testing new modulation technology over a limited geographical area. Compared to requesting FCC experimental authorization at an existing broadcast station, the process to authorize a new experimental station is a more rigorous, "paper transaction" using FCC Forms 309, 310 and 311, but is still not particularly complex to do or difficult to obtain. It is also to be noted that there is a strict documentation and reporting aspect after any party receives experimental authority.

FM-band Transmitters and Transmission Systems

Efficiency data for current and legacy FM transmitters were gathered from a number of different transmitter manufacturers. For analog FM, efficiency values were obtained for both legacy analog-only transmitters, and hybrid transmitters operating in an analog-only mode.

One manufacturer's solid-state older (pre-1995) transmitters and another manufacturer's tube-type legacy transmitters have comparable overall efficiencies at between 62% and 67%. Both these manufacturers have more current generation (post-1995) transmitters that become

[7] See 47 CFR §73.1510.

more efficient at between 70% and 73% efficiency. A third manufacturer has a line of older FM analog transmitters (1994-2007) that is between 60% and 64% efficient.

Based on the published specifications for currently available hybrid transmitters, the current solid-state IBOC transmitters are roughly the same efficiency as the older ones at pure analog – between 61% and 65% efficient. Yet another manufacturer has both tube and solid-state models that began manufacture in 1991 (and are still made today).

The tube models are more efficient with overall efficiencies between 58% and 80%, as compared with the solid-state models, which are between 40% and 50% efficient. This same manufacturer has current-model solid-state transmitters, which appear to be between 55% and 57% efficient, which is little improved from the older models. Overall, analog FM transmitters have improved somewhat in efficiency with the advent of new technologies in solid-state devices and tetrode tube applications, and have an average efficiency of 67%.

In addition to analog FM, this study considers digital hybrid IBOC co-generation and low-level combining, mid-level (also called "split-level") combining, and high-level combining along with some of the antenna combining methods as part of this efficiency study.

Co-generation and low-level combining modulation methods are considered "common amplification" techniques because in both, the analog and the digital RF signals are combined. This hybrid (analog plus digital) signal is then fed into a common RF amplifier, amplified, and radiated by a single antenna.

The terms co-generation and low-level combining are often confused with one another, as they both utilize a single hybrid FM transmitter. However, low-level combining generates the digital and analog signals separately and combines them at the common power amplifier's input, as shown in Figure 1.

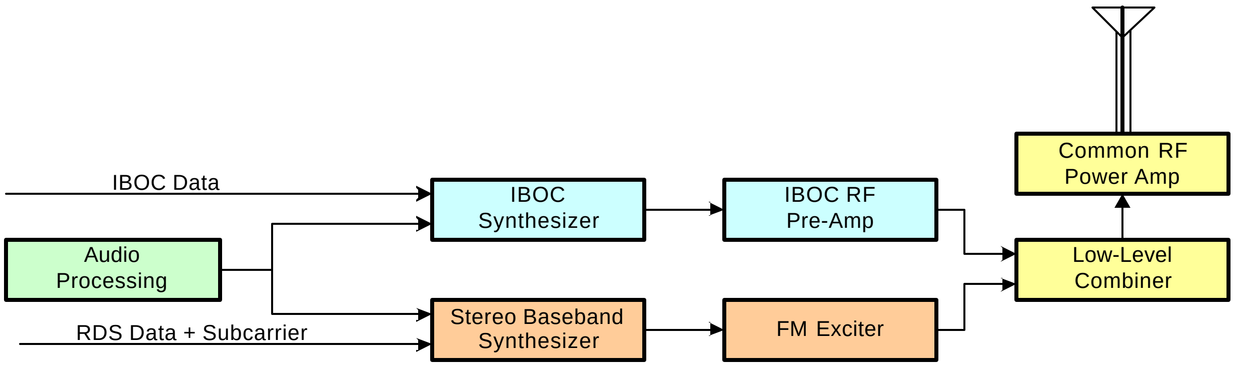

Figure 1 – Low-Level Combining

Co-generation generates the digital and analog signals in a single exciter, which are then fed into the common power amplifier's input, as shown in Figure 2.

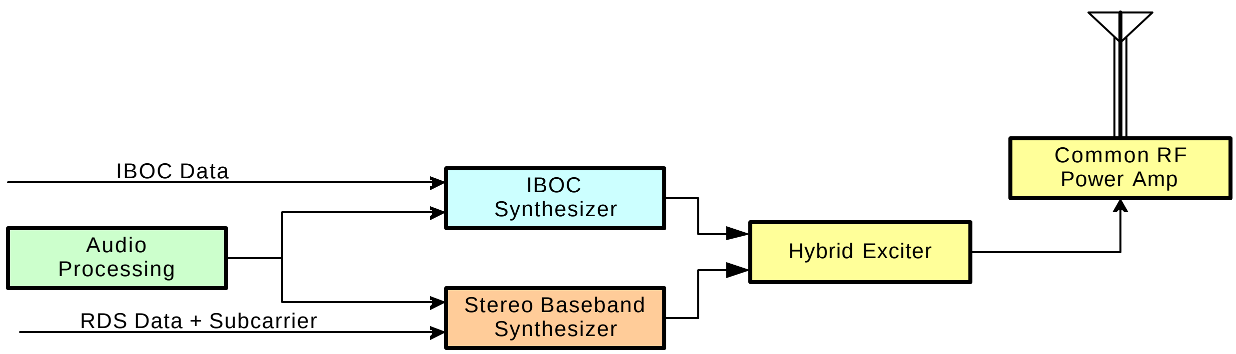

Figure 2 – Co-Generation

Whether co-generation of low-level combining is utilized, common amplification is quite popular with new IBOC adopters is because some existing transmitters can be modified to become a hybrid IBOC transmitter. Such operation is only feasible when the existing transmitter RF power amplifier can be modified to provide linear amplification ("Class AB" amplifier operation), and the transmitter has enough power to accommodate the increased "headroom" (difference between the output power required and the maximum output capability of the transmitter) required for the increased power demands of the digital waveform. Typically, 35%

headroom is required, that is, the transmitter maximum output power must be 35% greater than the power of the combined hybrid IBOC signal.

Once modified to accommodate common amplification, the resulting transmitter will be significantly decreased in efficiency in comparison to its prior analog-only operation. Based on available data, typical 10-year-old FM analog transmitters operating at Class C will be about 65% efficient. This is typically reduced to about 50% once the power amplifier is linearized for IBOC (and operating as a Class AB device). A full review of historical and current-technology hybrid transmitter efficiencies will follow the combining discussion below.

From an efficiency standpoint, there is virtually no difference between co-generation and low-level combining because common RF power amplifiers are used in both cases. However, there are differences with respect to relative cost and reliability. Low-level combining allows for continued FM operation if the digital exciter fails, while co-generation saves the cost of adding an additional digital exciter.

