WHITE PAPER

A Study And Comparison Of Efficiency Enhancement Techniques For RF Power Amplifiers

By Geoffrey N. Mendenhall, P.E.
VP Transmission Research and Technology — Harris Broadcast Communications

Purpose

The purpose of this paper is to acquaint broadcast engineers with several new techniques that can significantly improve the operating efficiency of broadcast transmitters that provide linear amplification of digital waveforms.

There is high interest among broadcasters and network operators in new RF power amplifier technology that offers improved efficiency over what is presently available. The benefits of higher power amplifier efficiency include: AC power consumption savings, reduction in physical size, reduction in cooling requirements and reduction of carbon footprint in support of green initiatives.

This paper investigates and compares several new applications of technology that significantly improve the DC to RF efficiency of solid-state, linear, RF power amplifiers operating in the VHF, UHF, and L-Band frequency ranges. The results of several advanced technology assessments focused on RF amplifier efficiency enhancement will be presented.

Peak-to-Average Power Ratio

Digital TV signals have a high Crest Factor or Peak-to-Average power Ratio (PAR) compared to a constant envelope signal. Digital modulation waveforms including OFDM and 8VSB contain complex, simultaneous, AM and PM modulation, which requires RF linear amplification.

Linear Amplification is Required for Digital Waveforms that have Envelope Variations

Linear amplification is needed to meet the RF emission mask and to minimize in-band RF IMD products that degrade the digital signal to noise ratio.

Efficiency Penalty of Linear Amplification

Efficiency is lost when the amplifier is operating in the region between saturation and cutoff, where the loading on the amplifier is not optimum for the RF waveform at that instant and when the static bias current through the amplifying device is a significant portion of the total current at that point in the waveform envelope.

Saturated RF PA Efficiency vs. Linear Range Efficiency

RF power amplifiers operate at highest efficiency when saturated for maximum power output. To accommodate a digital signal with an 8dB peak-to-average ratio, the amplifier needs to be biased into Class-AB, linear mode, and the average power needs to be reduced by approximately 8dB to achieve reasonable linearity. Current UHF solid-state devices can achieve saturated DC to RF efficiencies of up to 70%, but when backed off by 8dB into Class-AB operation, the DC to RF efficiency drops to typically less than 30%.

Digital Pre-Correction

Real-Time Adaptive Correction (RTAC) is used by Harris to pre-correct the linear amplifier for AM/AM and AM/PM nonlinearities. There is a trade-off between the level of in-band RF IMD products that can be tolerated and how far into saturation the amplifier can go on envelope peaks. Effective use of RTAC can help raise the efficiency of the linear amplifier by running it closer to saturation, while still meeting the required digital signal-to-noise ratio and RF spectrum emission mask.

Crest Factor Reduction

In order to get reasonable RF power amplifier utilization, the PAR of the digital signal must be reduced. This process introduces some degree of distortion, but intelligent techniques can be employed to minimize this distortion.

The amplitude of the digital signal has a statistical distribution that can be measured by estimating the Complementary Cumulative Distribution Function (CCDF). Instantaneous peaks at all levels are averaged over a large number of samples. Generally the PAR determines the RMS power back-off necessary to meet the required digital signal-to-noise ratio (EVM or MER) and the RF mask based on peaks that occur 0.01% of the time. Figure 1 shows a comparison of the CCDF (PAR ~6.3dB) for ATSC (8-VSB) vs. (PAR~8.2dB) for DVB (OFDM) vs. (PAR~8.5dB) for Gaussian power distributions over 1 million samples. These PAR values shown in dB on the horizontal axis are taken at a probability of 10-3 or 0.01% as shown on the vertical axis.

