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pushing the envelope of PA efficiency

ET Envelope Path from digits to PA

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RF & Microwave Society

ARMMS Conference
19th/20th November 2012

Agenda

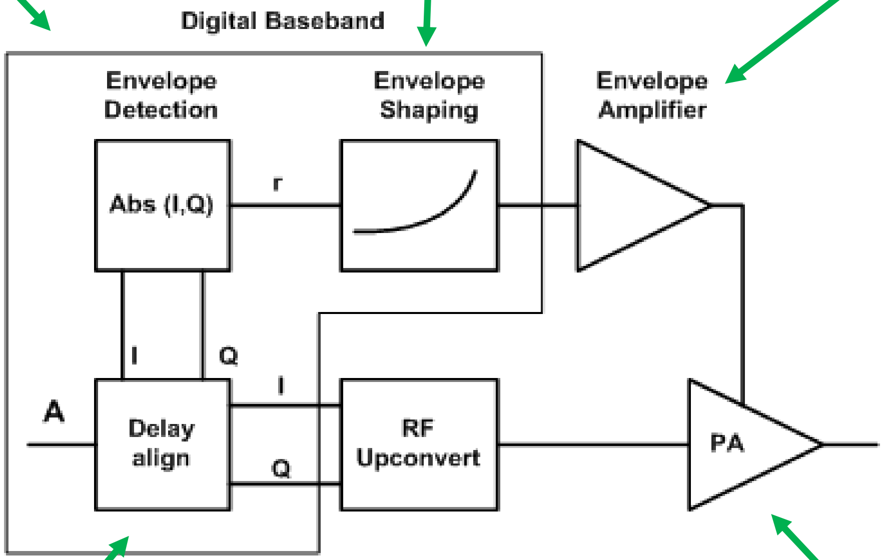
- Envelope Processing
  - ET PA Characterisation
  - Isogain shaping
  - CFR shaping
- Envelope Amplifier Design Requirements
  - Sources of Impairment
  - Integrated Modulator
  - Distributed Modulator

ET System Anatomy

Envelope detection: *most accurate if performed in digital domain*

Envelope shaping: *Determines relationship between RF power and PA supply voltage*

Envelope Amplifier: *High BW, Low Noise, High efficiency Amplifier used to generate PA supply voltage*



Delay Alignment: *ET requires accurate (~ns) timing alignment between envelope and RF paths. Most accurate / repeatable if performed in digital domain*

ET PA: *ET can be applied to standard fixed supply PA. Improved performance possible by optimising PA for ET operation*

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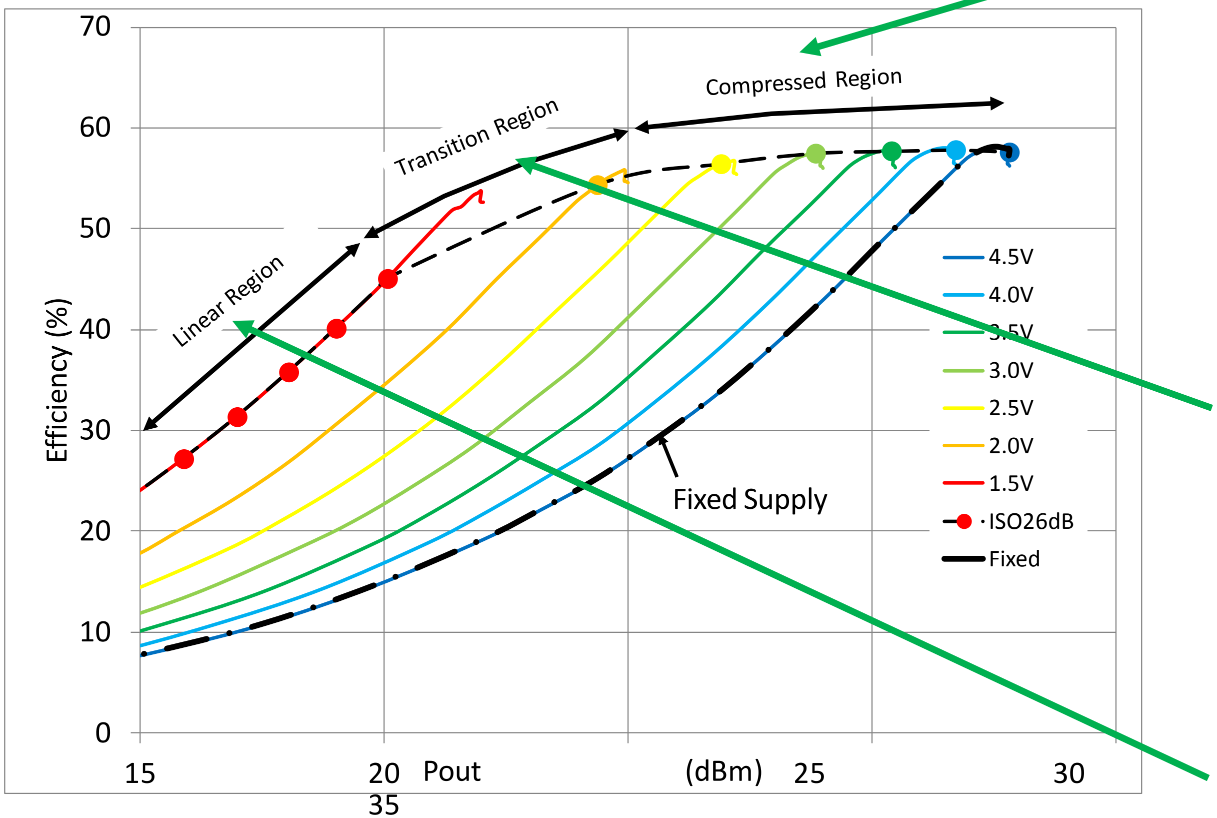
ET PA System Principles