Common amplification, however, has efficiency drawbacks at increased digital power levels. As the level of IBOC injection increases, the available output power decreases significantly for both tube and solid-state transmitters.[8] Separate amplification (mid-level or high-level combining), which has been a reasonable alternative at –20 dBc, is not as efficient at higher IBOC power injection levels. High-level combining becomes impractical at IBOC injection levels greater than about –18 dBc and mid-level combining also becomes too inefficient at IBOC injection levels greater than about –15 dBc.

If a station has considered all of the implications of attempting to convert an existing FM analog transmitter into a common amplification IBOC transmitter, and it is determined to be

[8] From *Transmission System Requirements for Increased HD Radio™ Sideband Power: 2008 National Public Radio Engineering Conference*, presented by Geoff Mendenhall and Tim Anderson of Harris Broadcast Communications.

unfeasible due either to cost or lack of capability, then high-level combining should be considered for injection levels less than about –18 dBc. As shown in Figure 3, in a high-level combining topology the amplified output of the existing FM analog transmitter (at its original efficiency) is combined with the amplified output of a much lower power (and a good deal less efficient) digital transmitter.

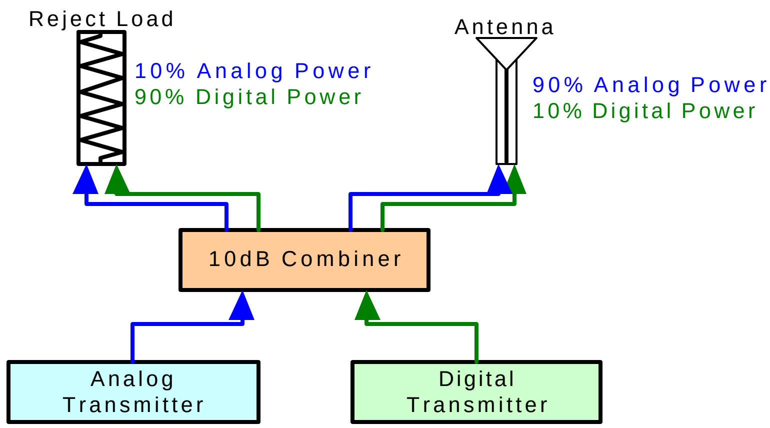

Figure 3 – High-Level Combining

Using a 10 dB combiner, the analog transmitter can continue to operate as a Class C device, and most of its power (and efficiency) is preserved, and an additional 10% increase in analog transmitter power output is needed to overcome the combiner losses. The digital transmitter must be additionally sized to accommodate this loss, however, the initial investment is far less than a new full-power hybrid transmitter. Digital-only transmitters are roughly 30% efficient. Further, roughly 90% of the digital transmitter power is wasted into the reject load, adding significant heat load to the transmitter building.

The concept of the reject load, which is required for high-level combining, brings an additional element into the transmission system equation: heat load in the transmitter building. The more heat the equipment expends, the more air-conditioning or ventilation is required to compensate for the excess heat.

For example, when a 10 kW analog transmitter is combined at high level with a 2 kW digital transmitter, the system will dissipate 1000 W (10%) of the analog power and 1800 W (90%) of the digital power, or 2800 W of waste heat. Converting to BTU/hour, there is 9556 BTU/hour going into the reject load for the HVAC system to handle.[9]

New studies have shown that high-level combining uses about 5% more air-conditioning than low-level combining if the reject load cannot be either placed outside the building or vented to the outside.[10] The prevailing outside climate at the transmitter location often will dictate the placement of the reject load. One by-product of high-level combining may be an increased power bill, which needs to be weighed against the capital cost of a new hybrid transmitter, or the linearization costs for the existing one.

George Cabrera, RF engineer at Harris Broadcast and Steve Fluker, Director of Engineering at Cox Radio, originally developed mid-level, or "split-level" combining as a way to manage reject power loads and a transmitter that could not provide enough analog power for the just-granted class upgrade for the station.[11] Specifically, mid-level combining becomes useful when the original FM analog transmitter is not capable of providing the power levels necessary to overcome the reject loss in high-level combining at IBOC injection levels from approximately –15 to -20 dBc. A basic block diagram of mid-level combining is shown in Figure 4.

[9] The conversion factor from W to BTU/hour is 3.413 BTU/hour/Watt; see www.conversion.org.
[10] See *The IBOC Handbook* by David P. Maxson, Copyright 2007, Focal Press
[11] *Radio Magazine*, July 1, 2004 from an article entitled "Split-level Combining" by Steve Fluker

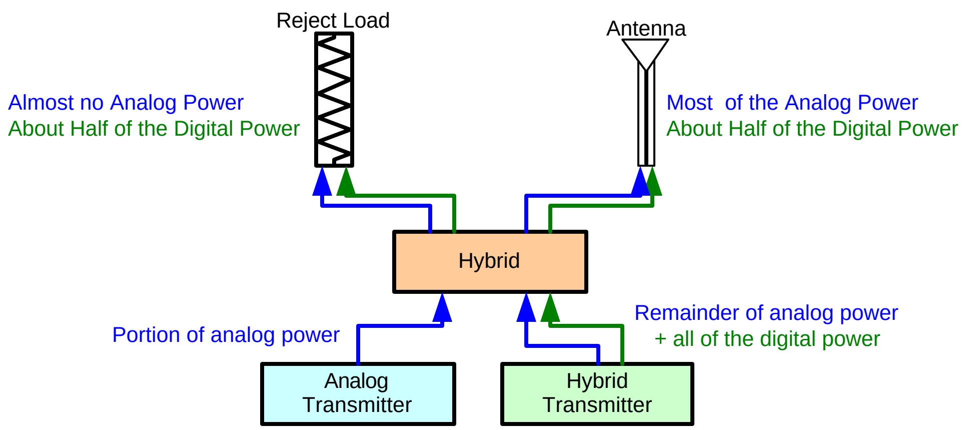

Figure 4 – "Split-Level" Combining

When the analog energy is equally provided by the two transmitters, and is properly phased in the combiner, nearly all of it will be present at the antenna, and almost none of it is wasted in the reject load. Careful phasing will also optimize the AC-to-RF efficiency of the entire system. There is capital cost benefit to this approach as well: the analog transmitter can be run at lower power and tube or solid-state device life is improved. Further, the station does not need to invest in as high a power hybrid transmitter as it would if low-level combining were employed.