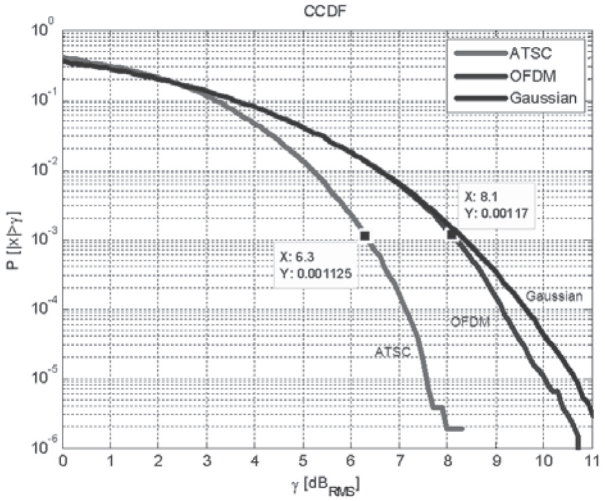

Figure 1 — CCDF Relative PAR of ATSC, OFDM and Gaussian

The reduction of the PAR within the limits imposed to meet a minimum Modulation Error Ratio or Error Vector Magnitude (MER/EVM) digital signal-to-noise ratio is the first step to improving RF linear amplifier utilization and efficiency.

New Solid-State RF Power Devices

Harris is constantly researching and evaluating new RF device technologies. Several new solid-state RF power device technologies have recently replaced previous generation V-MOS and T-MOS devices.

The most popular new solid-state power devices for VHF, UHF, and L-Band applications are based on Laterally Diffused Metal Oxide Semiconductor (LDMOS) technology. LD-MOS devices, like their V-MOS and T-MOS ancestors, are also Metal Oxide Semiconductor Field Effect Transistors (MOS-FET). LD-MOS technology has the advantage of placing the source terminal of the FET at ground potential, with a geometry layout that improves thermal performance, lower capacitances, and source inductance. All this combined translates into a device with higher gain, higher power density, and higher device efficiency.

32V LD-MOS devices are widely available for UHF and L-Band frequency ranges. 32V LD-MOS devices are easy to digitally pre-correct and have proved to be highly reliable.

50V LD-MOS devices offer the same advantages of 32V technology, with present offerings having three to four times the power density of 32V technology and about 8dB higher gain. 50V LD-MOS devices also operate about 4% more efficiently than 32V devices.

The higher voltage devices are well matched to the use of low-cost, 48V telecom power supplies. 50V, LDMOS technology was first introduced in a new line of UHF broadcast transmitters in October, 2008, and the reliability of this technology has now been field proven.

Gallium Nitride (GaN) semiconductors have become popular at frequencies above 1GHz. A few GaN devices are now available for the UHF and L-Band frequency ranges. They offer slightly higher efficiency and a much wider bandwidth (due to their lower parasitics) than LD-MOS technology, but are more costly at this time. Their combination of lower parasitics and higher breakdown voltage makes these devices ideal candidates to envelope tracking applications. The softer saturation characteristic poses a greater challenge to digital precorrection than LD-MOS (mainly in designs with a high content of time-dependent nonlinearities).

Power Supply Efficiency — AC Mains to RF Device DC Feed

After the RF device efficiency, the AC to DC conversion efficiency of the power supply is the second most important subsystem to achieve high overall AC to RF efficiency of the transmitter.

The latest switching power supply technology offers up to 95% efficiency converting the AC line input to the required DC voltage needed by the solid-state RF devices. The cost and reliability of the switching power supply technology is a key design requirement of the transmitter. Forty-eight volt switching power supplies designed for telecom applications have been highly evolved for reliability, and the large volumes that are produced have made these power supplies the most cost effective. The use of multiple, single-phase, switching power supplies provides redundancy and makes it easy to configure the transmitter for either three-phase or single-phase AC power sources.

Additional Techniques to Improve Efficiency

Envelope Elimination and Restoration

Envelope Elimination and Restoration (EER) allows the use of a highly efficient, nonlinear amplifier to amplify an RF waveform with an envelope component. This is accomplished by decomposing the RF waveform into separate envelope and phase components. If the RF amplifier is simultaneously AM modulated with the envelope component and phase modulated with the phase component, the original RF waveform can be reconstructed at the output of the amplifier.

