Doherty Amplifiers “101”, and How They Apply to DTV

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Abstract

This paper will discuss Doherty amplifiers and how they apply to digital broadcast television. In the past 10 to 15 years there have been vast improvements in LDMOS solid state amplifier technology all the while resulting in improvements to digital television broadcast transmitters. Over the past number of years, transmitter equipment manufacturers have been applying an old technique, Doherty, to solid state DTV transmitters thereby increasing transmitter efficiencies that, in most recent times, are starting to approach the most efficient high power MSCD IOT vacuum tube based DTV transmitters. So what is Doherty and how does it work? This paper will explain the basic Doherty principle, different methodologies for applying this principle, pros and cons of these different methodologies, and how they affect amplifier performance. There are also proposals in place to improve / update the original modulation standard used from ATSC1.0 (8VSB) to ATSC3.0 (OFDM). This has a RF impact on broadcast transmitters as the peak to average ratio (PAR) in the new standard is approximately 3dB higher affecting transmitter’s performance and or the ability to generate the same average output power. The paper will discuss some different techniques and methods for dealing with this update.

Background

Throughout the past six decades, vacuum tubes have been the amplifier device of choice used in television broadcast transmitters. For UHF broadcasters especially, transmitter efficiency has been increasingly critical to the cost of operation of these high-power systems. Over the past 25 years solid state VHF and UHF TV transmitters have been gaining popularity and their power levels, power densities and transmitter efficiencies have continued to increase. Additionally, solid state transmitters posses other endearing qualities such as; soft failure mechanisms, no potentially lethal high voltages, and less stringent requirements on maintenance and on the personnel required to perform this maintenance and repair.

LDMOS RF Transistor manufacturers have made great strides in the past 5 to 7 years dramatically increasing the power levels, and ruggedness of the devices, along with increasing their operating efficiencies. This coupled with a concept invented some 80 years ago by William H. Doherty for increasing efficiency, has made high power solid state DTV transmitters the current and foreseeable future technology of choice. ATSC 1.0 was adopted by the FCC and put into broadcast use 20 years ago (1996), but time and technology, especially digital technology, marches on. Broadcasters are on the cusp of being handed a new standard to work with, ATSC 3.0. Unlike ATSC 1.0, which is 8-VSB modulation with a peak to average power ratio of approximately 7dB, ATSC 3.0 is OFDM based and has a peak to average power ratio of approximately 10dB. This means that broadcast transmitters will need to produce approximately twice the amount of peak power with this new modulation as they have had to in the past to maintain their licensed average output power level. There are many ways to help deal with this change including but not limited to final amplifier configuration and operating points, as well as some “digital tricks” that can be accomplished in the modulators, all while trying to not have a negative impact on performance and or transmitter efficiency.

Traditional Class AB Amplifiers

Modern solid state television broadcast transmitters utilized LDMOS FETs for their active amplifier device. These FETs were run in Class AB linear mode. This mode of operation was a good compromise between linearity, efficiency, and peak power capability. The LDMOS FETs were initially operated at 24-28 VDC and had power capabilities of <100W peak per FET. Some strides were made with the LDMOS technology allowing them to run at 32VDC and this allowed power levels to get pushed up to the 150 watts peak level per FET. This level of operation was pretty much the “standard” in transmitters in the mid 1990’s to the early 2000’s. LDMOS FET manufacturers continued to push the 32 VDC technology and by 2005 had it up to the 300 watts peak per FET level. By 2006 transistor manufacturers were introducing LDMOS FETs that now operated at 50VDC. This allowed the power levels to be pushed again starting at approximately 450 watts peak to approximately 600 watts peak per FET. Once they got to this power level it was quickly realized they needed to enhance the thermal characteristics of these new high power parts. By 2007 to 2008 they had accomplished this and so the industry now had good quality high power FETs to build transmitters around.

Digital TV and the Class AB Amplifier

In 1996, along came the ATSC 8-VSB digital broadcast standard in the USA. Broadcasters were granted a second channel to “simulcast” what they were broadcasting in their original analog (NTSC) format. In analog NTSC format, the power of the vision carrier was measured as peak power during the horizontal sync pulse.

With the switch to digital TV, since the modulated signal was broadband and constant by design, the power measurement was now going to be an average power measurement. This made measuring the power relatively easy, but because of the nature of the ATSC signal the amplifier system had to be able to reproduce the modulation peaks or crest factor of RF that it created. These peaks on a pure 8-VSB signal are approximately 8.3dB above the average power level of the signal. Figure 1 shows a CCDF plot of an ATSC 8-VSB signal directly out of an exciter with all correction disabled. Because the digital TV exciters employed various schemes of linearization techniques, and the FCC allowed for out of channel intermodulation distortion "re-growth" as long as it fit into a compliance spectral mask, this allowed for running amplifier systems into peak power compression. The result means the crest factor instead of being 8.3dB could be reduced thereby increasing the average power capability of a particular amplifier. From an amplifier's perspective, it didn't matter as the amplifier would simply operate in saturation at the peaks of the signal and create distortion products that either needed to be filtered, corrected, or both. From a signal quality perspective and FCC spectral compliance perspective, one could really only push an amplifier system just so hard before the signal quality was degraded beyond a useful level, even with linearization and filtering. This compromise level for ATSC / 8-VSB resulted in a crest factor typically of 6.5 to 7dB. What this means from an amplifier perspective is that at a 7dB crest factor the amplifier would have to be "backed off" in *average* power level from its full peak saturated power capability by 7dB or 20% of its full capability. This means one of the latest 600 Watt peak LDMOS FET devices would operate at approximately 120 watts of *average* ATSC 8-VSB power.

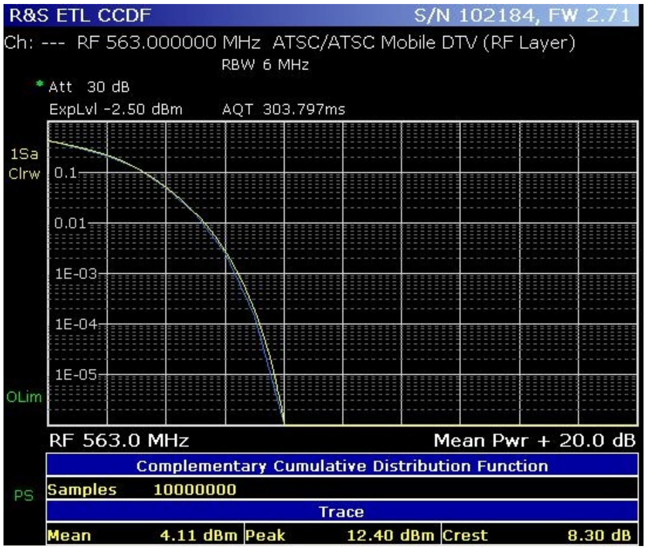

```
R&S ETL CCDF                                        S/N 102184, FW 2.71
Ch: ---  RF 563.000000 MHz  ATSC/ATSC Mobile DTV (RF Layer)
                          RBW 6 MHz
   * Att  30 dB
     ExpLvl -2.50 dBm       AQT 303.797ms
     RF 563.0 MHz                               Mean Pwr + 20.0 dB
              Complementary Cumulative Distribution Function
     Samples      10000000
                              Trace
     Mean          4.11 dBm Peak         12.40 dBm Crest           8.30 dB
```

Figure 1: CCDF Curve of an ATSC 8-VSB RF Signal

The other result of operating a class AB amplifier at approximately 20% of its peak rated output power is that the efficiency of the amplifier is fairly low. Figure 2 shows the efficiency versus power output curve of an Ampleon BLF888A running class AB and being driven with an ATSC 8-VSB modulated signal.

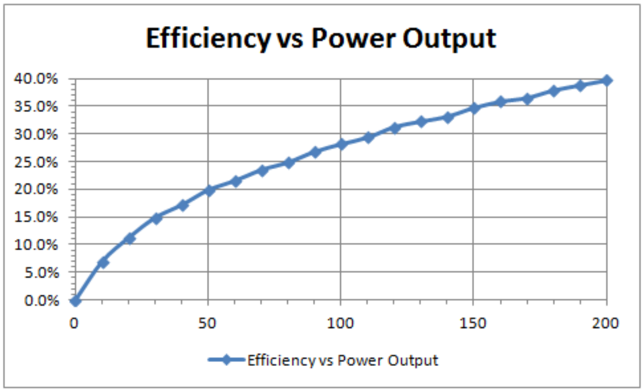


Figure 2: BLF888A Class AB Efficiency vs Power

As shown in Figure 2, the efficiency at 120 watts of output power is approximately 31%.

The other performance items to consider as mentioned earlier, is the amplifiers ability to reproduce the digitally modulated signal. In a traditional class AB amplifier, there is a "graceful degradation" of signal performance as the amplifier is "pushed" harder. Shown below in Figure 3 are the power input vs power output transfer curves of the BLF888A amplifier. The input power is in average watts, while the output power shows both average watts and calculated peak watts. The calculation was done by using the average power and factoring in the crest factor as read on the R&S ETL signal analyzer. As you can see, the average power curve is quite linear and straight while the peak power curve shows compression and saturation non linearities. This data was taken without any linearization applied to show the "natural" performance of the amplifier under test.

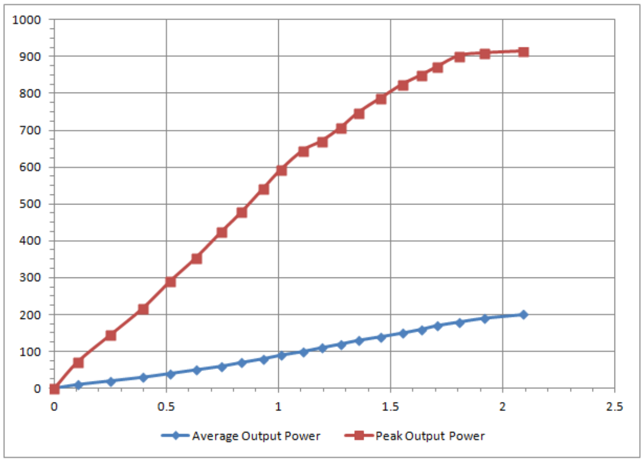


Figure 3: BLF888A Class AB Power In vs Power Out

We can also look at how the signal performance (shoulders and MER) are affected by the output power level from the amplifier. Figure 4 below is this same amplifier comparing shoulder level and MER to average output power. Again this is not using any linearization to allow for showing the natural performance of the amplifier.

