Improving the efficiency of military radio transmitters

1 Introduction

Power density of the new communications systems supporting the networked battlefield can be four times lower than that of the AM/FM radios they replace, due to the use of advanced modulation techniques to improve data throughput of Net-Centric communications systems. These software defined radios must operate over wide transmit bandwidths which combined with the newer waveforms compounding the already challenging task of making these radios lighter and last longer on fewer batteries. This White Paper describes how High Accuracy Tracking (HAT™), a technique based on the principle of envelope tracking first described by Bell Labs in 1937, and recently successfully implemented in commercial cellular and broadcast communication systems by Nujira , is attracting interest.

2 Context

Military communications systems will go through a dramatic upgrade cycle over the next 5-10 years. The upgrade, which has already started, will create a Net-Centric communication system where voice, data and video information can flow securely and rapidly throughout all theatre elements in the battlefield. The USA's JTRS (Joint Tactical Radio System) program is the vanguard of this change in how the military communicates in the battlefield. New Handheld, Manpack and Small Form Factor (HMS) radios under the JTRS program offer tactical vehicles and dismounted units with reliable, good quality connectivity over a wide bandwidth even in rugged and urban environments. Such secure, reliable high bandwidth voice, data and video communications technology is essential to deliver the required speed of command in today's conflict environment. It is the two-way backbone that connects the whole chain of command from the top down to the lowest level, giving critical and immediate situational awareness and maximising combat effectiveness.

These new standards derive their higher throughput by using more complex modulation schemes, but these reduce the efficiency of the RF power transmitters. The 2MHz to 2GHz bandwidth specification for JTRS radios imposes further challenges to the designer of the RF transmission circuits. Power density of the new radios can be worse than the established frequency hopping AM/FM technology by a factor of four, with a negative impact on the SWAP (Size, Weight, and Power) envelope of the communications systems a vehicle-borne or dismounted unit needs to carry.

These considerations are driving a major push to improve the efficiency of battlefield communications technologies. A major area of focus is the RF amplifier, which can end up consuming as much as half the power in a high speed modem. Power amplifier designers are faced with a difficult optimization challenge that must balance size and efficiency yet work over the demanded transmit bandwidth. Advances in power transistor technologies have allowed designers to meet their size goals by addressing the wide transmit bandwidth in only one or two power amps however the efficiency has suffered accordingly. It is time to take a fresh look at the design of the RF transmission amplifier chain.

3 RF Power Amplifier efficiency on the Network Battlefield

The waveforms used in the new networked battlefield communications protocols are usually OFDM or QAM based and support frequency hopping and adaptive signal to noise encoding schemes. For example, the Wideband Networking Waveform (WNW) specified by JTRS for ground to ground and ground to air communications and the Tactical Targeting Network Technology (TTNT) used for airborne sensor, shooter and ordnance communication is based on the OFDM modulation scheme. The Soldier Radio Waveform (SRW) for soldier to soldier communications is based on QAM modulation. The MUOS (Mobile User Objective System) for satellite to ground, sea or air communication uses both OFDM and QAM, and leverages the W-CDMA technology developed commercially for existing mobile phone networks.

Channel coding and modulation techniques like QAM, OFDM require faithful reproduction of the amplitude of the transmitted RF signal. RF PAs are classic AB class amplifiers (figure 1), which offer most efficient operation when the RF envelope waveform is closest to peak power. Efficiency is a function of the RF signal crest factor (peak-to average power ratio or PAPR) where the higher the peak power with respect to the mean power, the lower the efficiency. This in turn is determined by the type of modulation and coding scheme. There is no single formula that defines that relationship a good rule of thumb is that every dB of crest factor reduction provides a 2-2.5% efficiency change.

In a W-CDMA transmitter, the PA peak power is usually 4 – 6.5dB above the mean power. OFDM signals are composed of a large number of individual components, the power of each varying with time. The resultant amplitude of the composite signal over time is therefore not constant but 'peaky' in nature and results in even higher crest factors – up to 9.5dB - and even lower PA efficiencies. In general the higher the data rates, the higher the PAPR and the more difficult the amplification process becomes. This non constant amplitude modulation means that a typical amplifier rarely runs up to its saturated output power capability resulting in lower efficiency.