This technique requires a high-efficiency envelope modulator and highly accurate matching of the envelope and phase component channels over three times the channel modulation bandwidth through the system in order to accurately restore the RF waveform at the output of the amplifier. EER has proven to be practical at medium-wave AM frequencies with fairly narrow bandwidth signals such as DRM or HD Radio. This technique has not yet become practical with higher bandwidth DTV signals in the UHF spectrum.

Doherty Linear Amplification

Two or more amplifiers are combined in a way that keeps one of the devices near saturation during all parts of the conduction cycle, while the other device(s) operate in a linear mode for the bottom half of the envelope. Two-way, three-way, and four-way Doherty have been investigated for ODFM and 8-VSB applications.

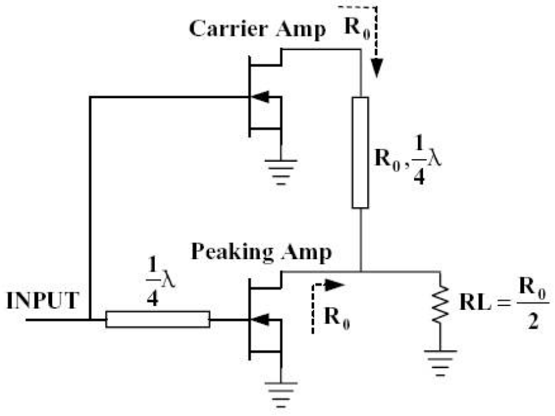

Figure 2 — Two-Way Doherty Linear Amplification

Two-way Doherty illustrated in Figure 2 seems to be the best compromise between minimizing the amplifier complexity and efficiency gain at PARs between 6dB and 8.5dB, which covers the popular DVB and ATSC waveforms, as shown in Figure 3.

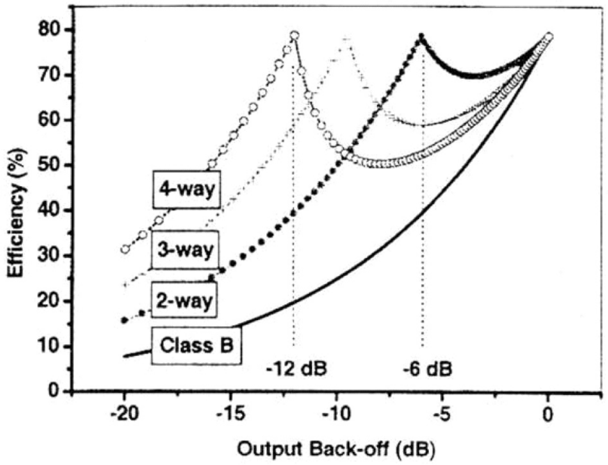

Figure 3 — Doherty Efficiency vs. PAR

Doherty linear amplifiers are relatively easy to digitally pre-correct for the residual nonlinearities, as shown in Figure 4.

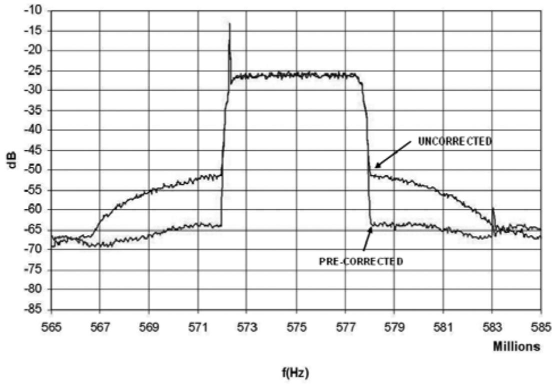

Figure 4 — Doherty Linear Amplifier RF Mask Compliance: Uncorrected and Digitally Pre-corrected ATSC @ 6.3dB PAR

Doherty Efficiency Benefit

The typical DC to RF efficiency improvement for LDMOS devices operating in two-way Doherty mode at UHF frequencies is ~10%, and the typical DC to RF efficiency improvement for LD-MOS devices at L-Band frequencies is ~8% with 8.5dB PAR RF waveforms.