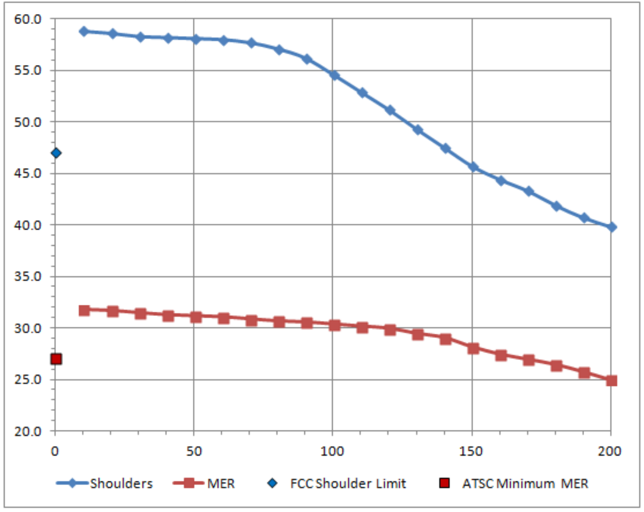
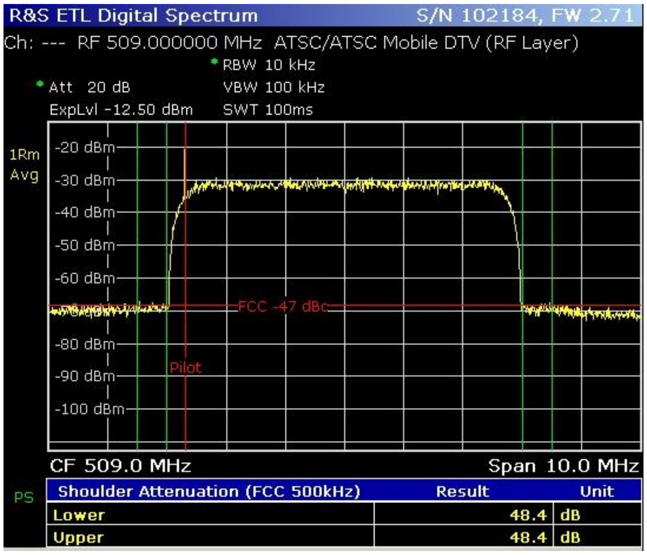


Figure 4: BLF888A Power vs Signal Performance

As can be seen, the amplifier when driven to higher power levels causes distortions in the signal resulting in degraded performance. This amplifier without linearization meets FCC performance criteria up to approximately 140 watts of average output power where the shoulder levels are the first to approach the performance limit at 47.5dB.

By using digital linearization techniques in the ATSC Digital Exciter this amplifier can be "corrected" to acceptable signal performance levels up to 170 watts of average output power. Figures 5, 6, and 7 show the "corrected" performance of this amplifier at the 170 watt power level.



R&S ETL Digital Spectrum S/N 102184, FW 2.71

Ch: --- RF 509.000000 MHz ATSC/ATSC Mobile DTV (RF Layer)

RBW 10 kHz

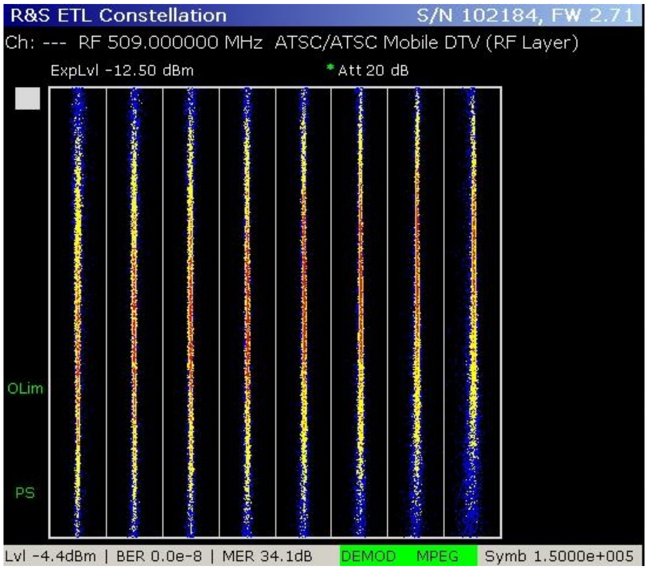
Att 20 dB VBW 100 kHz

ExpLvl -12.50 dBm SWT 100ms

CF 509.0 MHz Span 10.0 MHz

Shoulder Attenuation (FCC 500kHz)	Result	Unit
Lower	48.4	dB
Upper	48.4	dB

Figure 5: BLF888A Corrected Shoulders 170 Watts



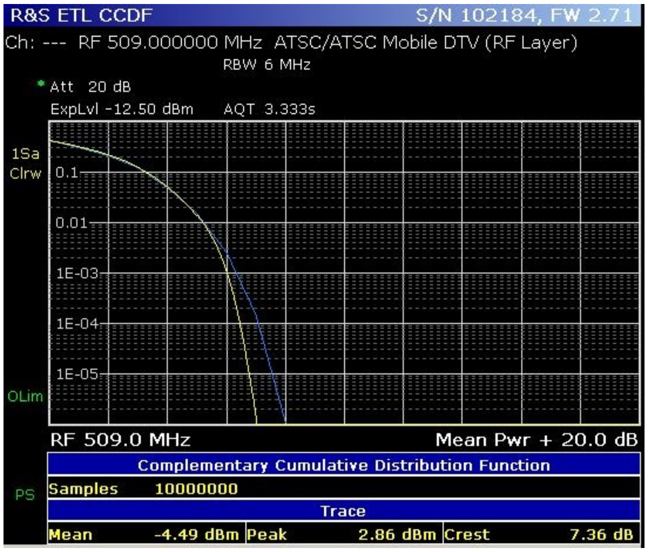
R&S ETL Constellation S/N 102184, FW 2.71

Ch: --- RF 509.000000 MHz ATSC/ATSC Mobile DTV (RF Layer)

ExpLvl -12.50 dBm Att 20 dB

Lvl -4.4dBm | BER 0.0e-8 | MER 34.1dB DEMOD MPEG Symb 1.5000e+005

Figure 6: BLF888A Corrected Constellation 170 Watts



R&S ETL CCDF S/N 102184, FW 2.71

Ch: --- RF 509.000000 MHz ATSC/ATSC Mobile DTV (RF Layer)

RBW 6 MHz

Att 20 dB

ExpLvl -12.50 dBm AQT 3.333s

RF 509.0 MHz Mean Pwr + 20.0 dB

Complementary Cumulative Distribution Function					
Samples	10000000				
Trace					
Mean	-4.49 dBm	Peak	2.86 dBm	Crest	7.36 dB

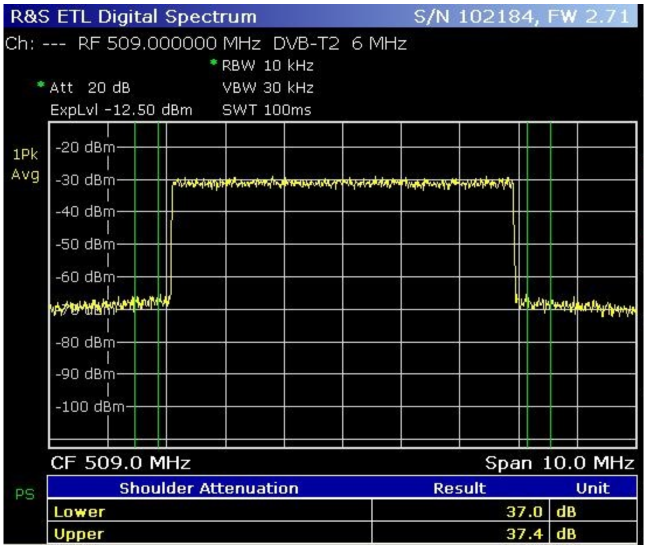
Figure7: BLF888A Corrected CCDF Curve 170 Watts

As shown in Figure 7 above this amplifier when corrected now has a crest factor of 7.36dB resulting in a peak output power level of 921 watts, which by comparison in the curve shown previously in Figure 3 is well into the compression region of the amplifier. By using "correction" and now running this amplifier higher in power the other benefit is higher efficiency. While this amplifier met FCC specifications at 140 watts output the efficiency of it was 33%. At the 170 watt level the efficiency is now 36.5%. This 3.5 percentage point increase may seem small but to the broadcaster running a large transmitter facility with a large monthly electricity bill, they will welcome the 10% plus reduction in that bill.

What about ATSC 3.0?

Up to now, all of the digital modulation used has been ATSC 1.0 or 8-VSB. The industry is on the cusp of releasing a new digital television standard called ATSC 3.0. The ATSC 3.0 standard is an OFDM type modulation. OFDM Modulation has a peak to average ratio or crest factor that is approximately 10dB. As discussed above, any amplifier can only make just so much power. Additionally, even if linearization techniques are used to improve signal performance, there is a limit on a particular amplifiers ability to produce power with acceptable signal specifications. It appears that the limiting factor for this again will be a shoulder specification as the FCC appears that it will not change the spectral mask requirements for transmitters when the modulation standard changes from ATSC 1.0 to ATSC 3.0, leaving the shoulder specification as originally measured.

To show the effect of this modulation and crest factor change, let’s take that same BLF888A amplifier and see what power levels it will make acceptable performance at both without and with correction using a DVB-T2 OFDM modulation having RF signal characteristics very similar to ATSC 3.0. Without correction this amplifier is now only capable of 90 watts of output power with the shoulders being the first parameter to approach minimum specifications. At the 90 watt average power level the crest factor is 9.8dB resulting in a peak power output of 852 watts from this amplifier. Now if we use the exciters digital linearization or “correction” capabilities we can push this amplifier up to 120 watts of average output power with acceptable signal performance results. Figures 8, 9, and 10 below show the DVB-T2 corrected signal performance of this amplifier.