*In **compressed region** O/P power is determined by supply voltage – RF input power has little influence*

*In **transition region** O/P power is determined by both supply voltage and RF input power*

*In **linear region** O/P power is determined by RF input power – supply voltage has little influence*

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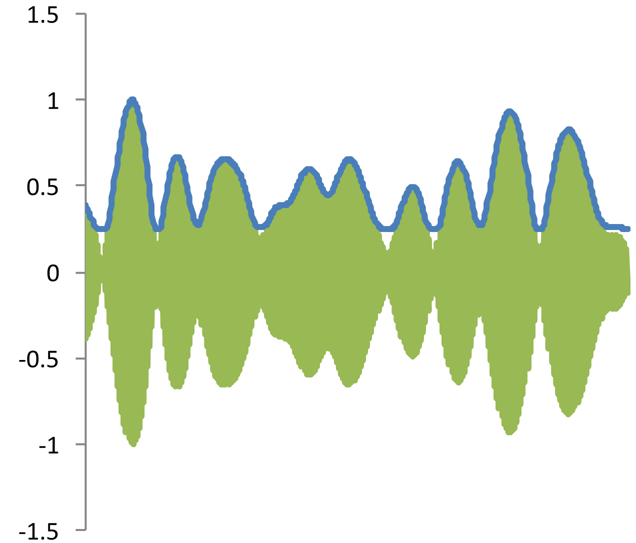
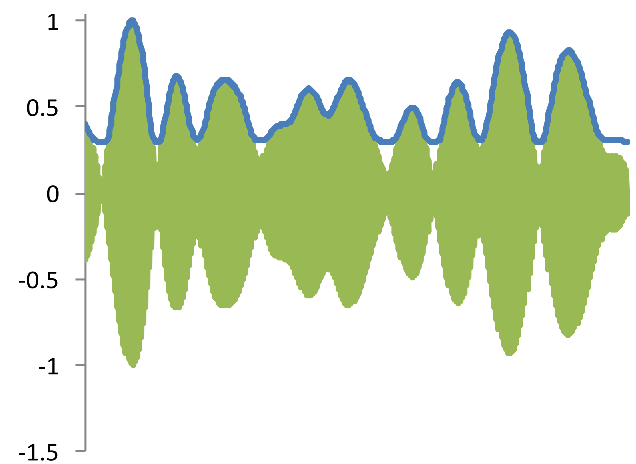
Envelope Processing Basics

- Swing Range
  - Optimise efficiency of combined modulator /PA
  - Prevent gross PA nonlinearity due IV curve ‘knee’
- Envelope ‘Shaping’
  - Control envelope bandwidth
  - Optimise efficiency
  - Can be used to linearise PA
- Timing Alignment
  - Timing error leads to ‘memory effect’ (AM-PM)
  - Fine adjustment necessary (~1ns)





PA Characterisation Methods

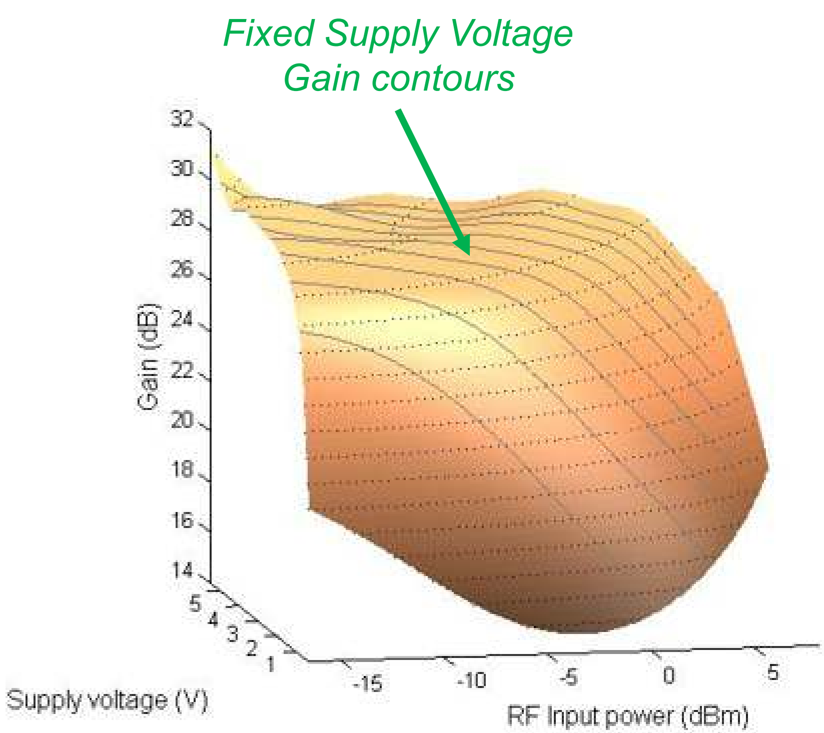
PA Characteristics must be known to determine Shaping table