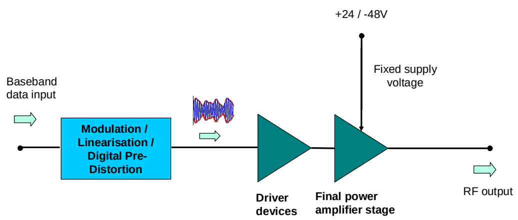

Figure 1: A conventional Class AB power amplifier configuration

High PAPR signals make the design of PAs difficult for two reasons: firstly, the amplifier must be linear over a wide dynamic range to preserve modulation accuracy and spurious performance. It is possible to use a technique called 'Crest Factor Reduction' (CFR) to allow the PA to operate closer to peak power for most of the time by limiting the peaks of the signal using DSP techniques - however this needs to be done with care to minimise distortion and maintain adequate signal EVM (error vector magnitude). Typical, CFR will reduce the PAPR to around 8.0 - 8.5 dB.

Secondly, the variation with time of the PA output power results in a poor overall power efficiency. The reason for this is shown in Figure 2. A Class AB (linear) PA is at it's most efficient at peak power, but the drain (power conversion) efficiency, as shown by the solid line, drops off rapidly as the output power decreases. The probability distribution of instantaneous output power for a typical OFDM signal (dashed curve [not to a specific scale]) shows that for much of the time the signal power lies well below the peak power and hence the device is operating at low (average) efficiency. Note that the PAPR value shown in this diagram assumes that CFR has been used to reduce the PAPR of the transmitted signal: without this, overall efficiency would be even lower.

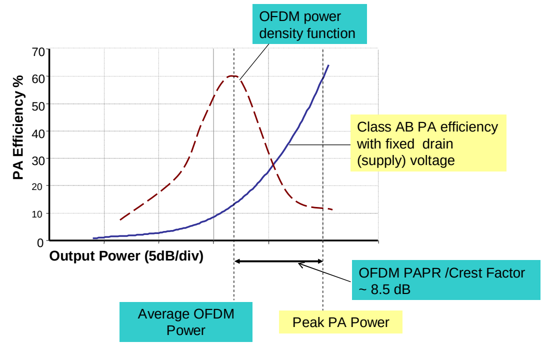

Figure 2: Comparison of drain efficiency vs. power output, and probability distribution of the instantaneous output power value

4 Possible solutions for improving PA efficiency

A number of techniques are now being used to improve PA efficiency. The majority of these have found their first use in the cellular industry, where the problems of high network power consumption and environmental impact have already caused many network operators to force the pace of change and demand significantly improved equipment efficiency from their suppliers.

The three major techniques are:

- Digital Pre-Distortion (DPD) and Linearisation
- Doherty
- Envelope Tracking

4.1 DPD and Linearisation

As already noted, Crest Factor Reduction can make a useful contribution to improving PA efficiency by allowing controlled compression of peak signals, effectively allowing the PA to operate nearer peak power and hence at a higher efficiency.

DPD (Digital Pre-Distortion) and Linearisation techniques build on this by compensating for non-linearities in the final RF output stage. In the process they also improve adjacent channel and EVM performance, and by allowing some compensation for the distortion caused by non-linearities near compression, the PA can be driven harder, resulting in an improvement in power efficiency.

The best improvements result when DPD and Linearisation are used as part of a system architecture incorporating active sampling of the output signal as part of a feedback loop: only then can the system fully compensate for changes in amplifier characteristics with time, temperature, and signal characteristics.

4.2 Doherty

The Doherty PA configuration uses two amplifying devices driven in parallel, with their outputs combined. One amplifier (the 'main' or 'carrier', typically a standard Class AB amplifier) provides all the output power (with the second device turned off) until the power required causes it to enter it's nonlinear region, at which point the second ('auxiliary' or 'peaking') amplifier (typically operating in Class C) is switched on and provides additional power. The novel feature of the Doherty amplifier is the way the outputs of the two transistors are combined using an impedance inverter, allowing the main amplifier to continue to provide power into the load as the signal increases.

Individually the two amplifier stages exhibit nonlinear transfer characteristics, but with careful design these can be made to be complementary and to provide a linear characteristic when combined. However in the breakpoint region care needs to be taken in coordinating the changeover: this is achieved by careful adjustment of the auxiliary amplifier in terms of the start point and gain expansion, in order to achieve full power at the same point as the main amplifier.