R&S ETL Digital Spectrum S/N 102184, FW 2.71

Ch: --- RF 509.000000 MHz DVB-T2 6 MHz

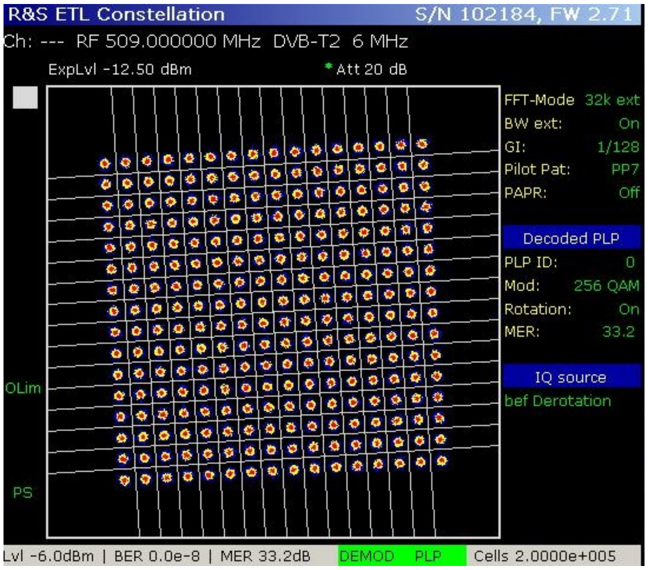
RBW 10 kHz
Att 20 dB
VBW 30 kHz
ExpLvl -12.50 dBm
SWT 100ms

CF 509.0 MHz
Span 10.0 MHz

Shoulder Attenuation	Result	Unit
Lower	37.0	dB
Upper	37.4	dB

Figure 8: BLF888A Corrected Shoulders DVB-T2

Since I used a DVB-T2 signal as a representative of an OFDM based signal such as ATSC3.0, the measurement technique for shoulders of this signal differs from that required by the FCC for the current ATSC1.0 signal. The current signal shoulder measurement is based on measuring the shoulders in a 500kHz wide “power band” as compared to the in channel signal in a 6MHz wide “power band”. The FCC specification for this is 47dB. When measuring a DVB-T2 signal, this measurement is commonly done by the simple use of markers both in band and on each shoulder. These 2 types of measurements result in a measured difference on the same signal of approximately 11dB making the 47dB current specification for shoulders appear like 36dB as measured with markers on the DVB-T2 signals.


R&S ETL Constellation S/N 102184, FW 2.71

Ch: --- RF 509.000000 MHz DVB-T2 6 MHz

ExpLvl -12.50 dBm
Att 20 dB

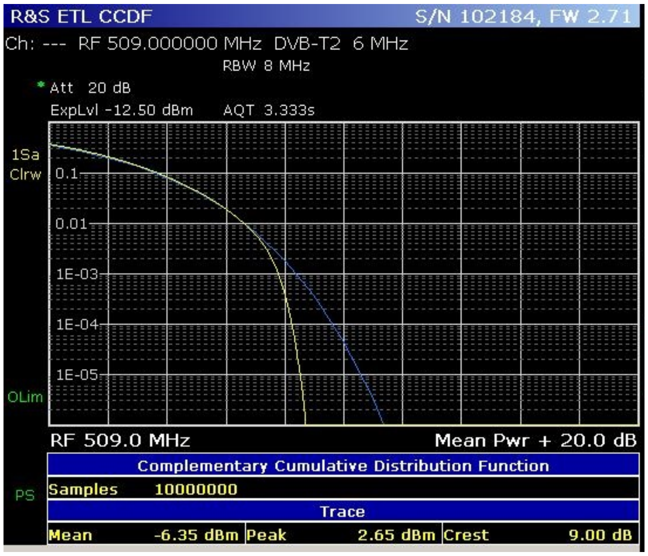
FFT-Mode 32k ext
BW ext: On
GI: 1/128
Pilot Pat: PP7
PAPR: Off

Decoded PLP
PLP ID: 0
Mod: 256 QAM
Rotation: On
MER: 33.2

IQ source
bef Derotation

Lvl -6.0dBm | BER 0.0e-8 | MER 33.2dB DEMOD PLP Cells 2.0000e+005

Figure 9: BLF888A Corrected Constellation DVB-T2


R&S ETL CCDF S/N 102184, FW 2.71

Ch: --- RF 509.000000 MHz DVB-T2 6 MHz

RBW 8 MHz
Att 20 dB
ExpLvl -12.50 dBm
AQT 3.333s

RF 509.0 MHz
Mean Pwr + 20.0 dB

Complementary Cumulative Distribution Function

Samples 10000000

Trace

Mean	-6.35 dBm	Peak	2.65 dBm	Crest	9.00 dB

Figure 10: BLF888A Corrected CCDF Curve

As shown in Figure 10 above this amplifier when corrected now has a crest factor of 9 dB resulting in a peak output power level of 953 watts. By using “correction” and now running this amplifier higher in power, again this places operation higher up the efficiency curve.

Unfortunately, because of the crest factor or peak to average ratio being 2dB higher than with ATSC 1.0 / 8-VSB, the amplifier must be backed off in average power level with the result of being lower on the power and efficiency curves with the efficiency now being 31.6% or 4.9 percentage points lower. The good news is that even with the lower efficiency, the power reduction required to meet signal performance with correction applied results in a power consumption decrease of 23%, which will result in lower electricity costs. However, the broadcaster now has to look at this and consider the choices of increasing the transmitter size to maintain the FCC licensed power and suffer the higher operating cost, or applying to change the licensed power level to the new lower power giving up coverage but gaining lower electricity costs.

What is a Doherty Amplifier?

A Doherty amplifier, named after its inventor William H. Doherty in 1936, was originally designed to increase the efficiency of high power vacuum tube AM and Shortwave broadcast transmitters. A basic block diagram of a Doherty amplifier is shown in Figure 11.

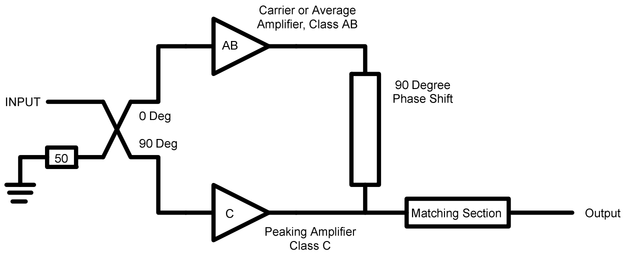


Figure 11: Doherty Amplifier Block Diagram

The basic operation of this amplifier configuration is the input signal is split with a 90 degree phase shift being applied to the signal that goes to the Class C peaking amplifier. To offset this phase shift the combining of the amplifiers has a 90 degree line inserted on the output of the carrier or average amplifier. When the 2 amplifiers are combined, this combination does not represent a 50 ohm output, so a matching section is required to step the impedance back to the 50 ohm point. As for operation, the average class AB amplifier is utilized for a vast majority of the RF modulated waveform. As shown earlier, the harder a class AB amplifier is driven, the higher the efficiency that is able to be attained from it. The drawback is peak power compression and distortion products which at high power levels become “un-correctable” with modern digital linearization techniques. By running the average amplifier farther up its curve, the operating efficiency gain is substantial. On the other side of the Doherty amplifier pair is the peaking amplifier. This is a class C amplifier. Class C amplifiers have 2 good qualities for this part of the amplifier. First, they are inherently efficient, and they also have lower gain at low input levels as they are not at all linear when referencing their power in to out transfer curve. They do have a poor quality and that is because their transfer curve is not linear they produce more distortion products than their class AB counterpart. Due to the “small signal” gain difference, this allows the class AB (average) side to be driven by the digital modulated RF signal up into the area of the transfer curve where they are approaching saturation and are operating very efficiently leaving the class C (peaking) side to amplify the peaks of the signal essentially “making up” for what the class AB (average) side cannot reproduce on its own. With digital modulation, as the peaks become larger in amplitude they become more infrequent, the class C amplifier is actually “off” more than it is “on”. This, coupled with the peak power capability and high efficiency, allows when these 2 amplifiers are then properly combined, to reproduce the digital modulated RF signal at a much higher efficiency than would be available if just a class AB amplifier were used. One of the “downsides” of Doherty configured amplifiers is the combination of “over” driving the average class AB side and then combining it with the inherently non-linear class C Peaking side. The resultant output, although it is reproduced reasonably well in amplitude, contains quite a lot of distortion products that without the use of modern correction techniques, pretty much renders the output from this type of amplifier unusable at nearly all power levels. This is not at all like the class AB amplifier covered earlier, where at lower power levels the amplifier can actually meet the required specifications for a broadcast signal.

There are many configurations of Doherty amplifiers. A number of these are explained in detail in the application brief produced by Ampleon. [1] For the purposes of this paper we will discuss 2 basic types both of which are configured as shown in the block diagram in Figure 11. These 2 types are, Symmetrical, and Asymmetrical.

The Symmetrical configuration has the amplifiers on both the average and peaking side being comprised of the same basic amplifier with the same power capability, and it is simply a matter of how each of the sides are biased and operated.

The Asymmetrical configuration is when one side of the amplifier is configured to have either more or less power capability dependent upon what the signal is that it will be used for and what the signal’s characteristics are. In the case of digital television, this is traditionally accomplished by increasing the size or capability of the peaking amplifier.

Symmetrical Doherty

For this paper the Ampleon BLF888D was tested as a pallet in the Ampleon demo circuit as shown in Figure 12.

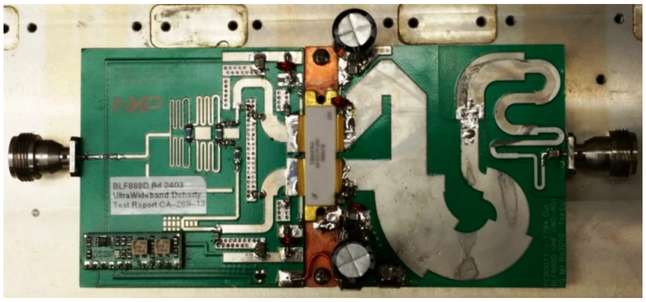


Figure 12: Ampleon BLF888D Symmetrical Doherty

As a comparison the BLF888A datasheet rates this LDMOS FET as a 600 watt part. The BLF888D datasheet rates this LDMOS FET also as a 600 watt part. I ran the same tests on this amplifier that I ran on the BLF888A class AB amplifier that were discussed earlier in the paper. Figure 13 below shows efficiency versus power output of both the BLF888A class AB and the BLF888D symmetrical Doherty amplifiers.

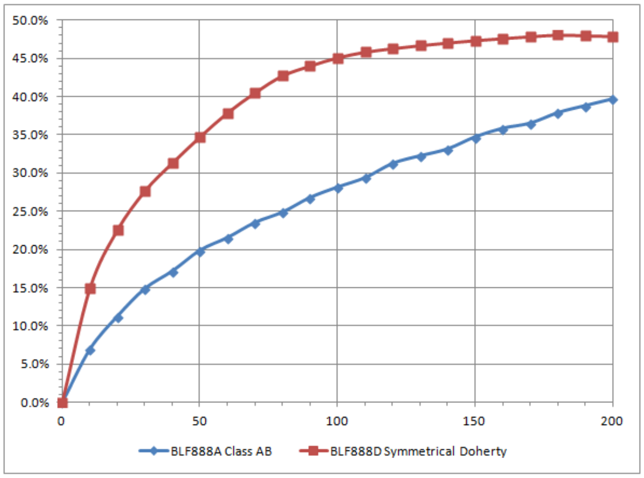


Figure 13: Class AB and Symmetrical Doherty Efficiency vs Power Output

The curve of efficiency versus power for the symmetrical Doherty configuration is markedly different from the traditional class AB amplifier curve. Not only does this Doherty configuration have substantially improved efficiency throughout the curve, the curve is much "steeper" having the efficiency rise quickly and be within only a few percentage points of maximum with the amplifier only at the 100 watt level. Above the 100 watt level only a few more percentage points are gained as the power is increased.