Data for various levels of IBOC injection were also requested: at -20 dBc, -14 dBc, and -10 dBc.[12] The most readily available data were at the -20 dBc injection level, with some available for higher injection levels. At -20 dBc injection, one manufacturer has both tube and solid-state hybrid transmitter models, and two other manufacturers each have a few solid-state models. Tube-type hybrid transmitters have made the most significant efficiency advances – 40% for 1991 models up to 62% for 2009 models. From published data, several current-generation hybrid transmitters have efficiencies of 50 to 55%. All of another manufacturer's digital transmitters are 50% efficient in hybrid mode at -20 dBc injection. Published data for a third manufacturer show efficiencies between 50 and 55%. New-generation (2000 and newer)

[12] The FCC authorized FM IBOC stations to voluntarily increase their digital power up to -10 dBc in January 2010 – see http://hraunfoss.fcc.gov/edocs_public/attachmatch/DA-10-208A1.pdf. Previously, stations were required to operate FM IBOC stations with a digital power of -20 dBc.

solid-state transmitters made by a different manufacturer also show 50% to 55% efficiency, up from 40% efficiency for their 1991-vintage models.

Space combining in the antenna system is now recognized as one of the most efficient ways to increase the HD Radio power to injection levels. Space combining can be designed with separate feeds to a single antenna, separate antennas on the same tower, or even an entirely separate site, such as an auxiliary transmitter site. The shortcoming of space combining is amount of potential mis-tracking between the analog FM and digital HD signal levels in the far field. Even systems that use a single antenna array with opposite circular polarizations for the FM and HD signals still suffer from some mis-tracking potential at receive locations with multipath signal reflections where the two separate polarizations add up differently.

Some limited data is available at -10 dBc injection for a few solid-state transmitters at 38% to 40% efficiency, and for tube transmitters at 42% efficiency. The limited data for -14 dBc injection that was made available shows overall efficiency for solid-state transmitter at about 48%, and 50% for tube transmitters.

Power efficiency is at its lowest in "digital-only" operation (*i.e.*, generation of only the digital portion of a hybrid IBOC signal) due to the strict linearity requirements of the amplifier and the need to keep the digital spectral re-growth strictly limited. One manufacturer has published data that indicates 26% efficiency for digital-only operation. Published digital-only efficiency for yet another company's current models is 33%. This data has no interest by itself alone, as digital-only operations are not authorized by the FCC currently, but has import as part of a mid- or high-level combining scheme.

<u>Choosing an FM IBOC combining method</u>

A number of complicated considerations must go into making a decision about what kind of FM hybrid digital combining operations to choose. Each of the methods discussed has significant impact on overall transmission system efficiency, as well as operational and capital expenditures. The variables include:

- The existing transmitter – its size, age, and ability to be made linear for hybrid operations, current efficiency and operating cost;
- Available floor space – more floor space must be made to install additional transmitters and equipment for high-level combining;
- The existing HVAC system – its capacity and age;
- Current electrical power costs – some cities have higher electrical costs than others and stations in cities that have relatively low energy costs may find that increased electrical consumption is a smaller burden than the cost of new equipment;
- External climate may dictate how heat loads are handled.

When it comes to both digital-capable FM transmitters and TV transmitters, power amplifier (PA) efficiency is significantly reduced in comparison to analog amplifiers by the wider bandwidth signal and the need to keep the power amplifier in the linear portion of the amplification device. Amplifier linearity is crucial to meeting the FCC “emission mask” (and the more stringent iBiquity mask in FM digital) as well as keeping spectral re-growth to a minimum. Therefore, in order for the amplifier stage of any digital FM (or TV) transmitter to remain in the linear portion of the device’s operation at the same output level as analog, the devices must be sized larger than they were at analog and de-rated for digital operation. Thus, digital amplifiers are typically much less efficient than their analog counterparts. For example, the same device that would provide 14 kW of peak power in an analog TV transmitter can only provide less than 5.5 kW of average power in an ATSC digital TV transmitter in order to stay linear.

Full-power TV Transmitters and Digital TV Transmission Systems

A number of television transmitter providers were invited to provide efficiency data on both new model and legacy ATSC transmitters. In the case of full-power TV transmitters, there are no legacy analog transmitters to consider, as there are none in use since the U.S. transition to digital TV, which was completed on June 12, 2009.

DTV transmitters are required to have a “mask filter” that is used to filter out-of-band emissions that may be generated in the transmitter’s final amplifier. This filter is typically added externally to the transmitter and is sometimes provided by companies other than the transmitter manufacturer. As with any component added to the transmission path, the “mask filter” has power loss associated with it that causes a slight reduction in the output power of the DTV signal. Consequently, transmitter manufacturers that provide the “mask filter” tend to include it in their efficiency calculations. Those that don’t provide the mask filter will provide efficiency calculations that do not include the filter, which results in a slightly higher efficiency due to increased transmitter power output. Some manufacturers provide only the efficiency rating for the power amplifier section of the transmitter. Where possible, we have considered the pre-mask filter efficiency on all TV transmitters.

Many TV transmitter manufacturers have new VHF solid-state TV transmitter lines that feature 50 Volt (V) Laterally-diffused Metal Oxide Semiconductor (LDMOS) Field Effect Transistors (FETs) in both liquid-cooled and air-cooled versions for VHF and UHF ATSC digital operation. These models range in efficiency from 20% for the lower-power air-cooled solid-state transmitters to approaching 30% for the higher-power liquid-cooled models.

Liquid cooling of the LDMOS is more energy efficient for two reasons – liquid cooling keeps the silicon junction devices operating more efficiently, and there’s no need for a lot of high-BTU/hour air-conditioning because the heat is dissipated into the liquid and carried away through a heat-exchanger, usually located outside of the building. The new LDMOS FETs also allow the manufacturers to pack more power output into a smaller transmitter footprint.

Some manufacturers still make transmitters that use the lower-capacity (32 V) LDMOS FETs. These devices are cheaper to purchase, but more expensive to operate. They are air-cooled, and more PA cabinets are required to achieve the same power level as a smaller 50 V LDMOS FET transmitter. Efficiencies for these transmitters are not available from published sources, but for a typical pre-2009 VHF transmitter, efficiencies are in the 20-22% range.

At UHF, it is also the case that higher-power solid-state transmitters are more efficient than the lower power models. Per the manufacturer, the more PA modules there are, the more efficient the transmitter is. Efficiency is 18.7% at 1.7 kW, and 28% at 30 kW, but this high-power transmitter has a cooling requirement of 80,000 BTU/hour, or more than 27,300 W of air cooling. This is true of virtually all of the TV transmitter product lines from which data was obtained; when PA modules are added, efficiency increases, but so does the proportional need for additional cooling.

Using the 50 V LDMOS FETs, some manufacturers manage up to 8.5 kW average digital power from the new liquid-cooled solid-state transmitters, with overall efficiency figures in the 20% to 22% range for these models. Early indications are that the liquid cooled solid-state devices are also more efficient at UHF frequencies.