Test methodology	PA current measurement	Supply impedance	Supply bandwidth requirements	ET Efficiency prediction	ET Linearity prediction	Parameters measured
Swept CW testing	Bench PSU	Low (decoupling Capacitor)	Low (Bench PSU)	Poor, due to PA die heating	Poor, due to PA die heating	Gain (AM:AM), Efficiency
Pulsed RF /DC testing	Instrumentation grade current probe, ~5 us resolution	Low (decoupling Capacitor)	Low (Bench PSU)	Good, if short pulses (~10 us, 10% duty cycle).	Fair (if device has low AM/PM)	Gain (AM:AM), Efficiency
Dynamic supply modulation	Challenging – high BW with high common mode voltage current sense	Requires low impedance dynamic supply (no decoupling)	High (~60 MHz BW)	V. Good	V. Good (if device has low memory effects)	Gain (AM:AM), Phase (AM:PM), Efficiency

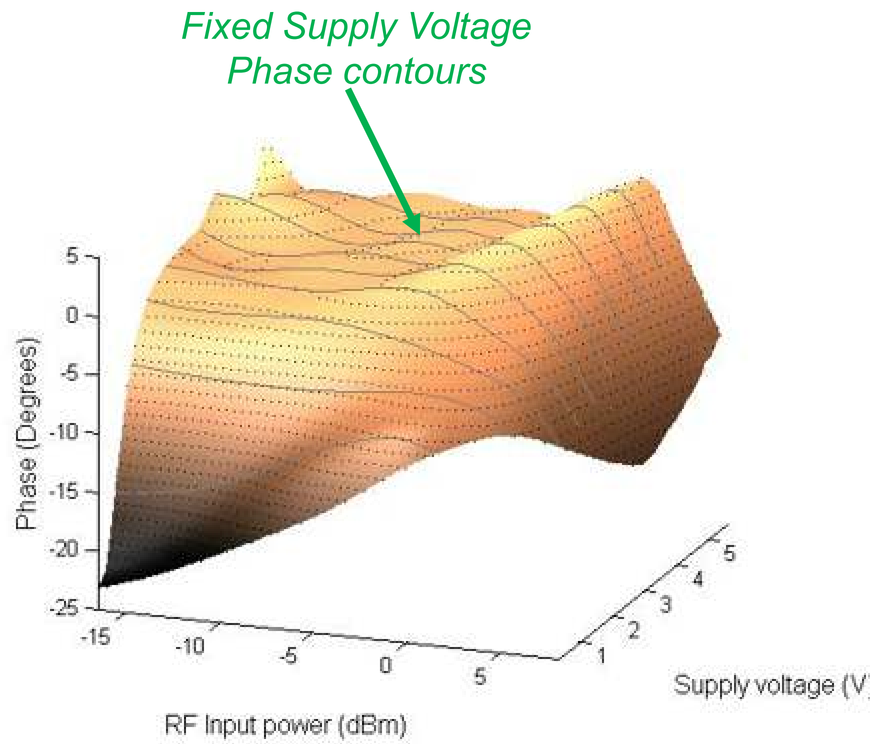
Phase measurement possible in principle – but accuracy poor due to heating effects and phase reference 'wander'