These efficiency improvements at the RF device level can result in a 32% to 36% reduction in overall dissipated power at the transmission system level.

Advantages of Doherty Amplification

- Simpler to implement
- Small impact on parts count or reliability
- Well understood, mature, technology
- Easy to digitally pre-correct
- Shortest development time to market
- Adds little additional cost
- Operating bandwidth is sufficient for 6% BW applications
- L-Band
- UHF (~ 6 x 6 MHz channels per band segment)

Disadvantages of Doherty Amplification

The key disadvantage of Doherty is the limited operating bandwidth (~6 %) limitation that requires the VHF or UHF bands to be segmented.

PA Device Power Supply Voltage Modulation

Adjusting the supply voltage to the RF amplifying device to track the RF waveform envelope can keep the amplifier running closer to saturation throughout the more of the waveform. Earlier implementations of this technology on vacuum tube amplifiers include:

Anode Voltage Pulsing

The UHF klystron "mod anode pulser" uses a voltage modulated anode ring located near the cathode to pulse the current through the tube. It was used to increase the static beam current only during the synchronization pulse interval of an analog TV signal. This allowed the use of a lower collector current during average picture level thereby improving the efficiency of the linear amplifier.

MSDC Klystron and MSDC IOT

The Multi-Stage Depressed Collector (MSDC) technology uses multiple collectors operating at progressively lower voltages, which allow the electrons to be returned to the optimum collector voltage, depending on the RF envelope amplitude at that instant in time. This technique significantly improves the DC to RF efficiency of the amplifying device. The MSDC Inductive Output Tube (IOT) increases the DC to RF efficiency of a high-power UHF amplifier from typically less than 35% up to approximately 55%. The MSDC IOT is by far the most efficient linear amplifier for the UHF frequency range that is currently available.

Drain Voltage Modulation

New technology now makes it possible to modulate the LD-MOS FET drain voltages to track the peak envelope power and keep the amplifier operating near high-efficiency saturation over a significant portion of the envelope depth. Actually, this technique has a lot in common with the MSDC IOT in that it keeps the RF device operating closer to a saturated condition as the RF envelope amplitude changes. An example of drain voltage modulation technology is Nujira HAT® (High Accuracy Tracking).

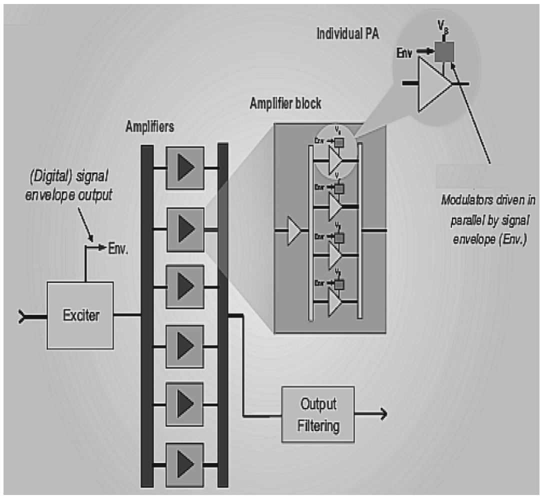

Figure 5 — Simplified Block Diagram of Transmitter with Modulated Drain Voltage

Relative Complexity of Drain Voltage Modulation

- In addition to the main digital waveform modulator in the exciter, there are additional drain voltage modulators for every power device in the transmitter
- The exciter must calculate the envelope peaks and send a time aligned digital command to each voltage modulator at each RF device via a wide bandwidth control buss
- An additional layer of digital pre-correction must be added to correct for drain modulation nonlinearities
- Each drain voltage modulator must be located very close to the associated LD-MOS FET drain to avoid memory effects
- Part of the RF efficiency gain is lost to the inefficiency of modulator

Drain Voltage Modulation Efficiency Improvement

Depending on voltage modulation depth, up to 40% DC to RF efficiency improvement, before subtracting the inefficiency of the modulator (~20-25%) leaving net DC to RF drain efficiency improvement of ~ 15%.