Looking at tube-type DTV transmitters, the "Energy Saving Collector" Multi-stage Depressed Collector (MSDC) liquid-cooled Inductive Output Tube (IOT) that some companies use in their current UHF TV transmitters have much better efficiency figures than solid-state devices, in the 33% - 39% range. In addition to liquid cooling the IOT, the solid-state pre-amplifiers are also liquid-cooled to decrease the junction operating temperatures of these silicon devices. This provides the additional benefits of increasing available power out of the solid-state devices, and increasing the overall transmitter efficiency. Another manufacturer builds only solid-state transmitters that have published efficiencies of between 25% and 27%.

During the DTV transition, many stations sought opportunities to improve their coverage over their originally allotted DTV footprint. However, the amount of power to improve DTV signal coverage can be staggering even with the more power-efficient 8VSB modulation used in the U.S.

For example, the original 1997 studies on a Channel 2 coverage pattern at a representative TV station indicated that they would need about 2 megawatts (MW, one megawatt equals 1 million watts) of total radiated power at Channel 31 to replicate the legacy analog

Channel 2 coverage that the station had previously enjoyed. In the mid-90s, that translated to a Channel 35 liquid-cooled transmitter with five (5) tube cabinets. Tubes at that time were less than 25% efficient, and the thought of not only the initial cost of five 25% efficient tubes and the power with which to cool them operating continually (not to mention the replacement cost) horrified many station managers and engineers. More efficient tubes for DTV transmitters have enabled stations to maximize power and significantly reduce energy use at the same time by purchasing a new transmitter.

Additionally, manufacturer data shows that there is some frequency-dependent efficiency loss across the UHF band from 470 to 862 MHz. TV transmitters at Channel 14 are marginally less efficient than TV transmitters at Channel 51. While a station's channel allocation may be a given, station engineers need to be aware of the ramifications of operating frequency on efficiency.

Cooling

As discussed in prior sections, there are a number of ways to cool television transmitters. Lower-power solid-state devices at VHF and older klystron tubes at UHF are capable of being air-cooled. The newer high-output LDMOS FETs require liquid cooling, and new MSDC IOT manufacturers specify oil or water cooling as the best method for cooling.

For air-cooled transmitters, airflow and cooling capacity are critical. The higher the power output of the transmitter, the more waste heat the HVAC system has to overcome.

Having a more efficient transmitter may mean a slightly lower cooling bill. Additionally, the newer FETs require liquid cooling, which removes the waste heat from the environment through an outside heat exchanger so less HVAC is necessary to cool the transmitter.

It is possible to re-use waste heat from transmitters to heat water or personnel space in the wintertime, especially in colder climates. A number of instances can be documented where stations have successfully used the waste heat from a transmitter heat exchanger in the winter to heat the personnel space in the building. The lower-efficiency air-cooled FET devices don't need as much air cooling as their newer counterparts, but at 30% efficient they are relatively expensive to cool if the transmitter cannot be exhausted to the outside and the closed environment needs to be cooled.

One manufacturer has implemented a "positive pressure cooling" system, internal to the transmitter cabinet (solid-state TV transmitters), which keeps more of the waste heat out of the environment so the HVAC does not have to work as hard. Air-conditioning is an expensive utility, and various approaches can be employed to try to offset the high cost of energy, such as ducting waste heat to the outside, as opposed to utilizing air-conditioning to cool all of the transmitter waste heat.

Cooling a transmitter and keeping the air that surrounds it clean is the basis of many lively discussions among engineers. Most engineers agree that (economic considerations aside) the best way to cool a transmitter is to take transmitter exhaust heat, cool it with air-conditioning and re-admit it to the transmitter environment. Temperature in the transmitter area can, in this fashion, be kept clean, dry and temperature stable. However, it requires an enormous amount of cooling to do so.

Conversely, if the waste heat from a transmitter is exhausted outside the transmitter area—to the exterior of the building, perhaps—then that air has to be replenished. The incoming air needs to be cooled, filtered and de-humidified, depending on the outside environment. An engineer or maintenance person needs to be available to routinely change filters and clean the transmitter area, and keep the intake area clean. In order to save energy, this type of cooling should be explored in dry, cool environments where it makes more sense. Partial cooling using outside air can be employed in many areas of the country in the winter months.

Again, some current-model transmitters use a technology described as "positive pressure cooling", where a slight positive pressure is maintained inside the equipment cabinets (this is done both for this manufacturer's tube-type and solid state equipment). Air is ducted directly into and out of the transmitter cabinets. This effect can be achieved with HVAC ducts and some drywall for other models of transmitters.

Several specifics should to be kept in mind for the airflow when air cooling transmitters, including where the intake air is coming from, where the exhaust air goes, and how it flows over the equipment to cool it. Air can be ducted directly into the equipment racks, or can be generally diffused over the entire environment. All of these are considerations that have to be weighted in the overall “plant efficiency” equation.

In light of the discussion above regarding closed vs. open cooling systems, there are a number of methodologies that are general practice: maintaining a “positive pressure chamber” in the area behind the racks keeps the cooling bill a bit lower, and keeps any operators or maintenance technicians working in the area from having to work in too-cold conditions. Many commercial air conditioning units today can be purchased and used on a graduated basis – they might be designed with a 10-ton capacity, but if only 6 tons of cooling are needed, the units only supply 6 tons of cooling, instead of the entire 10, saving energy and cost. It requires the investment in a new cooling unit, with multiple compressors and specialize control circuitry.

Additional Efficiency Measures

There are a number of other ways to keep the overall efficiency of the entire transmission system as high as possible. The following are some that are outside the realm of the transmission equipment:

- Insulation: often there is no insulation in the walls or ceiling of a transmitter building. Higher efficiency windows and doors can also be installed to minimize heat transfer. An enormous amount of heat and cooling can be lost in the hot and cold seasons, requiring HVAC systems to overcome not only equipment loads, but also environmental ones;

- Lighting: fluorescent lighting is typically used in transmitter plants today instead of incandescent lighting. Current tower lighting is a fixed constant – LED or fluorescent-type lights for tower lighting have gained mixed acceptance and may not be suitable (or approved) in certain types of situations. High-arc sodium or mercury vapor exterior lighting for safety and security on the exterior of buildings is expensive, but necessary;

- Newer, more efficient (higher SEER) air conditioning equipment: each station will have to decide, based on the current equipment's age and condition, whether or not this sort of investment makes sense.

Green Alternatives to "Shore Power"

Green alternatives to conventional electric grid power will be mentioned here, but are not part of the calculations in the transmission efficiency web-based tool, as there is not enough data at this point to generate any kind of measurable economies.