While several academic papers have quoted impressively high efficiency capabilities for Doherty amplifiers, in practice the typical efficiency being achieved with these designs is around 25-30%. However this improved efficiency comes with a number of drawbacks, for instance the difficulty in maintaining matching and linearity over time and with temperature and device variations. The most important limitation, however, is the limited PA bandwidth due to the complicated and essentially narrow-band matching required between the two amplifiers. Whilst the bandwidth available is adequate for cellular systems, it doesn't address all battlefield communications requirements.

4.3 Envelope Tracking

Envelope Tracking as a technique for improving power efficiency of RF Power Amplifiers was first described by Bell Labs in 1937. Instead of optimising a final RF stage power transistor supplied by constant voltage, the supply voltage to the Power Amplifier output transistor is adjusted dynamically, in synchronism with the envelope of the modulated RF signal passing through the device. This ensures that the output device remains in its most efficient operating region (i.e. in saturation) dramatically reducing the energy dissipated. Figure 3 shows Envelope Tracking in operation: without envelope tracking, the difference between the constant power into the RF amplifier and the RF output waveform is dissipated in the RF power transistor as heat. With envelope tracking, the supply voltage tracks the signal envelope, dramatically reducing the energy dissipated.

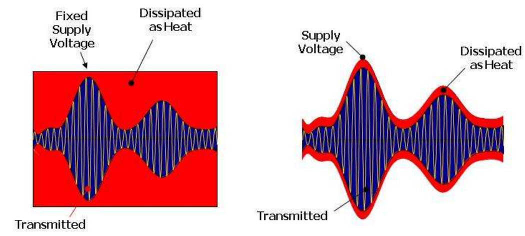

Figure 3: Envelope tracking reduces the voltage difference between the supply voltage and the signal envelope, dramatically reducing the energy dissipated as heat

Figure 4 demonstrates the high efficiency of an envelope-tracking amplifier throughout the high-probability region of continuous output power. It is essentially a superposition of the previous Figure 2, showing a series of drain efficiency vs. RF power output curves as the supply voltage is varied. The locus of these curves represents the efficiency of a power amplifier driven by variable voltage.

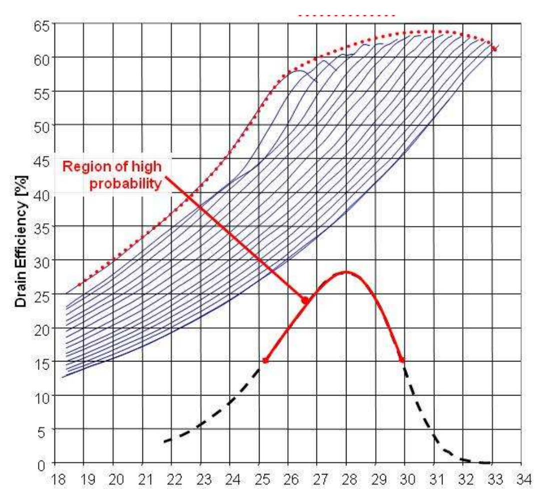

Figure 4: efficiency of a power amplifier driven by variable voltage

5 Implementation of Envelope Tracking

Although the principles of Envelope Tracking have been known for some time, the practical difficulties of implementing a working system have prevented the concept from being employed until recently. The challenge is making a power supply modulator capable of achieving the accuracy, bandwidth and noise specifications necessary at a level of conversion efficiency that delivers a significant energy saving for the system as a whole. Critical performance issues include tracking accuracy, modulator efficiency, stability, compliance with spurious-signal and noise specifications, and bandwidth for multi-carrier support. However, an evolution of this principle, High Accuracy Tracking (HATTM) is showing an impressive improvement in efficiency, going from typically a low 30 percent for standard a class AB amplifier to beyond 60 percent with HAT. Japanese cellular infrastructure vendor Sumitomo has recently launched a product based on the HAT principle, and multiple other base station and Digital TV transmitter manufacturers are at an advanced stage of adopting this new technology in their products. A solution for handsets is in development.

HAT technology has been demonstrated on a GaN PA. With QAM based waveforms similar to SRW, they have shown a potential 30% less power consumption and 42% more battery life for a manpack radio based on SRW. This was achieved over a wide frequency range and across multiple modulation modes. The power dissipation of the PA transistor itself is reduced by two-thirds, leading to a significant reduction in device thermal management requirements. Significant reduction in device temperature also leads to increased PA device reliablility. Also, for handset applications, demonstrations have shown an improvement in linearity with HAT, eliminating the requirement for DPD altogether.