No phase measurement

AM/PM Input Surfaces

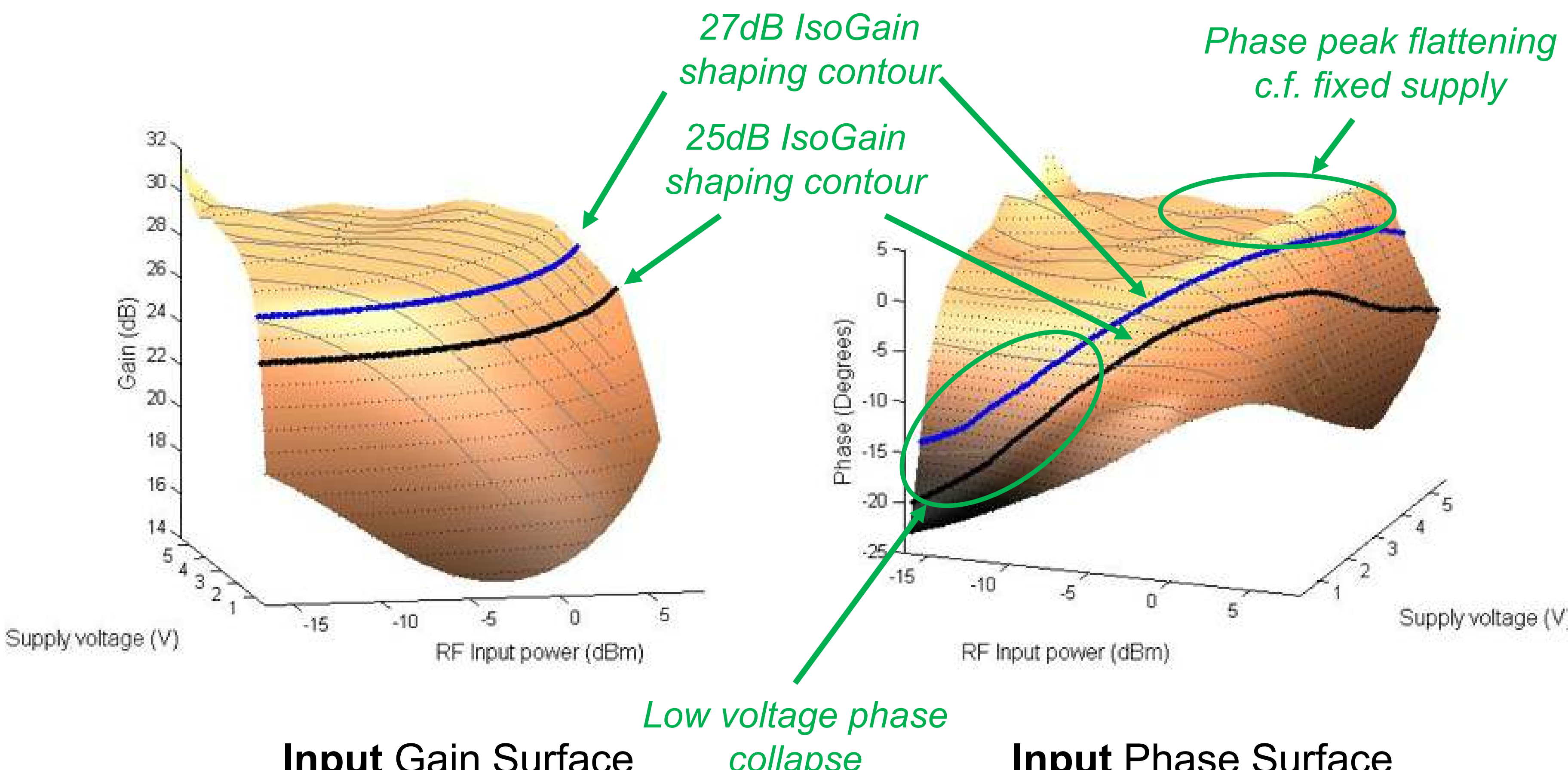


Input Gain Surface



Input Phase Surface

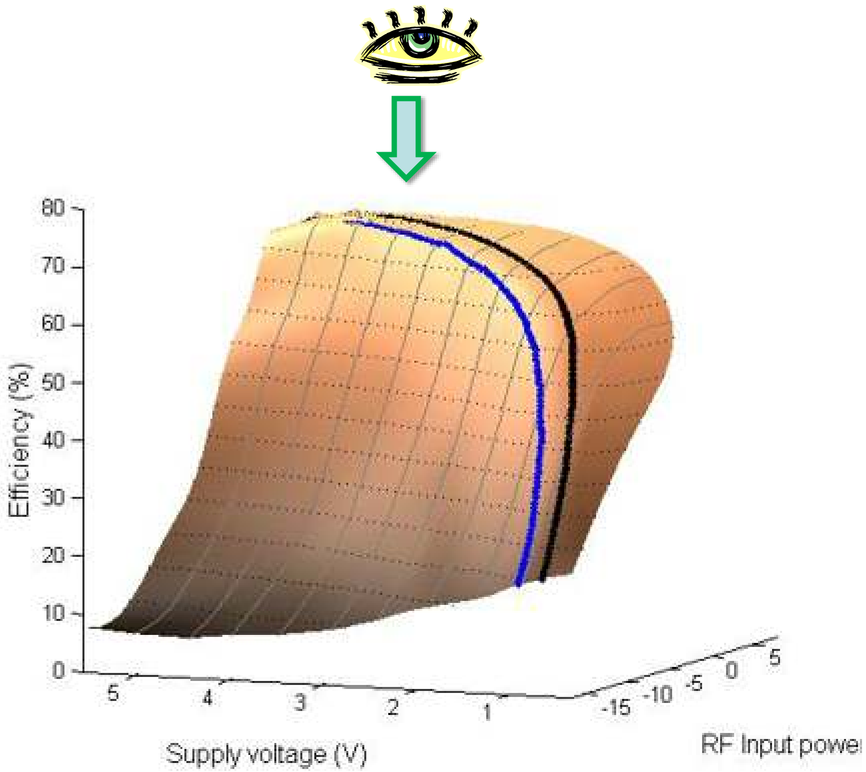
Isogain Contours



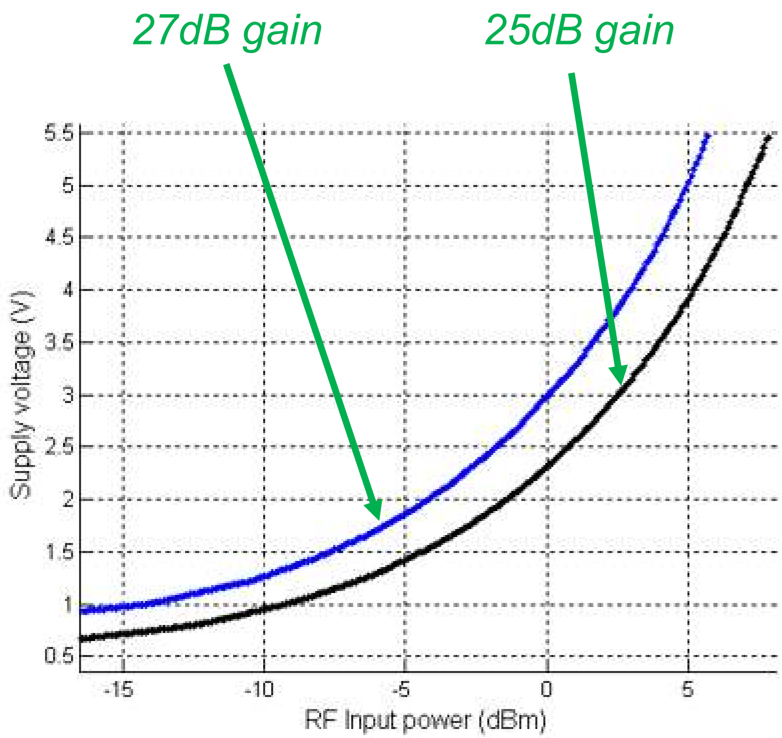
Input Gain Surface

Input Phase Surface

Isogain Shaping Functions