It is questionable as to whether there is a good return on investment for adding solar or wind power assistance. Much depends upon the initial costs and the price and/or availability of commercial power. It might be practical for low-power applications in very small installations, but photovoltaic systems for higher-power stations are not yet practical. It is possible in smaller installations that power could be sold back to the power company when the solar-assist system makes more power than it uses, but again, this opportunity only exists for the minimally powered stations with access to the grid.

Issues with solar power system use include high entry costs, local permitting, zoning and approval considerations, sustainability in winter conditions or in overly cloudy environments, snow removal from panels, and even location and sun "look angles" all have to be given considerable thought.

Many wind turbine solutions are theoretically practical given the available generating power from each device. However, if the area wind profile is not consistent, use of conventional utility feeds an/or some sort of reserve battery system are necessary.

Wind turbine systems are often controversial due to their "visual impact" on the area. Often, local community opposition to one or several wind turbines can be stronger than local opposition to a tower construction project. Further, wind turbines near a transmitting facility could impact transmission and create multipath distortion for FM and television operations.[13]

Placement of a wind farm is a matter that warrants study and consideration. It should not be situated such that it blocks, or potentially blocks incoming microwave paths (studio-to-transmitter links, or intercity relays) or outgoing signal paths. Minimally, first Fresnel zone clearances are needed. Further, other spectrum users may object due to interference concerns.

In early 2011, Broadcast Australia upgraded the Mt. Owen site in Tasmania.[14] It is now majority-powered by a renewable energy system, combining 36 square meters of solar photovoltaic panels with a constant-output horizontal-axis wind turbine. Broadcast Australia estimates that the savings will be close to 60 megawatt-hours of conventional power each year for the one site. This is an excellent illustration of a site that can take advantage of height and prevailing winds to implement a wind turbine solution which, combined with a solar panel array, can provide most of the required power demand of 8 kW.

While energy technology alternatives are attractive in general, each has practical power limitations and high initial costs. For most situations, such systems should be thought of for supplementary, rather than primary use, perhaps for minimizing peak energy demands during critical periods.

In summary, such systems are still in need of technology advances, and are perhaps only presently suited for use in remote and "low power need" situations.

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[13] See, for example, *An Empirical Comparative Study of Prediction Methods for Estimating DTV Signal Scattering from Wind Turbines*, Itziar Angulo - University of the Basque Country, Spain, 60th Annual IEEE Broadcast Symposium, October 20-22, 2010.

[14] See http://blog.wheatstone.com, January 17, 2011 posted by Scott Johnson.

Conclusions

For all transmitter types, evolving technology has made a difference to the efficiency of transmitters. New solid-state devices in AM, FM and television transmitters have clearly made them more efficient. In high-power UHF TV transmitters, the evolution of high-power tubes is creating efficiencies that are better than the solid-state devices and better overall than have ever been seen. Solid-state transmitters have advanced from 22% efficiency in the mid-1990s to more than 30% today, and the new UHF tube transmitters approach 40% efficiency.

Solid-state FM transmitter efficiency has made small advances with the advent of new silicon-based devices, and overall, an FM analog transmitter has efficiencies of up to 75%, up some 10 percentage points from 20 years ago. Tetrode tube-based analog FM transmitters are slightly more efficient than solid state in the high 70 percent range.

The key to more efficient FM hybrid transmission systems lies in the combining method that each station uses, depending on the equipment available at the station, capital expense money available to the station, and prevailing conditions in terms of climate, power costs and condition of the HVAC equipment. FM station engineers have the most research and calculations to do to find the solution that is best for their needs.

AM transmitters have gotten fractionally more efficient as solid-state devices have evolved, and the addition of digital technology to the transmission chain does not affect the overall efficiency of the system. For AM, the key to greater efficiency lies in the work that is yet to be done with modifying current modulation schemes to those that are more power-efficient, while maintaining the existing receiver base.

PART 2 – PROPOSED EFFICIENCY RATING AWARD

Objective

The objective of developing a proposed Transmitter Energy Efficiency Award ("TEEA") for broadcast transmitters is to provide a tool that broadcasters may use in making "greener" decisions when purchasing transmission equipment. These decisions may save money in the form of lower commercial electric power bills. In some cases, the reduced operating expenses are significant enough to be able to provide an accelerated return on investment ("ROI") for the transmitter purchase.

The TEEA, much like the Environmental Protection Agency's ENERGYSTAR™ Rating, establishes a set of criteria and measurement methods that can be used to compare various transmitter products against each other. [15] Products that surpass a certain predetermined efficiency threshold (or thresholds, for multi-level ratings) are given the TEEA. With the TEEA system, all transmitters above a threshold will be eligible to receive a "seal" or the right to mention that their products have achieved this TEEA (corresponding to that threshold) in their literature. CMA suggests that 25% be the threshold used for the top rating developed under this proposed system.

In order to set up testing and rating categories for the TEEA, transmitters are separated into general categories, such as AM, FM and TV. Comparisons are then made on sub-sets of each category, such as power amplification device (i.e., solid-state or tube-type), UHF or VHF (for the television transmitters) and analog, hybrid or digital (for the FM transmitters).

[15] ENERGYSTAR is a registered trademark of the U.S. Environmental Protection Agency.

Testing Methodology

In order for the transmitter efficiencies to be comparable between each manufacturer and transmitter type, a testing methodology is recommended to specify the parameters for each category. Testing procedures for each category (AM, FM TV) are similar:

1. Set the RF power out of the device to the manufacturer's recommended "nominal output power";
2. Measure the actual RF output power of the device with an accurate calorimetric load;
3. Divide that number by the measured AC input power consumed by the device including power factor.

This resulting ratio constitutes the transmitter's efficiency rating.[16] In addition, each category has its own specific testing criteria, as detailed below, unique to the particular band or mode of operation.

For all transmitter categories, the need to consider the power consumption of individual transmitter cooling calculations as part of the *TEEA*, was extensively examined and ultimately discarded, under the premise that input power that is not converted to RF output power is converted to heat. A more efficient transmitter will generate less heat and therefore require less cooling energy. Additionally, varying climates will result in large differences in cooling needs and costs for a single transmitter model are difficult to account for with these variations all across the country.

Rating Methodology

Within each category, each transmitter's efficiency percentage is compared against the others to determine the universe of comparison. To establish the *TEEA* rating, an appropriate threshold is established for the top ranking transmitters within that universe. For the discussion presented here, two separate thresholds are proposed. The first awards a "silver seal" *TEEA* to a transmitter in the top 40 percent of its class. The second awards a "gold seal" *TEEA* to only the

[16] For a device having a "nominal power output" of 4,000 W and consuming 18,900 W of energy, the calculation is 4,000/18,900 or 0.2116. Rounded and displayed as a percentage, the efficiency rating is 21.2%.

top 25 percent of the tested universe of transmitters.[17] This TEEA gold seal has been chosen as the current award, and is highlighted in green in the tables that follow.