In Figure 14, the power input versus average output curves are not substantially different between the two amplifier types other than the class AB amplifier is showing approximately 3dB more gain. The peak power curves however, both ending at the same power level show a much more graceful gain degradation on the symmetric Doherty amplifier showing that there is potentially more peak power available from this amplifier as it has not yet appeared to reach saturation as has the class AB amplifier.

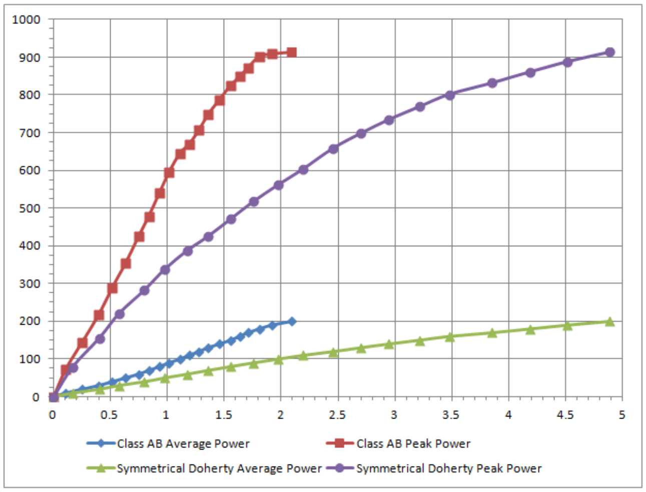


Figure 14: Power Input vs. Power Output of Class AB and Symmetric Doherty

When looking at the signal performance of the symmetrical Doherty amplifier and comparing it to the traditional class AB amplifier, the natural signal performance (uncorrected), as mentioned before, appears to be poor in comparison to the class AB amplifier performance. Figure 15 below shows the uncorrected shoulder and MER levels of both the class AB and Symmetrical Doherty amplifiers.

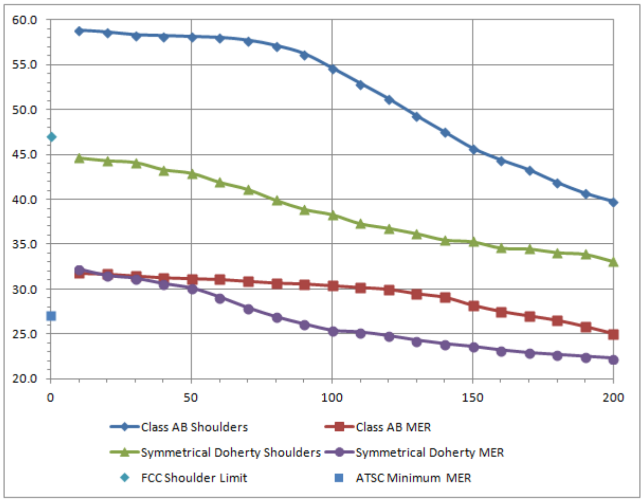
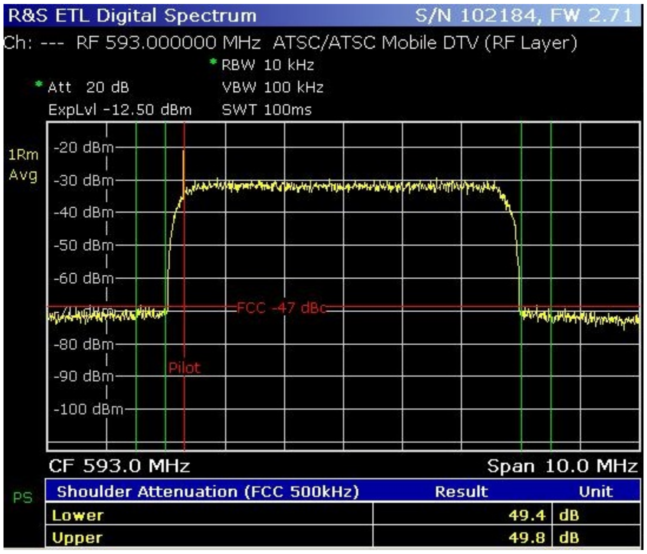


Figure 15: Uncorrected Signal Performance of Class AB and Symmetrical Doherty Amplifiers

As can be seen, the symmetrical Doherty amplifier's natural uncorrected performance actually never meets the requirement for FCC shoulder minimum specifications and is only acceptable for MER performance below the 70 watt output level. The good news is that this amplifier is quite “correctable” with modern digital linearization techniques. Shown below in Figures 16, 17, and 18 is the performance of the symmetrical Doherty amplifier when corrected at the 150 watt level for ATSC 1.0 / 8-VSB.



R&S ETL Digital Spectrum S/N 102184, FW 2.71

Ch: --- RF 593.000000 MHz ATSC/ATSC Mobile DTV (RF Layer)

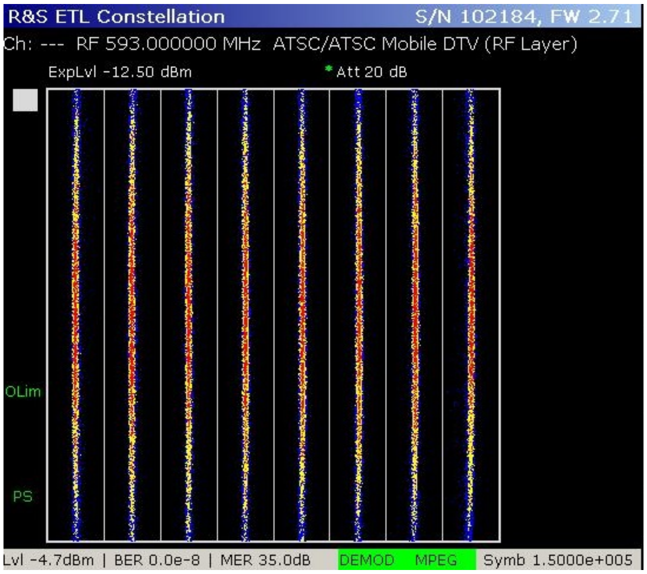
* RBW 10 kHz

* Att 20 dB VBW 100 kHz

ExpLvl -12.50 dBm SWT 100ms

Shoulder Attenuation (FCC 500kHz)	Result	Unit
Lower	49.4	dB
Upper	49.8	dB

Figure 16: BLF888D Symmetrical Doherty Shoulders Corrected at 150 Watts Output Power



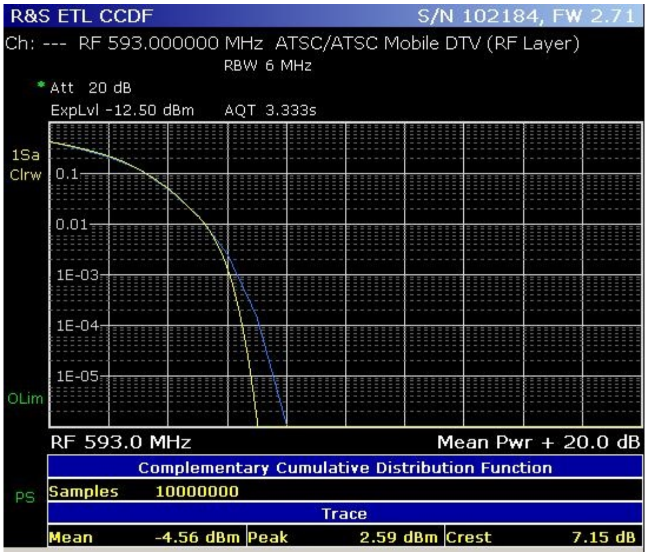
R&S ETL Constellation S/N 102184, FW 2.71

Ch: --- RF 593.000000 MHz ATSC/ATSC Mobile DTV (RF Layer)

ExpLvl -12.50 dBm * Att 20 dB

Lvl -4.7dBm | BER 0.0e-8 | MER 35.0dB DEMOD MPEG Symb 1.5000e+005

Figure 17: BLF888D Symmetrical Doherty Constellation Corrected at 150 Watts Output Power



R&S ETL CCDF S/N 102184, FW 2.71

Ch: --- RF 593.000000 MHz ATSC/ATSC Mobile DTV (RF Layer)

RBW 6 MHz

* Att 20 dB

ExpLvl -12.50 dBm AQT 3.333s

Complementary Cumulative Distribution Function

Samples 10000000

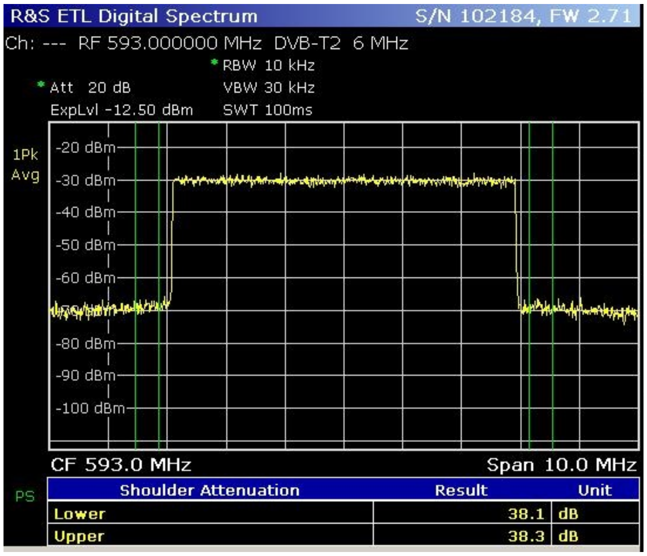
Trace

Mean	-4.56 dBm	Peak	2.59 dBm	Crest	7.15 dB

Figure 18: BLF888D Symmetrical Doherty CCDF Curve Corrected at 150 Watts Output Power

As shown in Figure 18 above, this amplifier when corrected has a crest factor of 7.15dB. This results in a peak output power level of 778 watts, which in the curve shown previously in Figure 14 shows the amplifier is not running at its peak power limit at this power level. The shoulders are still the limiting factor and are at minimum 2.4dB above the minimum limit. This amplifier should be capable of a bit higher output power if necessary. However in looking at the efficiency vs. power curve in Figure 13, it shows that at 150 watts output the efficiency is less than 1 percentage point from maximum for this amplifier. Driving this amplifier harder doesn’t gain any advantage over operating it at this point as at 150 watts it has good corrected performance with headroom on the minimum required performance specifications along with being essentially at its maximum efficiency, and not being “pushed” to its maximum power level.