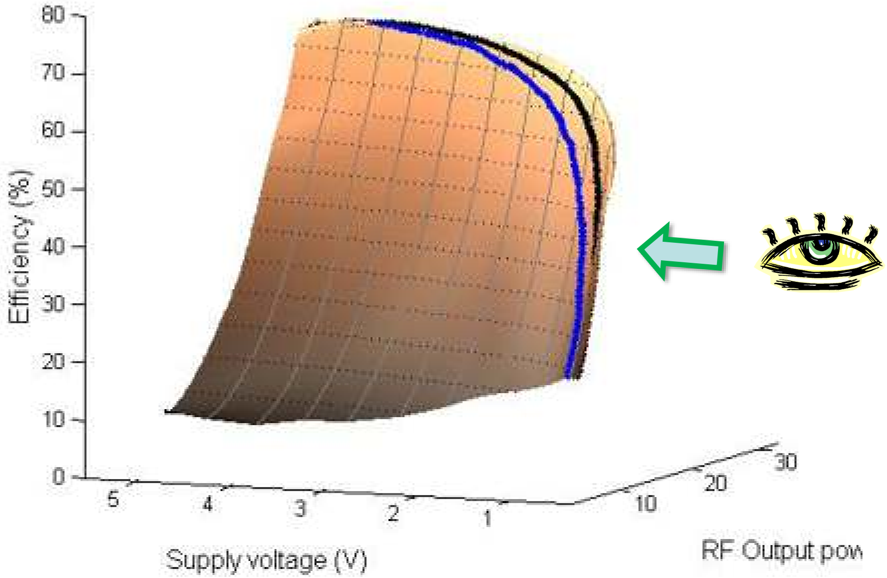


Input Gain Surface

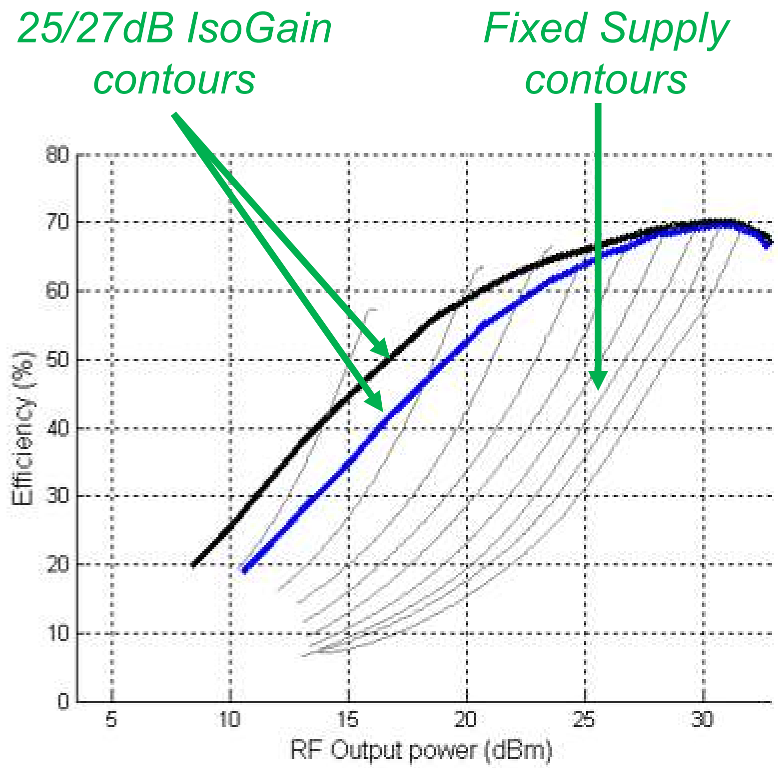


Isogain Shaping Functions

Useful 2D Slices - Efficiency



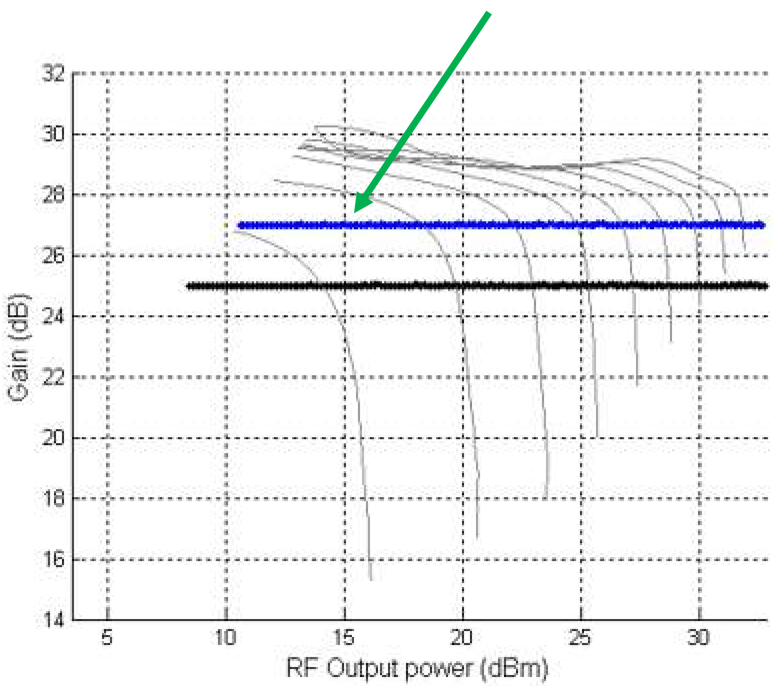
Output Efficiency Surface



Output Efficiency locus

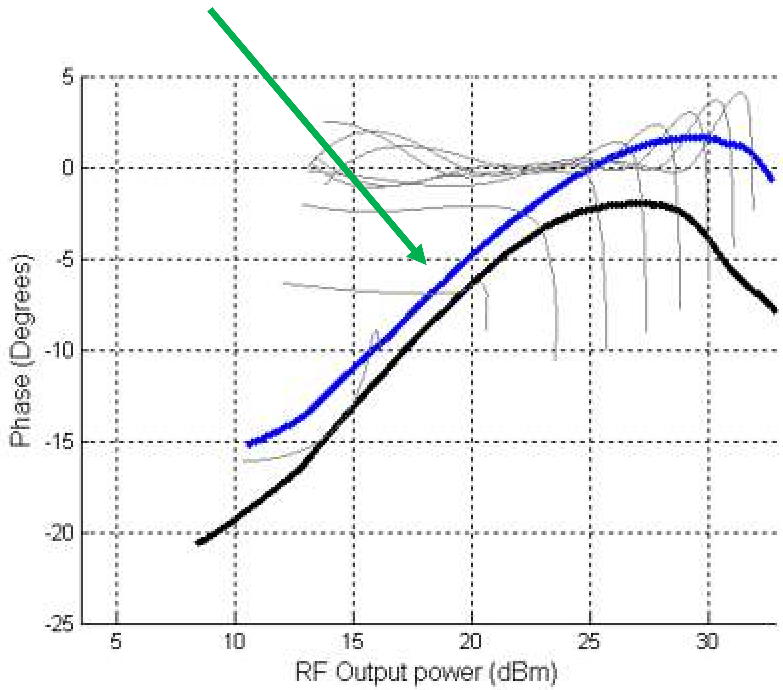