HAT implementation is relatively straightforward (Figure 5), involving the addition of a HAT Modulator module. The only addition required to the standard PA architecture is an output from the DPD/Linearisation function to drive the HAT Power Modulator with a digital representation of the modulation envelope.. The module can be a small box (70mm x 70mm x 18mm for the commercial units supporting 40W cellular base station transmitters as shown in Figure 6), or can be a silicon chip for lower power handheld transmitters. In the future, the HAT algorithm may be integrated into power management chips already used in a radio transmitter. In addition, some minor redesign of the PA layout is needed to ensure optimal matching and hence efficiency.

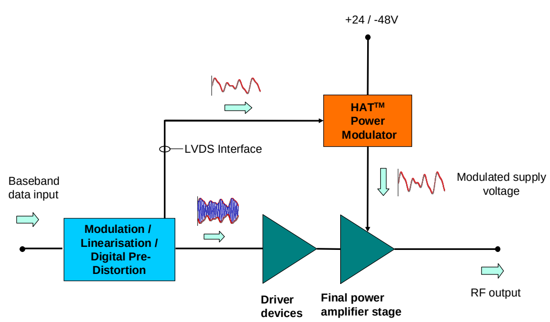

Figure 5: Application of a High Accuracy Tracking Power Modulator to a standard power amplifier

Figure 6: Nujira HAT Power Modulator integrated with PA

To retain compliance with demanding noise and spurious specification, the power modulator tracks the RF signal envelope with utmost accuracy in both timing and amplitude. It does so by calculating the amplitude from the digital signal ($\sqrt{I^2 + Q^2}$) and applying a simple function to arrive at the optimum instantaneous drain voltage. In parallel, a delay is calculated and applied to the RF signal before it is input to the amplifier, cancelling out the delay in the modulator.

6 Efficiency improvement across entire UHF band

The following diagram shows the level of energy efficiency improvement that can be obtained when using an envelope tracking HAT power modulator in a wide band UHF system. It can be seen that the efficiency improvement exactly tracks the normal Class A/B “fixed drain” solution across the whole band, whilst maintaining strong linearity and providing some additional benefit in the form of increased power output from the transistor (due to thermal management improvement). The results below were measured in the Nujira Laboratory and are a real example of the benefits that this technology offers.

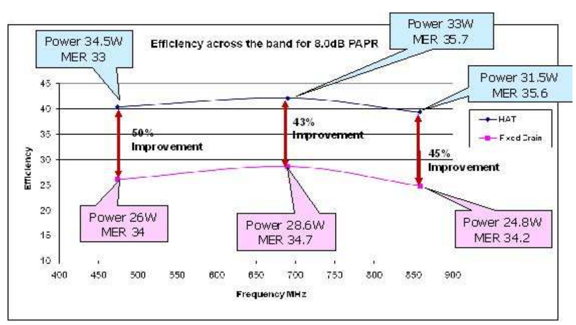

Figure 7: HAT delivers efficiency improvements over a wide bandwidth

Note that the efficiency enhancement is maintained across a very wide band – a characteristic of envelope tracking. This need to provide adequate linearity with enhanced efficiency over a wide band with high Peak to Average signals is exactly the type of challenge now facing designers for the next generation of Networked Battlefield communications systems. It has been shown that that linearity with Envelope Tracking is actually intrinsically improved compared to Class A/B designs and these result can be achieved without the use of Digital Pre Distortion and the added system complexity that this would bring.

7 Conclusion

To put the above discussion into context, the 40% of the 50-55kg kit carried by the 21st century infantryman can be power related, and 30% of the load carried by a platoon can now be related to powering the communications and other electronics it carries. There is high level realisation that the benefits of new communications standards need to be realised while reducing, rather than adding to this burden. In consequence, western armed forces are giving focus to the power density of their systems, defined as watt hours per kilogram. The vision is to drive power density upwards from today's 200Wh/kg through 400Wh/kg to a goal of 600Wh/kg by 2011. Though DPD, linearization and Doherty can all make a contribution towards this target, only HAT is capable of fully compensating for the inherent inefficiencies of transmitting OFDM, QAM and similar signals, and reversing the trend of rising RF transmitter energy use.

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