So how does this perform with an OFDM signal? As before with the class AB amplifier, due to the higher crest factor this amplifier will need to be backed off from the level used in ATSC 1.0 / 8-VSB. The class AB amplifier needed to be backed off from 170 to 120 watts or 1.51dB. In the case of the symmetrical Doherty amplifier, because of the “softer” peak compression curve, this amplifier needed to be backed off from 150 watts to 130 watts or less than 1dB to attain acceptable corrected signal performance. At the 130 watt level, the amplifier efficiency had dropped from 47.3% to 45.9% or only 1.4 percentage points compared to the class AB being nearly 5 percentage points off. As you can see this would make quite a nice amplifier system for both ATSC 1.0 / 8-VSB and an OFDM based modulation such as the new ATSC 3.0. Shown below in Figures 19, 20, and 21, are the performance plots of this amplifier operating in DVB-T2 OFDM format and corrected at 130 watts output.


R&S ETL Digital Spectrum S/N 102184, FW 2.71

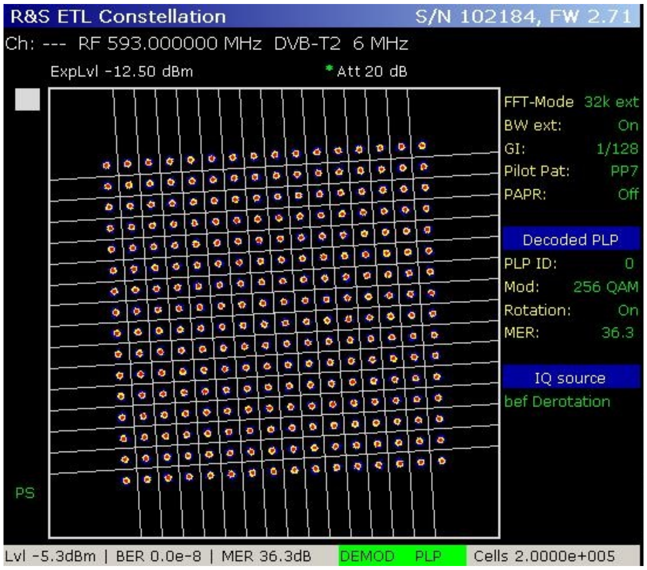
Ch: --- RF 593.000000 MHz DVB-T2 6 MHz

* RBW 10 kHz
* Att 20 dB
VBW 30 kHz
ExpLvl -12.50 dBm
SWT 100ms

Shoulder Attenuation	Result	Unit
Lower	38.1	dB
Upper	38.3	dB

Figure 19: BLF888D Corrected Shoulders DVB-T2

Figure 19 above show the shoulders as measured at 38dB. The current FCC shoulder requirement is 47dB, however, this is supposed to be measured using a 500kHz power band for the shoulders versus a 6 MHz power band for the in band level. When measuring in DVB-T or DVB-T2 the measurement convention is to simply measure between the in band level and the shoulder by means of a marker or as it is seen directly on the display of the instrument. The power band measurement method versus the marker method results in approximately an 11dB difference in readings i.e. shoulders measured at 47dB with power band measurements will measure 36dB with a direct marker measurement method. For the purposes of this paper all DVB-T2 measurements will use the marker method making anything better than 36dB "in spec".


R&S ETL Constellation S/N 102184, FW 2.71

Ch: --- RF 593.000000 MHz DVB-T2 6 MHz

ExpLvl -12.50 dBm
* Att 20 dB

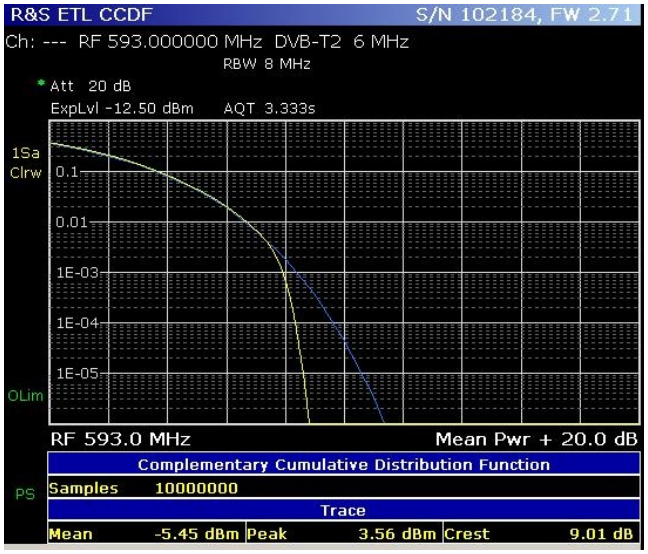
FFT-Mode 32k ext
BW ext: On
GI: 1/128
Pilot Pat: PP7
PAPR: Off

Decoded PLP
PLP ID: 0
Mod: 256 QAM
Rotation: On
MER: 36.3

IQ source
bef Derotation

Lvl -5.3dBm | BER 0.0e-8 | MER 36.3dB DEMOD PLP Cells 2.0000e+005

Figure 20: BLF888D Corrected Constellation DVB-T2


R&S ETL CCDF S/N 102184, FW 2.71

Ch: --- RF 593.000000 MHz DVB-T2 6 MHz

RBW 8 MHz
* Att 20 dB
ExpLvl -12.50 dBm
AQT 3.333s

Complementary Cumulative Distribution Function

Samples 10000000

Trace

Mean -5.45 dBm Peak 3.56 dBm Crest 9.01 dB

Figure 21: BLF888D Corrected CCDF Curve

Again, as shown in the CCDF curve in Figure 21 indicates a crest factor of 9.01dB. With this amplifier operating at 130 watts this puts the peak power level from this at 1035 watts. This is certainly higher up the curve than is plotted in Figure 14 above, again demonstrating the "soft compression" curve of a Doherty amplifier due to the class C peaking amplifier.

Asymmetrical Doherty

For this paper the Ampleon BLF888E was tested as a pallet in the Ampleon demo circuit shown in Figure 22.

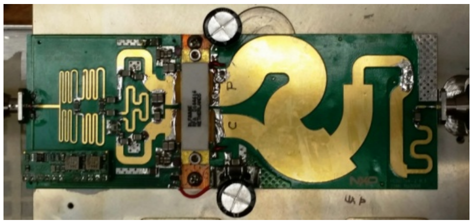


Figure 22: Ampleon BLF888E Asymmetrical Doherty

Again, as a comparison, the BLF888A datasheet rates this LDMOS FET as a 600 watt part. The BLF888D Symmetrical Doherty datasheet rates this LDMOS FET also as a 600 watt part, however the datasheet for the BLF888E rates this LDMOS FET as a 750 watt part. This is due to the asymmetrical nature of the part in that the peaking amplifier capability has been increased over that of the BLF888D. I ran the same tests on this amplifier that was run on the BLF888A class AB amplifier that was discussed earlier in the paper. Figure 23 below shows efficiency versus power output of the BLF888A class AB, the BLF888D symmetrical Doherty, and the BLF888E Asymmetrical Doherty amplifiers.

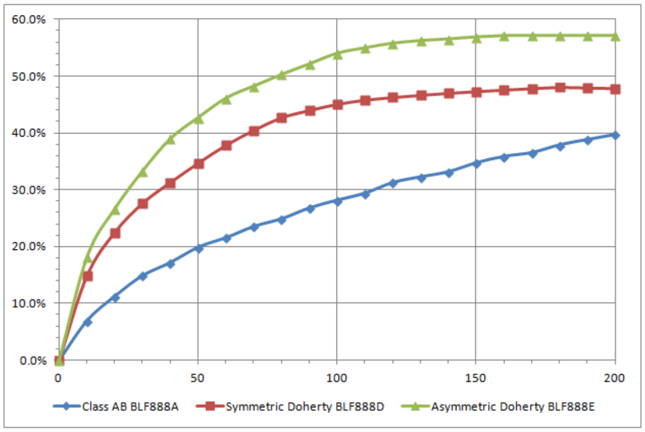


Figure 23: Class AB, Symmetrical Doherty, and Asymmetrical Doherty Efficiency vs Power Output

The curve of efficiency versus power for the Asymmetrical Doherty configuration is different even from the Symmetrical Doherty configuration and as shown before. Both Doherty types are markedly different from the traditional class AB amplifier curve. Again, not only does the Asymmetrical Doherty configuration have substantially improved efficiency throughout the curve over the other 2 types, the curve is much "steeper" having the efficiency rise quickly and be within only a few percentage points of maximum again with the amplifier only at the 100 watt level. Above the 100 watt level only a few more percentage points are gained as the power is increased.

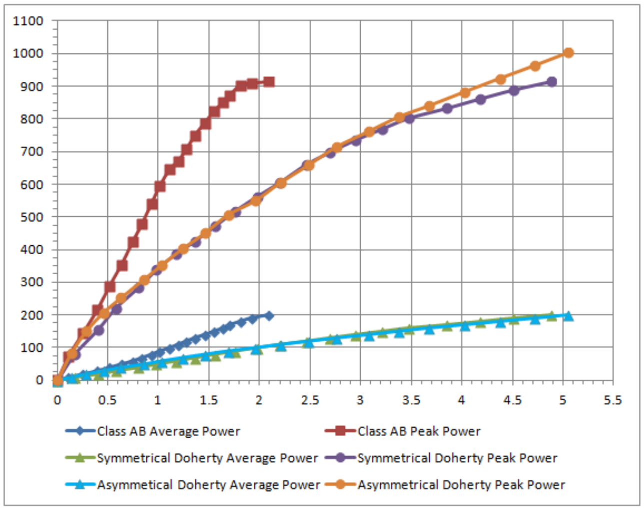


Figure 24: Power Input vs. Power Output of Class AB, Symmetric Doherty, and Asymmetric Doherty

In Figure 24, the power input versus average output curves are essentially the same between the symmetrical Doherty and the asymmetrical Doherty as would be expected knowing that the average side of the Doherty amplifier pair is unchanged. The peak power curve, however, for the asymmetrical Doherty shows the same type of graceful gain degradation as the symmetric Doherty amplifier but with increased peak power capability and again not showing any signs of hard compression or saturation even at the 1kW peak output level. This, coupled with the increase in efficiency, should mean this part is even more suitable for reproducing an OFDM type signal that has a high peak to average ratio / crest factor than the symmetrical Doherty configuration.

When looking at the signal performance of the asymmetrical Doherty amplifier and comparing it to the symmetrical Doherty and traditional class AB amplifiers, the natural signal performance (uncorrected), as mentioned before, again appears to be poor in comparison to the class AB amplifier performance. Figure 25 below shows the uncorrected shoulder and MER levels of the class AB, Symmetrical, and Asymmetrical Doherty amplifiers. As can be seen both the symmetrical and the asymmetrical Doherty amplifier's natural uncorrected performance never meets the requirement for FCC shoulder minimum specifications and is only acceptable for MER performance at the 50 watt level making it inferior to the symmetrical Doherty when uncorrected as the symmetrical Doherty meets the MER specification below the 70 watt output level. The good news is that this amplifier is also quite "correctable" with modern digital linearization techniques. Shown below in Figures 26, 27, and 28 is the performance of the symmetrical Doherty amplifier when corrected. The other good news is the added peak power capability allows it to be corrected meeting signal quality specifications now at the 200 watt output power level for ATSC 1.0 / 8-VSB.