2D Slices AM/AM, AM/PM

AM/AM distortion removed



Output Gain

Residual PM distortion



Output Phase

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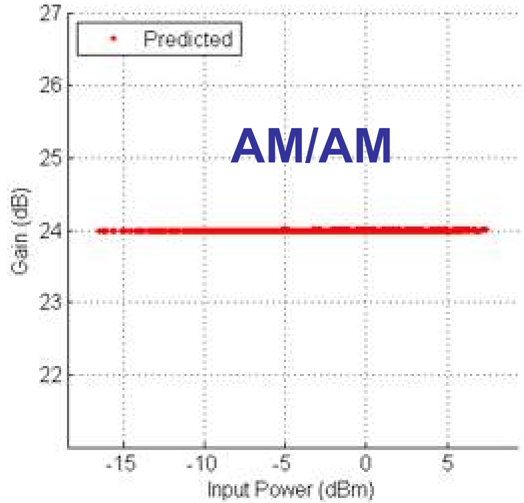
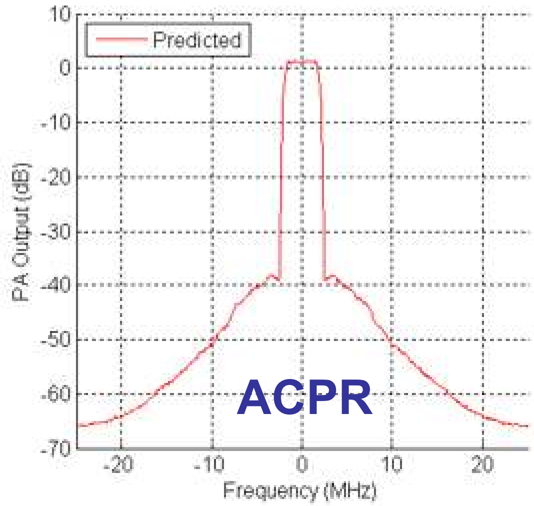
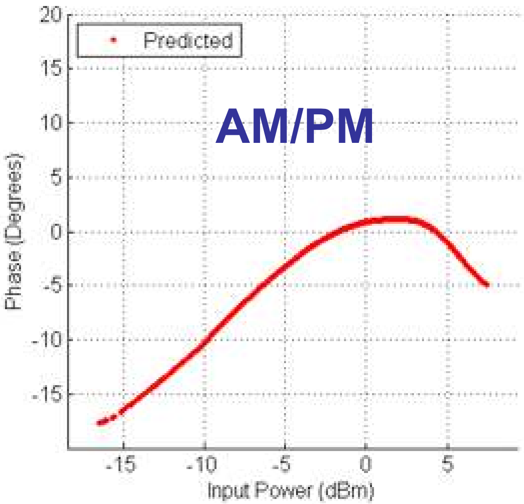
Predicted Performance