AM Transmitters

As discussed above, manufacturer-provided efficiency data revealed a number of interesting facts:

- Adding IBOC digital capability to analog AM transmitters does not affect the efficiency in the sample that was studied;
- Efficiency differences between legacy tube-type and legacy solid-state AM transmitters were negligible;
- There were no current-model AM tube-type transmitters available for the study.

Therefore, for the purposes of this demonstration, all AM transmitters will be tested as a single category.

All AM transmitters should be tested at the "nominal power output" for the specific device as recommended by the manufacturer for operation. Testing should be carried out with ±100% modulated carrier. Carrier should be modulated with 1 kHz tone. The commercial electricity source voltage and current draw of each transmitter should be measured using appropriate calibrated instruments. Multiplying the two resulting measurements will yield power consumption for the unit operating at "nominal power output." The RF output power of the transmitter can then be measured with an appropriate calibrated calorimetric load. From a power loading standpoint, modern broadcast transmitters are mostly resistive, having no large motors or other highly inductive components, and normally operate from a dedicated single- or balanced three-phase power source. Thus, with the largely resistive load, total power consumed equals the sum of the power consumed in each leg.[18] Current transmitter literature corroborates this, as

[17] In the case of household appliances, each appliance is awarded an "Energy Star Rating" when is it is more efficient than 50 percent of the "universe" of same-type appliances.
[18] $P_{total} = 3P_{phase}$

power factors are listed at between 0.96 and 0.98. However, using the power calculation for complete accuracy is recommended. [19]

In the sample shown below in Figure 5, the sample efficiency percentages were either taken from data provided by manufacturers or retrieved from published manufacturer literature. In total, data from seven manufacturers is shown in the example, with as few as two transmitters from one manufacturer, and as many as twelve transmitters from another. The transmitter efficiency average is 76.9%, and transmitter efficiencies scoring better than 83.0% are in the 25th percentile and would be eligible for the rating.

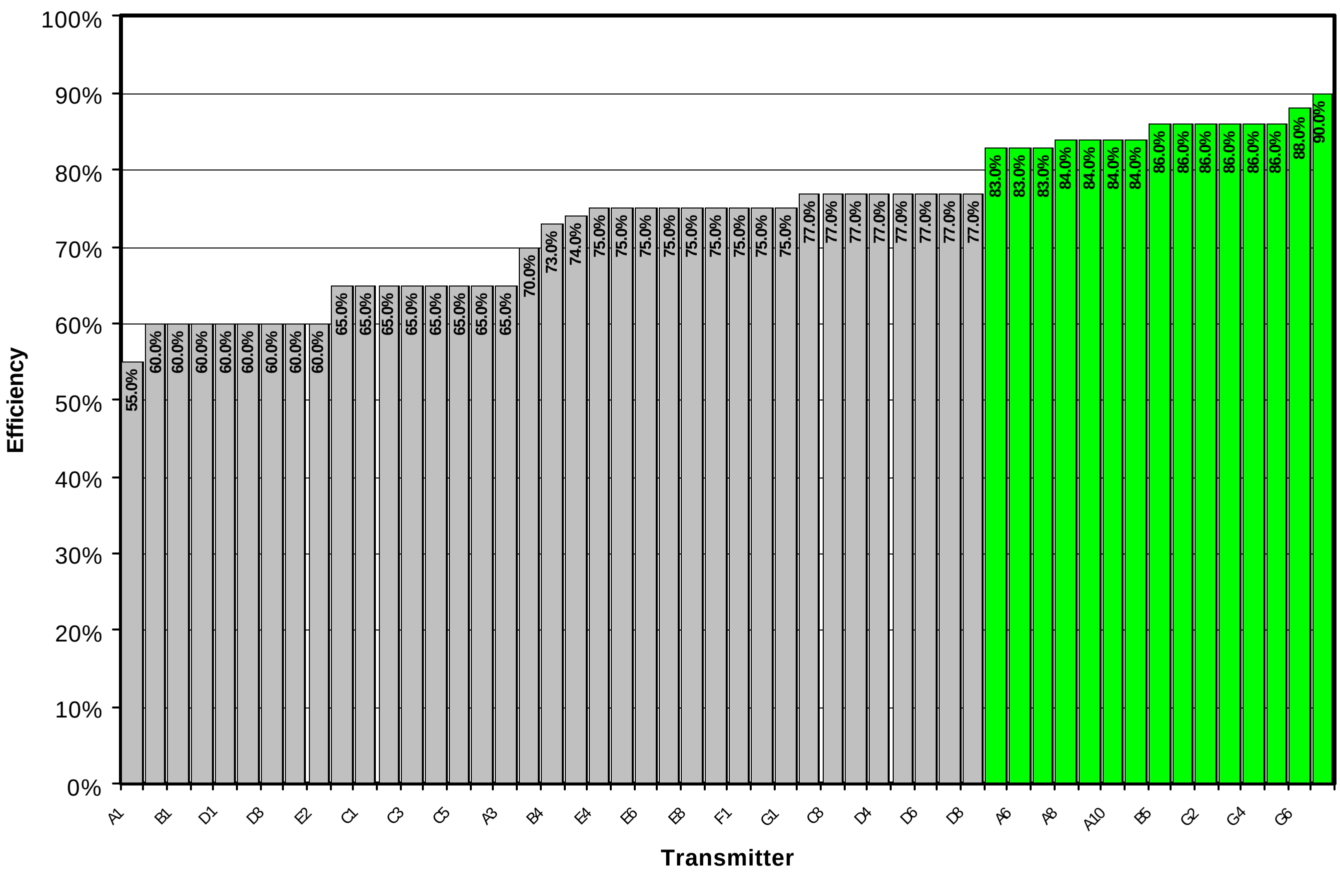

Figure 5 – Transmitter Efficiencies For Sample AM Transmitters @ 100% modulation

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[19] $P_{total} = \sqrt{3} V_{line} I_{line} \cos\phi$

FM Transmitters

FM transmitters should have the AC input power and the RF output power measured in the same fashion as recommended for the AM transmitters.

Unlike AM, FM transmitter efficiency is significantly different between analog mode, the analog+HD hybrid mode, and digital only mode. In some cases, a station must consider both the existing analog transmitter and new digital transmitter efficiencies when mid-level and high-level analog/HD combining are being evaluated as combining options.

Figure 6 shows the ranking of forty-three transmitters manufactured by seven different companies operating in analog mode. Some of these devices are models that are only capable of analog operation (both legacy and current-model), whereas others are current-model, IBOC-capable transmitters. Five of the analog-only devices are tube-type. Notably, there are minimal efficiency differences between solid-state transmitters and tube-type transmitters of this generation.