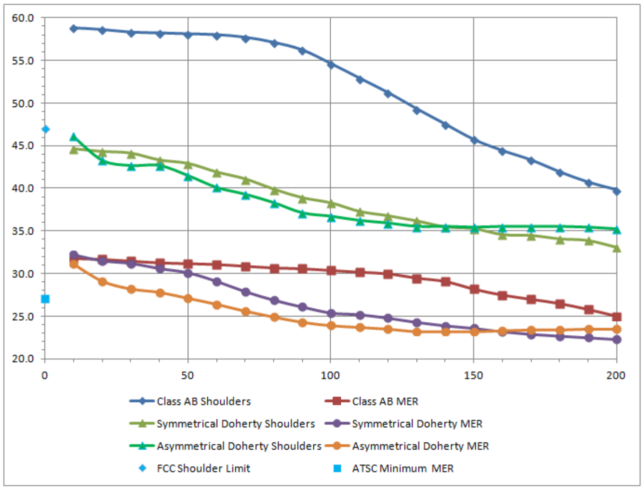
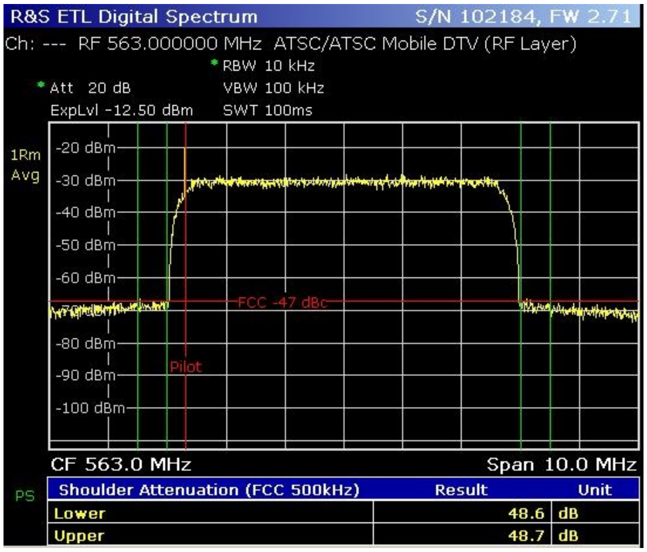


Figure 25: Uncorrected Signal Performance of Class AB, Symmetrical and Asymmetrical Doherty Amplifiers



R&S ETL Digital Spectrum S/N 102184, FW 2.71

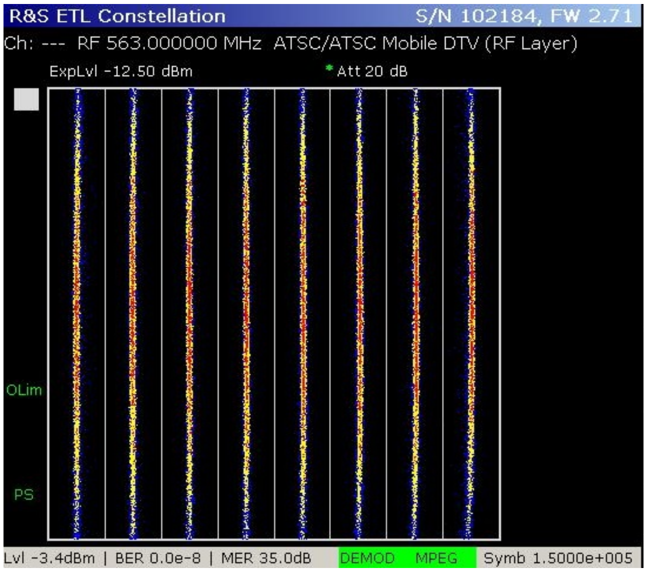
Ch: --- RF 563.000000 MHz ATSC/ATSC Mobile DTV (RF Layer)

* RBW 10 kHz
* Att 20 dB VBW 100 kHz
ExpLvl -12.50 dBm SWT 100ms

CF 563.0 MHz Span 10.0 MHz

Shoulder Attenuation (FCC 500kHz)	Result	Unit
Lower	48.6	dB
Upper	48.7	dB

Figure 26: BLF888E Asymmetrical Doherty Shoulders Corrected at 200 Watts Output Power



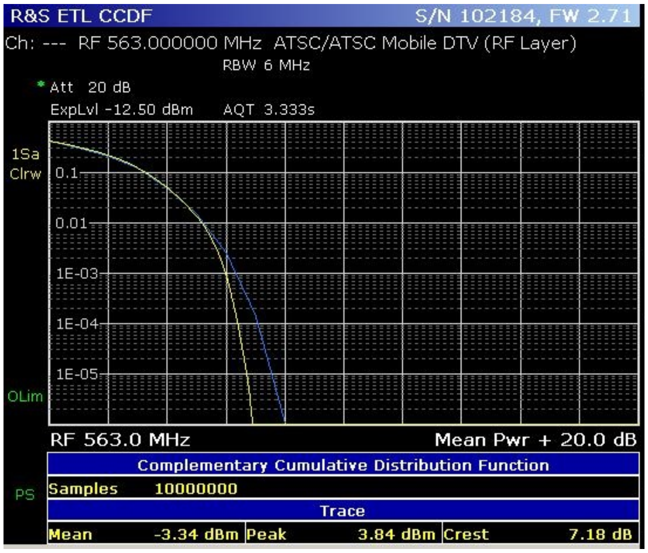
R&S ETL Constellation S/N 102184, FW 2.71

Ch: --- RF 563.000000 MHz ATSC/ATSC Mobile DTV (RF Layer)

ExpLvl -12.50 dBm * Att 20 dB

Lvl -3.4dBm | BER 0.0e-8 | MER 35.0dB DEMOD MPEG Symb 1.5000e+005

Figure 27: BLF888E Asymmetrical Doherty Constellation Corrected at 200 Watts Output Power



R&S ETL CCDF S/N 102184, FW 2.71

Ch: --- RF 563.000000 MHz ATSC/ATSC Mobile DTV (RF Layer)

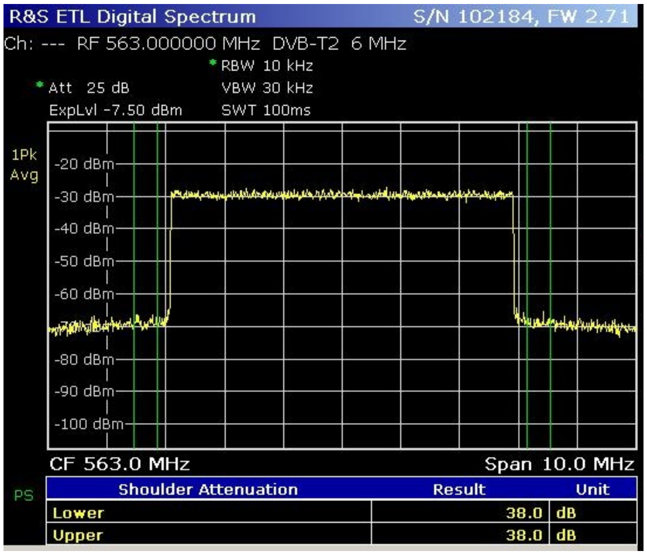
RBW 6 MHz
* Att 20 dB
ExpLvl -12.50 dBm AQT 3.333s

RF 563.0 MHz Mean Pwr + 20.0 dB

Complementary Cumulative Distribution Function					
Samples	10000000				
Trace					
Mean	-3.34 dBm	Peak	3.84 dBm	Crest	7.18 dB

Figure 28: BLF888E Asymmetrical Doherty CCDF Curve Corrected at 200 Watts Output Power

As shown in Figure 28 above, this amplifier, when corrected has a crest factor of 7.18dB. This results in a peak output power level of 1045 watts, which in the curve shown previously in Figure 24, shows the amplifier is not running at its peak power limit at this power level. The shoulders are still the limiting factor and are at minimum 1.6dB above the minimum limit. Looking at the efficiency vs power curve in Figure 23, it shows that at 200 watts output the efficiency is at the maximum for this amplifier. The nice advantage of this asymmetric Doherty configuration is that not only is it correctable at 200 watts and the maximum efficiency when backed off for OFDM operation to where correctable performance is acceptable this is at the 150 watt output level. When backed off to this level, the efficiency drops from 57.1% at 200 watts to 56.9% at 150 watts, or only 0.2 percentage points. Virtually not at all! In fact dropping all the way to the 100 watt level only decreases the efficiency to 54.1% or 3 percentage points. This is a very nice characteristic of this amplifier especially when facing a modulation format change from ATSC 1.0 / 8-VSB to ATSC3.0 / OFDM. The OFDM performance corrected at the 150 watt level is shown below in Figures 29, 30, and 31.