Advantages of Drain Voltage Modulation

The primary advantage of drain voltage modulation over Doherty is that this technique is not RF bandwidth limited. This makes it possible to build a wideband RF linear amplifier with high efficiency. Drain voltage modulation also can be a few percent more efficient than two-way Doherty at PARs above 7.5dB.

Disadvantages of Drain Voltage Modulation When Compared to Doherty

- The complexity of additional hardware and precorrection
- Decreased reliability due to increased parts count
- Increased cost of extra hardware
- Longer development time to market

Benefit of Efficiency Enhancement Techniques vs. Waveform PAR

These efficiency enhancement techniques only provide significant efficiency benefit when the PAR is greater than 6dB, and the benefit increases as the PAR increases. This makes application of this technology attractive to DTV, DAB and DRM+ waveforms with high peak-to-average ratios. There is little benefit to applying these techniques to HD Radio, which has a lower PAR.

System Thermal Efficiency Improvement

The reduction in heat dissipation at the RF power amplifier devices has a far-reaching impact on the design of the cooling system. As heat sink power dissipation and temperatures drop, the amount of air flow or liquid flow can also be reduced. The size and power consumption of the air- or liquid-cooling system can be proportionately reduced. If air cooling is used, the size and power consumption of the HVAC system external to the transmitter can be reduced thereby saving additional energy.

Even modest DC to RF efficiency improvements in the power amplifier, as discussed above, can have a more significant impact on the overall AC power consumption of the transmitter system when the reduction in power supply and cooling system requirements are taken into account. A 15% improvement in DC to RF efficiency can result in a greater than 30% reduction in overall system power consumption. The proportional cost reduction in power supplies and cooling system components can help offset the cost of the efficiency enhancement components.

Market Needs and Cost Tradeoffs

The introduction of these new efficiency enhancing technologies is dependent on customer need to reduce power consumption and the customer's willingness to pay more for this technology at the time of equipment purchase in order to have a lower overall cost of ownership in the longer run. The initial cost of investing in these higher efficiency products can be reclaimed in as little as one year depending on current electrical power rates and the specific technology that is chosen.

Narrowband technologies like Doherty are very attractive from a simplicity, speed to market, and cost standpoint, but most users, for the sake of module interchangeability, prefer a wideband power amplifier technology that allows the transmitter system to be frequency agile across the entire VHF or UHF band. Wideband efficiency enhancement technologies like Drain Voltage Modulation are more complex and costly to implement, but offer full frequency agility across the frequency band of interest.

Harris has been seeking market feedback on the tradeoffs between these technologies, as part of the new product introduction process.

Summary

- New LD-MOS RF devices, crest factor reduction, and advanced digital pre-correction have enabled up to 5% DC to RF efficiency improvements
- Two specific technologies have been reviewed that can further improve solid-state power amplifier DC to RF efficiency by 10 to 15%
- Doherty linear RF amplification is the simplest and least costly efficiency improvement if broadband frequency coverage is not mandatory
- Two-way Doherty amplification nearly equals drain voltage modulation efficiency enhancement at lower cost and simplicity
- L-Band applications fall within the bandwidth capabilities of Doherty amplification
- Drain voltage modulation has the key benefit of offering broadband frequency coverage when frequency agility is required
- Drain modulation is preferred for covering the entire VHF or UHF band because it has no RF bandwidth limitation
- Both Doherty and drain voltage modulation offer a significant reduction in transmitter system cooling requirements

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Broadcast Communications Division
9800 South Meridian Boulevard, Suite 300 | Englewood, CO USA 80112 | Tel: +1 303 476 5000
www.broadcast.harris.com