For the analog FM transmitters, the average efficiency is 62.4%. An efficiency score of 67.0% (shown in green in Figure 6 below) earns a *TEEA* "gold star."

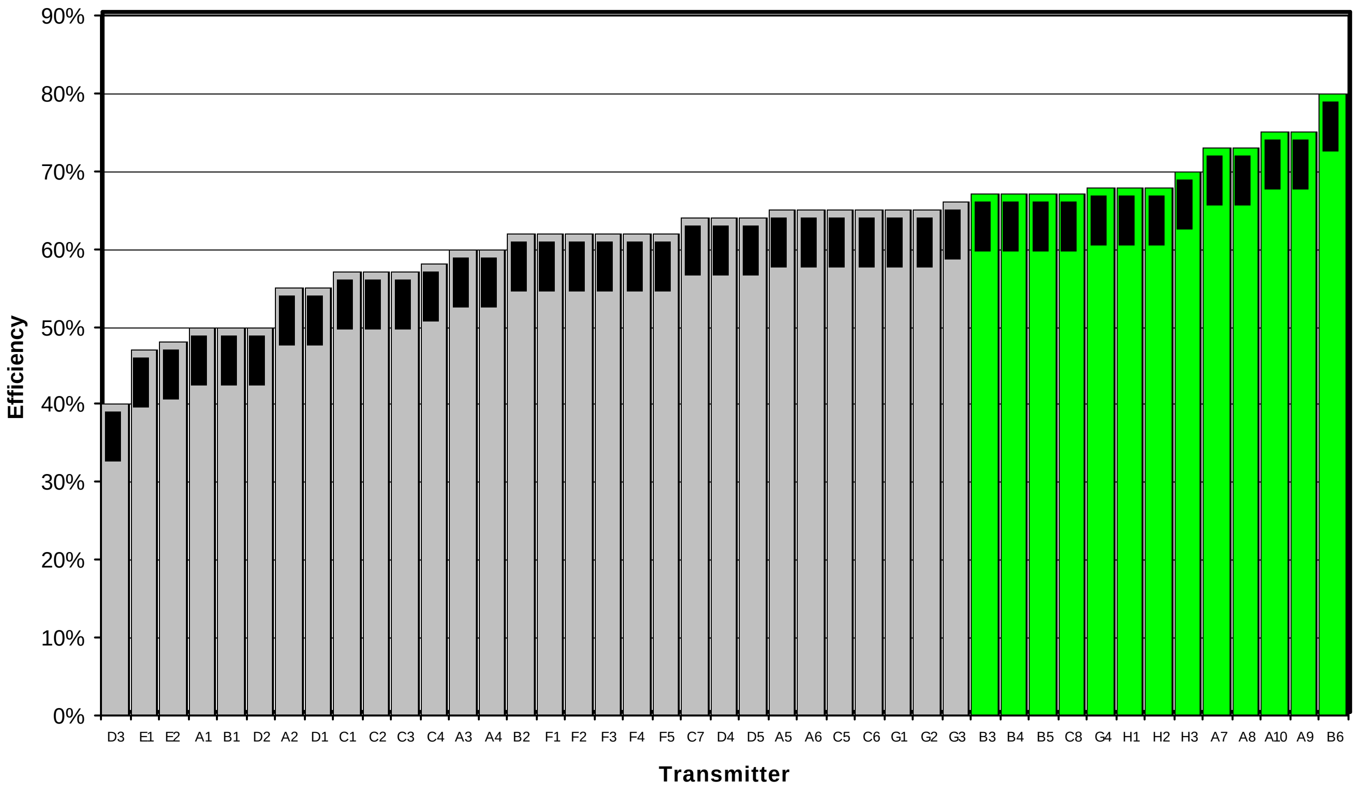

Figure 6 – Transmitter Efficiencies For Sample FM Analog Transmitters

Figure 7 shows samples of the FM transmitters capable of hybrid analog/digital operation and of digital FM transmitters. The efficiency reported below for the hybrid transmitters is for low-level combined hybrid operation with -20 dBc IBOC injection. Little additional data for transmitter efficiency of low-level combined hybrid operation at other IBOC power levels was available.

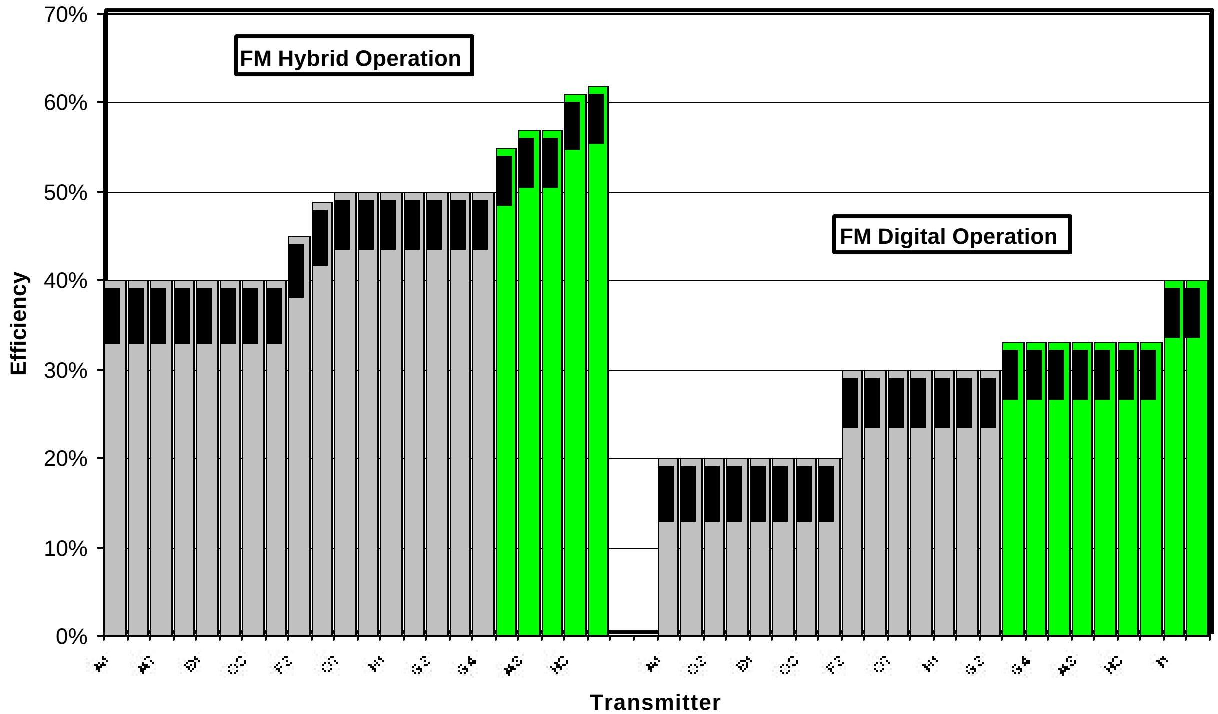

Figure 7 – Transmitter Efficiencies For Sample FM Hybrid (-20dBc) and FM Digital Transmitters

For the Hybrid FM transmitters, average of all the transmitter efficiencies is 48.0%, while an efficiency score of 52.5% and above (shown in green) earns a *TEEA* for being in the top 25 percent of the sample.