R&S ETL Digital Spectrum S/N 102184, FW 2.71

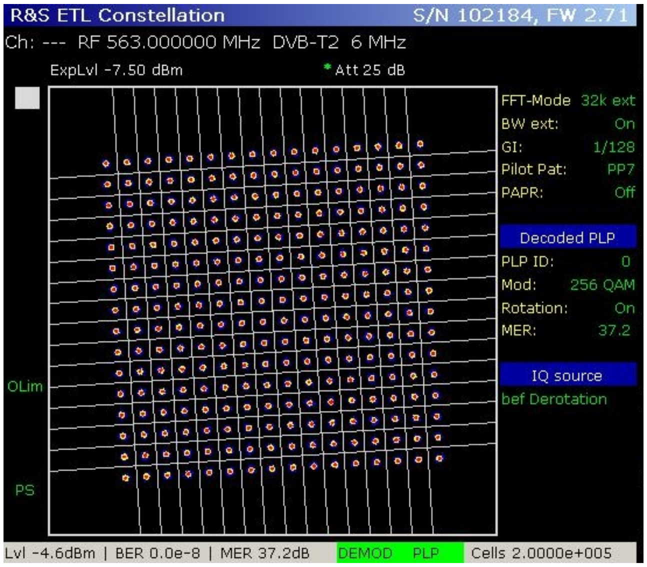
Ch: --- RF 563.000000 MHz DVB-T2 6 MHz

*RBW 10 kHz
*Att 25 dB
VBW 30 kHz
ExpLvl -7.50 dBm
SWT 100ms

CF 563.0 MHz Span 10.0 MHz

Shoulder Attenuation	Result	Unit
Lower	38.0	dB
Upper	38.0	dB

Figure 29: BLF888E Corrected Shoulders DVB-T2


R&S ETL Constellation S/N 102184, FW 2.71

Ch: --- RF 563.000000 MHz DVB-T2 6 MHz

ExpLvl -7.50 dBm
*Att 25 dB

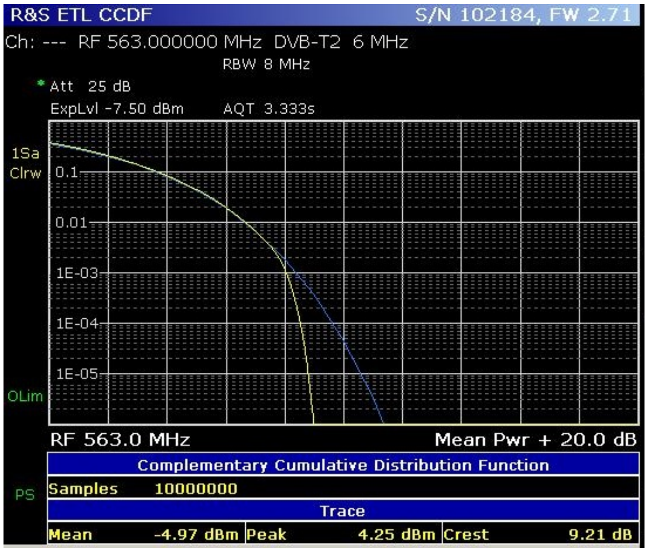
FFT-Mode: 32k ext
BW ext: On
GI: 1/128
Pilot Pat: PP7
PAPR: Off

Decoded PLP
PLP ID: 0
Mod: 256 QAM
Rotation: On
MER: 37.2

IQ source
bef Derotation

Lvl -4.6dBm | BER 0.0e-8 | MER 37.2dB DEMOD PLP Cells 2.0000e+005

Figure 30: BLF888E Corrected Constellation DVB-T2


R&S ETL CCDF S/N 102184, FW 2.71

Ch: --- RF 563.000000 MHz DVB-T2 6 MHz

RBW 8 MHz
*Att 25 dB
ExpLvl -7.50 dBm
AQT 3.333s

RF 563.0 MHz Mean Pwr + 20.0 dB

Complementary Cumulative Distribution Function

Samples 10000000

Trace

Mean	-4.97 dBm	Peak	4.25 dBm	Crest	9.21 dB

Figure 31: BLF888E Corrected CCDF Curve DVB-T2

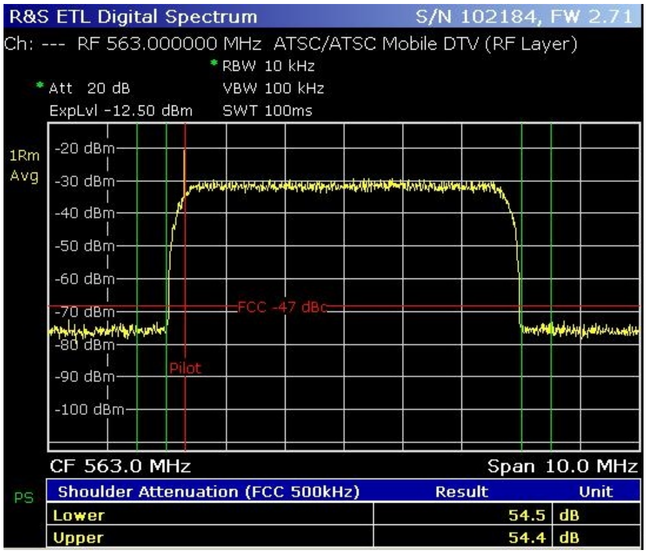
Again, as shown in the CCDF curve in Figure 31 has a crest factor of 9.21dB. With this amplifier operating at 150 watts, this puts the peak power level from this at 1251 watts. This is certainly higher up the curve than is plotted in Figure 24 above, again demonstrating the “soft compression” curve of a Doherty amplifier due to the class C peaking amplifier and also demonstrating the capability of the larger peaking amplifier in the asymmetrical Doherty as this is the highest peak power available from any of these amplifiers.

How does this apply to the broadcaster?

With the looming FCC channel re-pack coupled with the also looming modulation format change from ATSC 1.0 / 8-VSB to ATSC3.0 / OFDM the broadcasters will need to look at how best to cope with their currently aging equipment some of which is approaching the 20 year old mark. They may also be required to move frequency, and have their transmission plant be capable of providing the necessary power with the new modulation standard. The best case from the broadcaster’s perspective is 2 out of 3… to only have to take care of aging equipment and accommodate the new modulation standard. If their current transmitter plant was initially built with enough peak power headroom to accommodate the new ATSC 3.0 modulation standard, then they’re down to aging equipment and or channel change. In any case, time, and technology marches on and with the efficiency and power level advances in solid state technology outlined above chances are the broadcaster will be looking at new transmitter gear. This makes the technology choice and its features critical to allowing for future changes.

The most operationally efficient high power transmitters still employ vacuum tube final amplifiers, specifically the L3 CEA (Constant Efficiency Amplifier) which is a Multi-Stage Depressed Collector IOT (Inductive Output Tube). Although the most efficient transmitter, it requires periodic maintenance of equipment which contains voltages up to 40kVDC. This requires highly skilled individuals to do the work. Solid state LDMOS based transmitters employing Doherty based amplifier configurations, while being not quite as efficient, are virtually maintenance free and can be maintained and repaired by less specialized personnel. These will be the transmitter of choice in most cases.

As shown throughout this paper, there are ways to configure and deal with "optimizing" the LDMOS amplifiers and Doherty configuration to make best use of their characteristics to provide an efficient transmitter that is capable of being used at the same power level for ATSC 1.0 / 8-VSB as it will for ATSC 3.0 / OFDM without having to give up either power or efficiency. Throughout this paper, it talks about back-off for higher peak to average ratio modulation formats. This is because even though we measure average power of the signal, the amplifiers limitation is the peak power it can produce. The other factor is that typically it has been the case to run the amplifier as "hard" as possible to meet signal specs as this will result in the best efficiency. With the case of the asymmetric Doherty configuration for the modulations of interest, the test data shows that any power level above about 120 watts makes little to no difference in operating efficiency. This means that if one operates the LDMOS FETs at the 150 watt level as shown above, they will easily correct to meet required signal specifications even for the ATSC 3.0 / OFDM type signal. One can also operate this same amplifier at the same 150 watt level with ATSC 1.0 / 8-VSB and attain the same efficiency level with added headroom in the power level department. This simply will result in even better corrected signal specifications with ATSC 1.0 / 8-VSB without any penalty for efficiency / power consumption. Below in Figures 32, 33, and 34 are the results of operating the asymmetric Doherty amplifier corrected at the 150 watt level with ATSC 1.0 / 8-VSB.



R&S ETL Digital Spectrum S/N 102184, FW 2.71

Ch: --- RF 563.000000 MHz ATSC/ATSC Mobile DTV (RF Layer)

* RBW 10 kHz

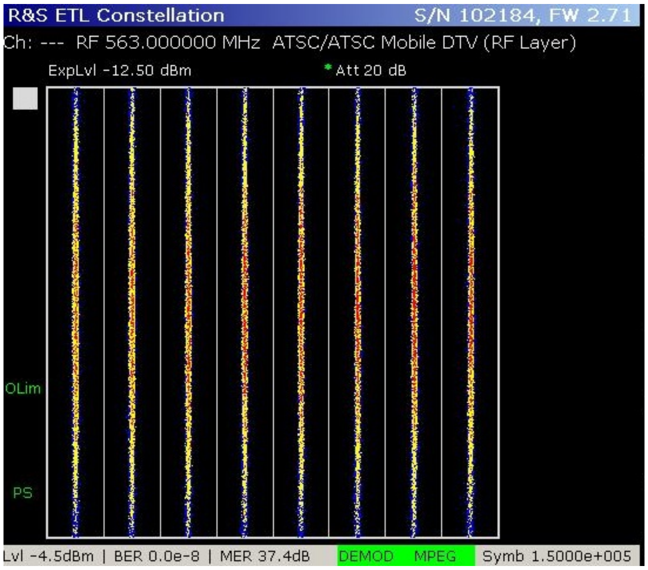
* Att 20 dB VBW 100 kHz

ExpLvl -12.50 dBm SWT 100ms

CF 563.0 MHz Span 10.0 MHz

Shoulder Attenuation (FCC 500kHz)	Result	Unit
Lower	54.5	dB
Upper	54.4	dB

Figure 32: BLF888E Asymmetrical Doherty Shoulders Corrected at 150 Watts Output Power



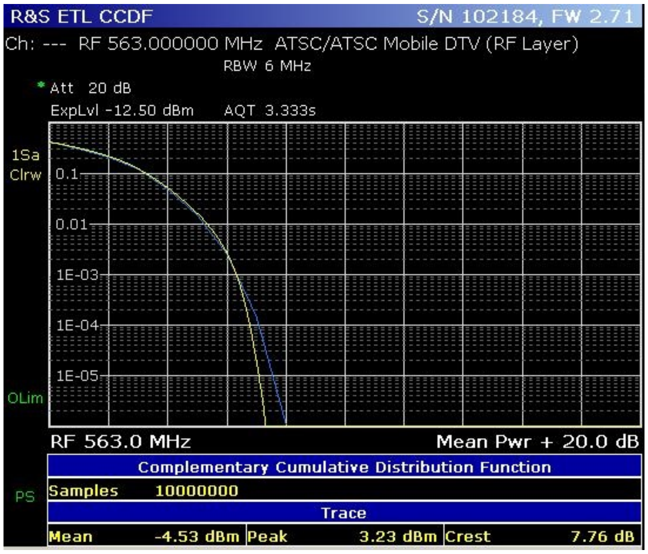
R&S ETL Constellation S/N 102184, FW 2.71

Ch: --- RF 563.000000 MHz ATSC/ATSC Mobile DTV (RF Layer)

ExpLvl -12.50 dBm * Att 20 dB

Lvl -4.5dBm | BER 0.0e-8 | MER 37.4dB DEMOD MPEG Symb 1.5000e+005

Figure 33: BLF888E Asymmetrical Doherty Constellation Corrected at 150 Watts Output Power



R&S ETL CCDF S/N 102184, FW 2.71

Ch: --- RF 563.000000 MHz ATSC/ATSC Mobile DTV (RF Layer)

RBW 6 MHz

* Att 20 dB

ExpLvl -12.50 dBm AQT 3.333s

RF 563.0 MHz Mean Pwr + 20.0 dB

Complementary Cumulative Distribution Function

Samples 10000000

Trace

Mean	-4.53 dBm	Peak	3.23 dBm	Crest	7.76 dB

Figure 34: BLF888E Asymmetrical Doherty CCDF Curve Corrected at 150 Watts Output Power

As shown in this paper, the advancement of solid state amplifier technology has allowed for production of efficient high power solid state broadcast transmitters for digital television. The advancement done within the LDMOS FETs coupled with an 80 year old idea can yield some impressive operating efficiency numbers, but they are useless without employing a modern digital linearization scheme of some sort that is utilized in most digital television exciters.