Predicted Efficiency = 67.7%

Waveform = HSUPA / 5.4dB PAPR
Shaping = Isogain 24dB

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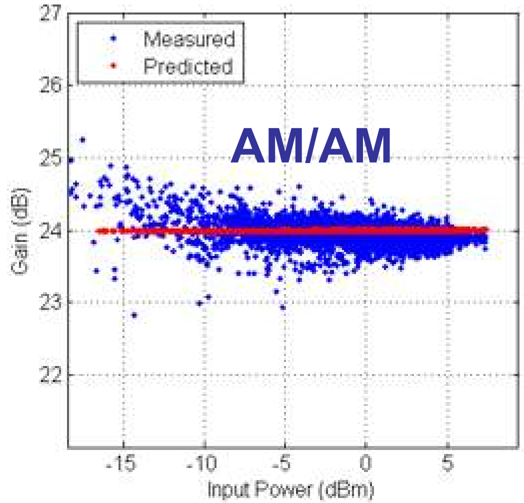
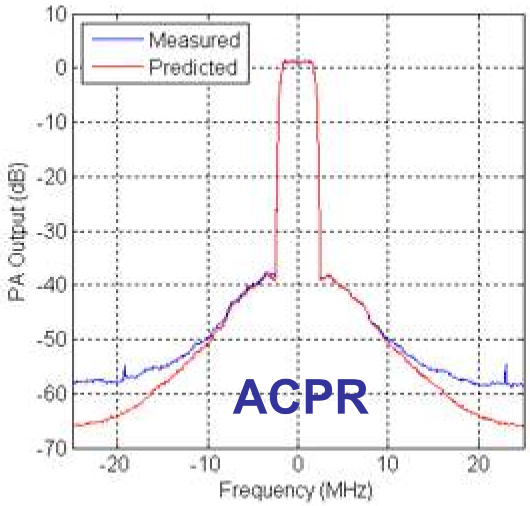
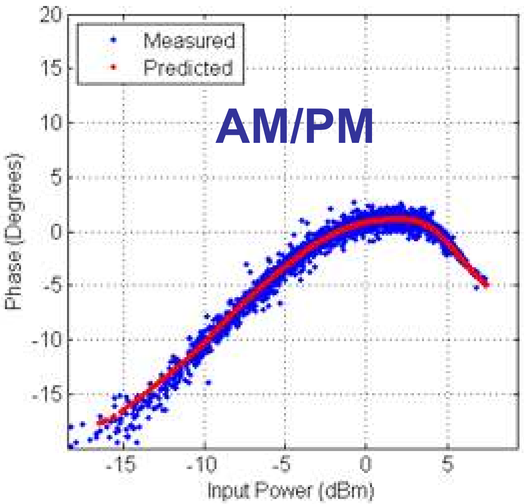
Measured Performance







Predicted Efficiency = 67.7%
Measured Efficiency = 67.6%

Waveform = HSUPA / 5.4dB PAPR
Shaping = Isogain 24dB

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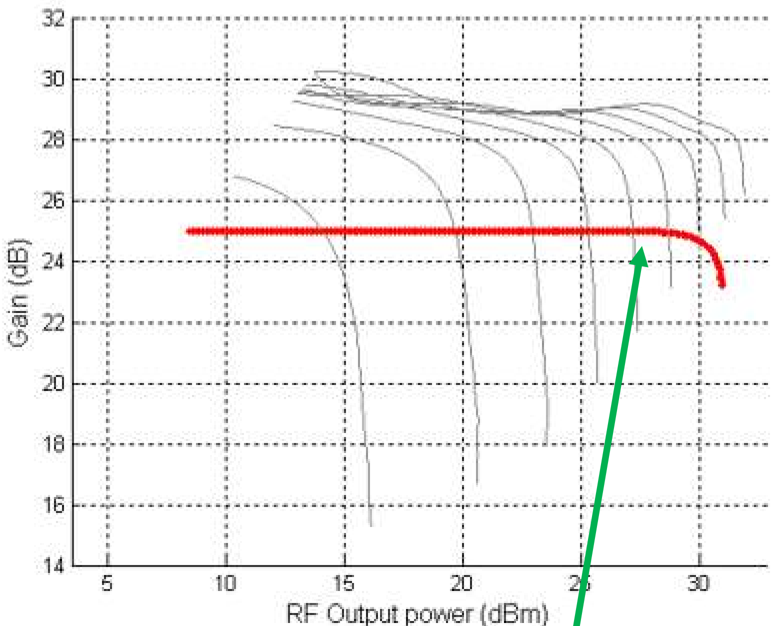
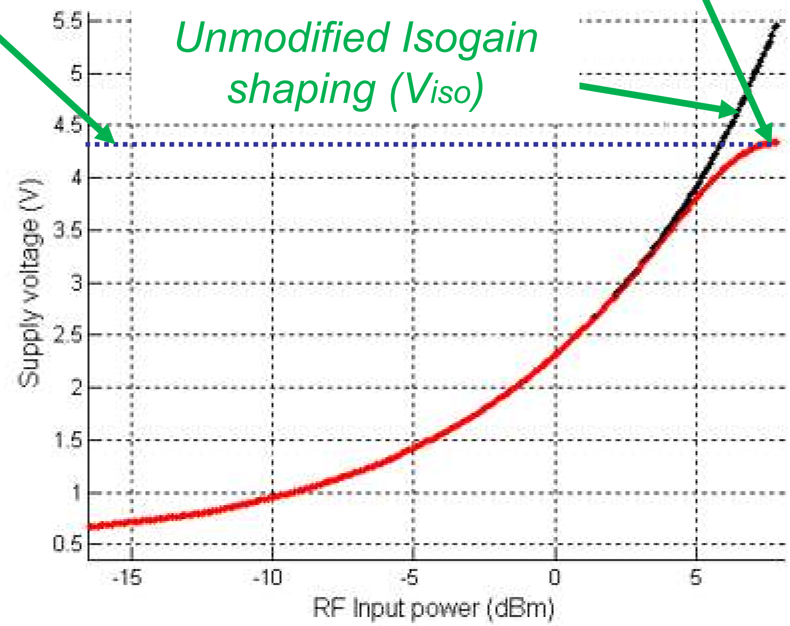
Shaping Table based CFR