Figure 7 also shows the efficiency rankings of the even smaller subset of FM transmitters for which digital AC-to-RF power efficiency data was available. This sample included not only transmitters capable of Analog, Hybrid and Digital operation, but also transmitters that are only capable of Digital operation.

The Digital FM transmitters have an average efficiency of 28.4%, and the efficiency score of that earns the *TEEA* for this category is 33.0% and above (shown in green).

TV Transmitters

The TV spectrum is split into two separate frequency bands with distinct power requirements and amplification characteristics. For this reason, this study separately evaluates UHF transmitters and VHF transmitters. Additionally, because UHF DTV transmitters with high-power tube-type output devices perform significantly more efficiently than their solid-state output device counterparts, UHF tube-type transmitters are rated separately from the UHF solid-state transmitters. Following the DTV changeover in 2009, all current model digital VHF transmitters in use today utilize solid-state output devices. As a result, no VHF tube-type transmitters were considered in this study.

The same testing methods for AM and FM transmitters should be applied to television transmitters of all types, where modulation applied is a standard digital waveform. The actual audio and video content applied to the transmitter has no effect on the power or efficiency since the RMS power of the digital waveform is independent of the modulation. . Additionally, the RF output power of all television transmitters should be measured *before* the mask filter[20]. Figure 8 details the findings.

Solid-state output device UHF transmitters have an average efficiency of 24.8%. The group of transmitters with an efficiency score of 27.0% earns a *TEEA* as the top 25 percent in their class.

There are fewer UHF TV transmitters on the market these days that use tube-type (IOT) output devices. The average for the sample shown in Figure 8 is significantly higher than the solid-state output device counterparts at 41.8%, and the results are more tightly packed. The 25th percentile group is only five-tenths of a percent higher than the average at 42.3%.

[20] The FCC required mask filter is an option on many TV transmitters, can be purchased from other sources, and adds further inherent losses. Therefore, efficiency calculations should exclude this mask filter in any comparison studies.

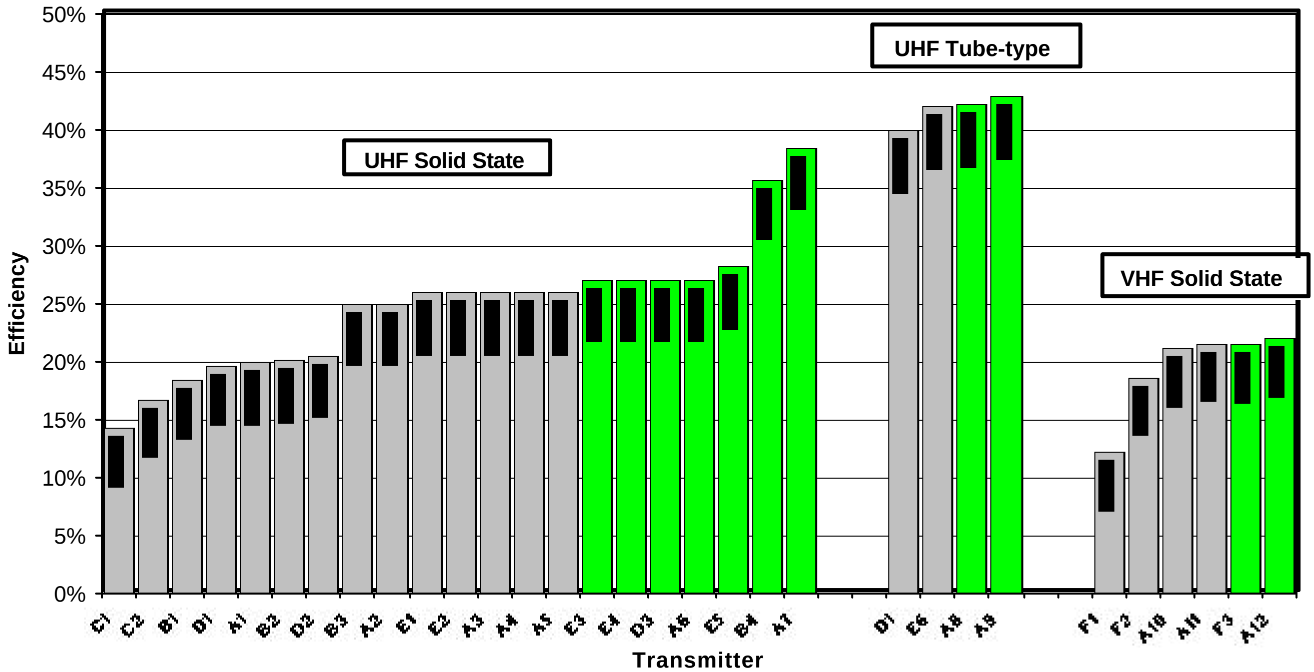

Figure 8 – Transmitter Efficiencies For Sample TV Transmitters (All Categories)

VHF television transmitters, regardless of VHF band, are the least efficient of all of the transmitter samples. Higher power units are more efficient than low power units. The average efficiency for the VHF transmitters shown is 19.6%. To obtain a 25th percentile TEEA rating would require having an efficiency score of 21.6%.

It is suggested for consideration that an alternative *TEEA* two-tier system could utilize a "good" rating when a transmitter shows better efficiency than 60% of its peers, or as a "best" rating if a transmitter is more efficient than 75% of the comparable "universe." It may be also advantageous to award different "stars" to both "good" and "best" category transmitters (as suggested earlier) if it is felt that rating criteria are too stringent to award only a "best" rating to the top 25% of the available transmitters.

Transmitter manufacturers will need to provide efficiency data, mathematical calculations, and traceable measurement certification for each transmitter that each company produces in order to provide the population of transmitter products to accurately determine efficiency rankings and provide a *TEEA* system.

Given the limited nature of the data voluntarily provided by manufacturers for this study, such an endeavor can only be done here for a sample subset.

As solid-state and tube-type device technology progresses, and new transmitters are developed, efficiency ratings and metrics should be periodically revisited.