When these technologies are put into practice, a high power transmitter with excellent performance and efficiency can be realized. As an example, the Hitachi Comark Parallax™ utilizes the BLF888E Asymmetrical Doherty amplifier design within the power amplifiers. Figure 35 shown below is a picture of one of these amplifiers and Figure 36 shows a configuration of 4 amplifiers with their associated power supplies.

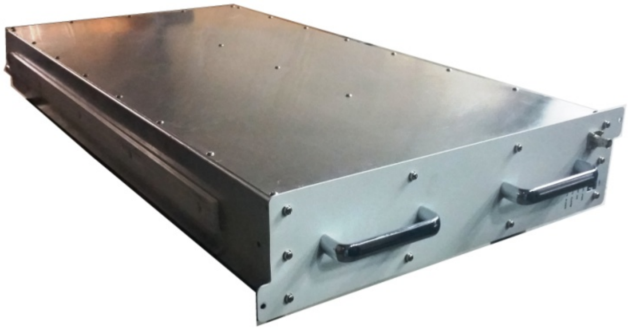


Figure 35: Hitachi Comark Parallax Liquid Cooled Doherty Amplifier

Figure 36: 4 Amplifiers In Parallel With Associated Power Supplies

Below in Figure 37, is a power versus efficiency curve of one of the Hitachi Comark Parallax amplifiers. As can be seen, it has the same basic curve shape but at a bit lower overall efficiency. The efficiency "loss" can be accounted for in a number of areas. First is this amplifier is high gain at approximately 62dB. The driving stages are class A and AB thereby impacting the overall efficiency. Second, the combining network used to parallel 16 amplifier modules is not without loss, also impacting the efficiency. Lastly is this efficiency also includes the inefficiencies realized in the AC to DC switching power supplies as this efficiency curve is measured from AC mains consumption to RF output power.

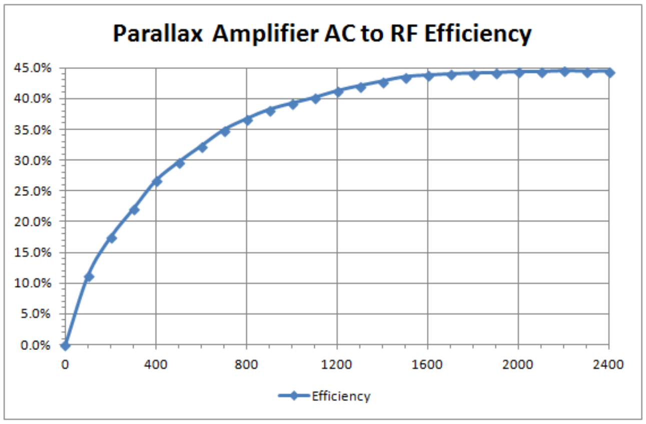
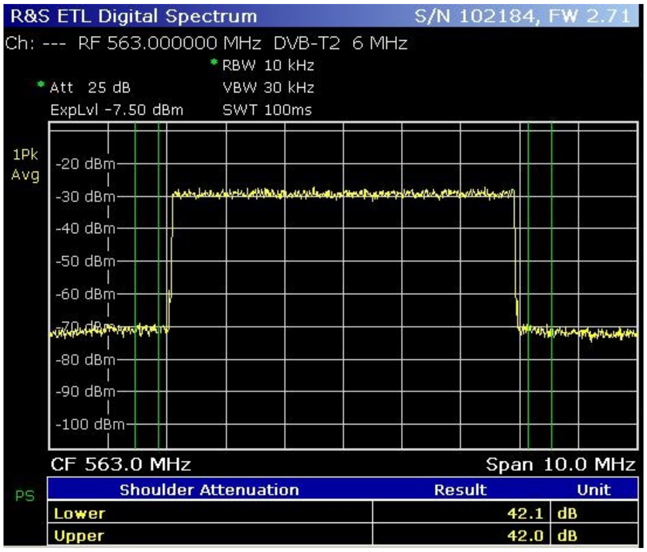


Figure 37: Parallax Amplifier AC to RF Power Efficiency Curve

The amplifier is rated for 2000 watts output in either ATSC 1.0 / 8-VSB or OFDM formats such as ATSC 3.0 or DVB-T or DVB-T2. As you can see, even if the power is decreased to 1500 watts the efficiency decrease is less than 1 percentage point. This allows for a transmitter to be purchased that has operational headroom without paying a penalty for normal operation below the equipment's full rated power. This will allow for a transmitter to maintain full power operation even in the event of a failure on a component of the system while maintaining maximum operating efficiency.

Digital "Tricks"

As demonstrated above, the limiting factor on an amplifiers ability to make power while producing a signal meeting certain specifications for Shoulders and MER is very much related on to the peak power capability of the amplifier and the digital corrector's ability to linearize the signal. Most often is the case where the first piece of signal criteria to approach the spec limit is the shoulders. Within most modern digital exciters / correctors is the ability to limit and or clip the digital peaks of the RF signal. This is typically done in the digital domain by removing these bits. The effect of this is a reduction of the signals natural crest factor or peak to average ratio. By doing this, the amplifier at a given power level will have more headroom and the corrected shoulder performance will be increased. There is a downside to this because when these pieces of the signal are clipped or removed, the demodulation process sees this as distortion and it shows itself in a reduction of MER. Figure 38 below shows the shoulder levels of the asymmetrical Doherty amplifier operating at 150 watts with "clipping" applied. Figure 39 shows the constellation diagram under the same conditions, and Figure 40 shows the CCDF curve. These can be directly compared to Figures 29, 30 and 31 above which had no "clipping" applied.



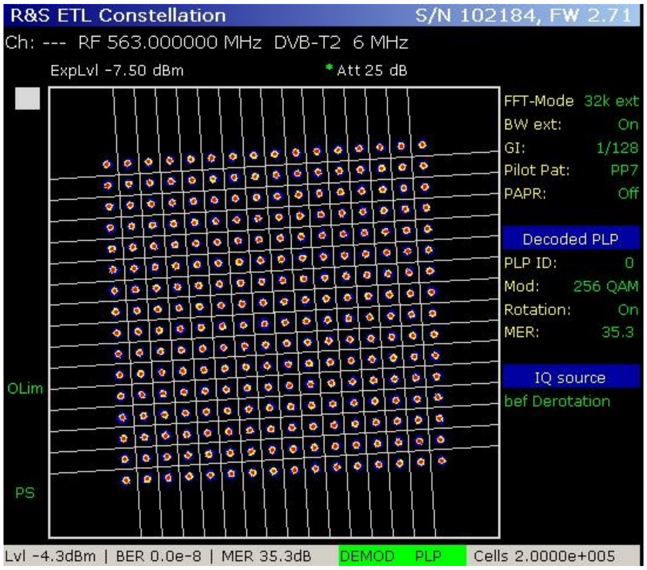
R&S ETL Digital Spectrum S/N 102184, FW 2.71

Ch: --- RF 563.000000 MHz DVB-T2 6 MHz

RBW 10 kHz
Att 25 dB
VBW 30 kHz
ExpLvl -7.50 dBm
SWT 100ms

Shoulder Attenuation	Result	Unit
Lower	42.1	dB
Upper	42.0	dB

Figure 38: BLF888E Corrected Shoulders DVB-T2 with Digital Peak Clipping Turned On



R&S ETL Constellation S/N 102184, FW 2.71

Ch: --- RF 563.000000 MHz DVB-T2 6 MHz

ExpLvl -7.50 dBm
Att 25 dB

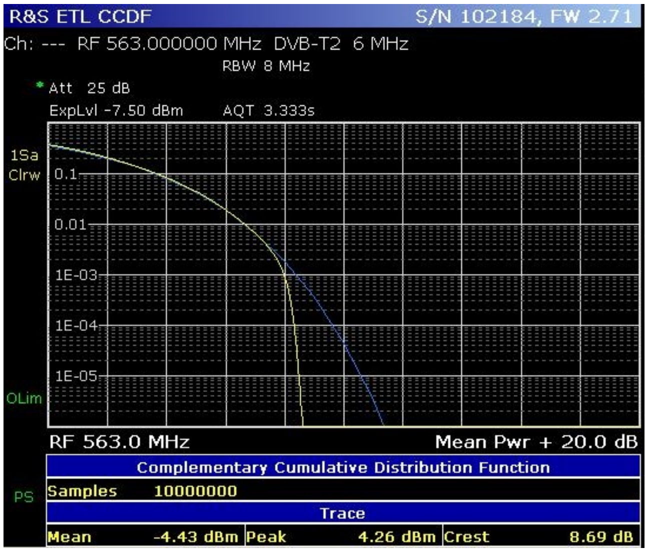
FFT-Mode: 32k ext
BW ext: On
GI: 1/128
Pilot Pat: PP7
PAPR: Off

Decoded PLP
PLP ID: 0
Mod: 256 QAM
Rotation: On
MER: 35.3

IQ source
bef Derotation

Lvl -4.3dBm | BER 0.0e-8 | MER 35.3dB DEMOD PLP Cells 2.0000e+005

Figure 39: BLF888E Corrected Constellation DVB-T2 with Digital Peak Clipping Turned On



R&S ETL CCDF S/N 102184, FW 2.71

Ch: --- RF 563.000000 MHz DVB-T2 6 MHz

RBW 8 MHz
Att 25 dB
ExpLvl -7.50 dBm
AQT 3.333s

Complementary Cumulative Distribution Function
Samples 10000000
Trace
Mean -4.43 dBm | Peak 4.26 dBm | Crest 8.69 dB

Figure 40: BLF888E Corrected CCDF Curve DVB-T2 with Digital Peak Clipping Turned On

With digital peak clipping turned on, as can be seen, the shoulder levels went from 38dB with it off to 42dB with it on. To gain this 4dB of shoulder margin it took giving up 1.9dB of MER as that went from 37.2dB with it off to 35.3dB with it on. Still, certainly very acceptable. The key is the peak power being produced without digital clipping was 1251 watts with a crest factor of 9.21dB and with it on it was reduced by just over 0.5dB to 8.69dB with the peak power now being 1109 watts.

This just shows one of many ways a transmitter can be "optimized" to get the required performance at maximum efficiency and headroom.

REFERENCES

[1] AMPLEON, Doherty Architectures in UHF, Walter Sneijers, RF Applications Engineer, 2016