Envelope Amplifier Max Vout

Isogain shaping modified to introduce soft clipping e.g using 'Rapp' function (V_{CFR})





Unmodified Isogain shaping (V_{iso})

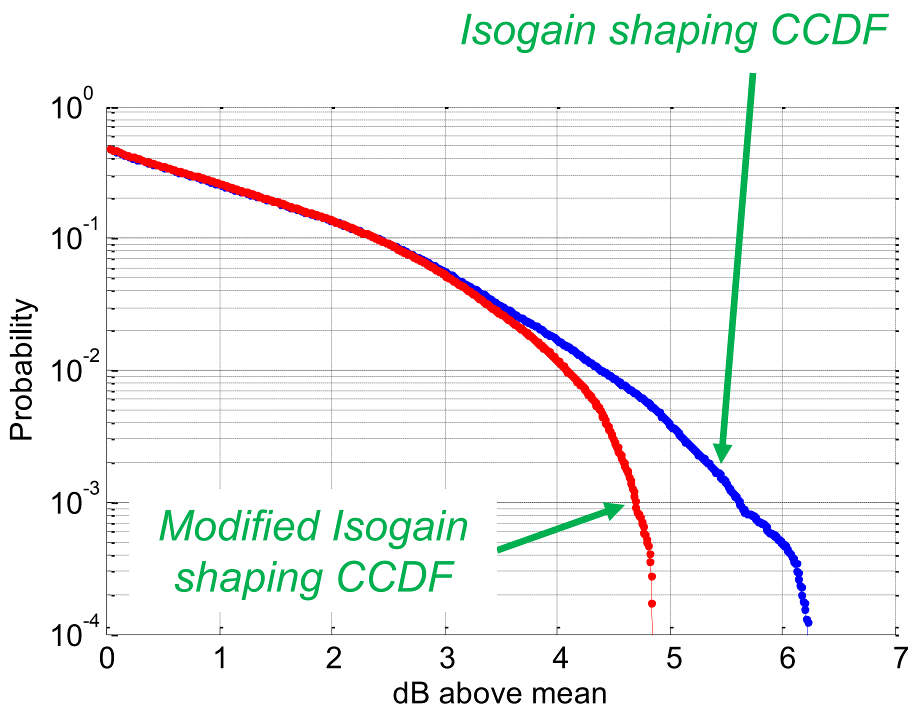
Desired PA gain profile

$$V_{CFR} = \frac{V_{iso}}{\left(1 + \left(\frac{V_{iso}}{V_{pk}}\right)^{p}\right)^{\frac{1}{p}}}$$

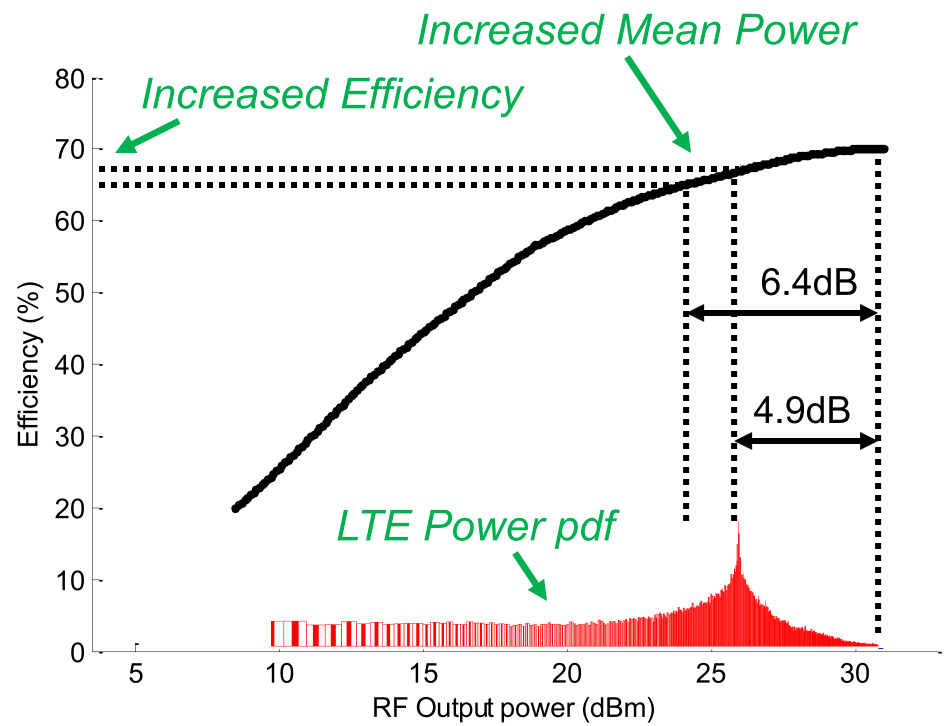
$p = \text{Smoothness factor}$

$V_{pk} = \text{Limiting voltage}$

Increased Pout using CFR

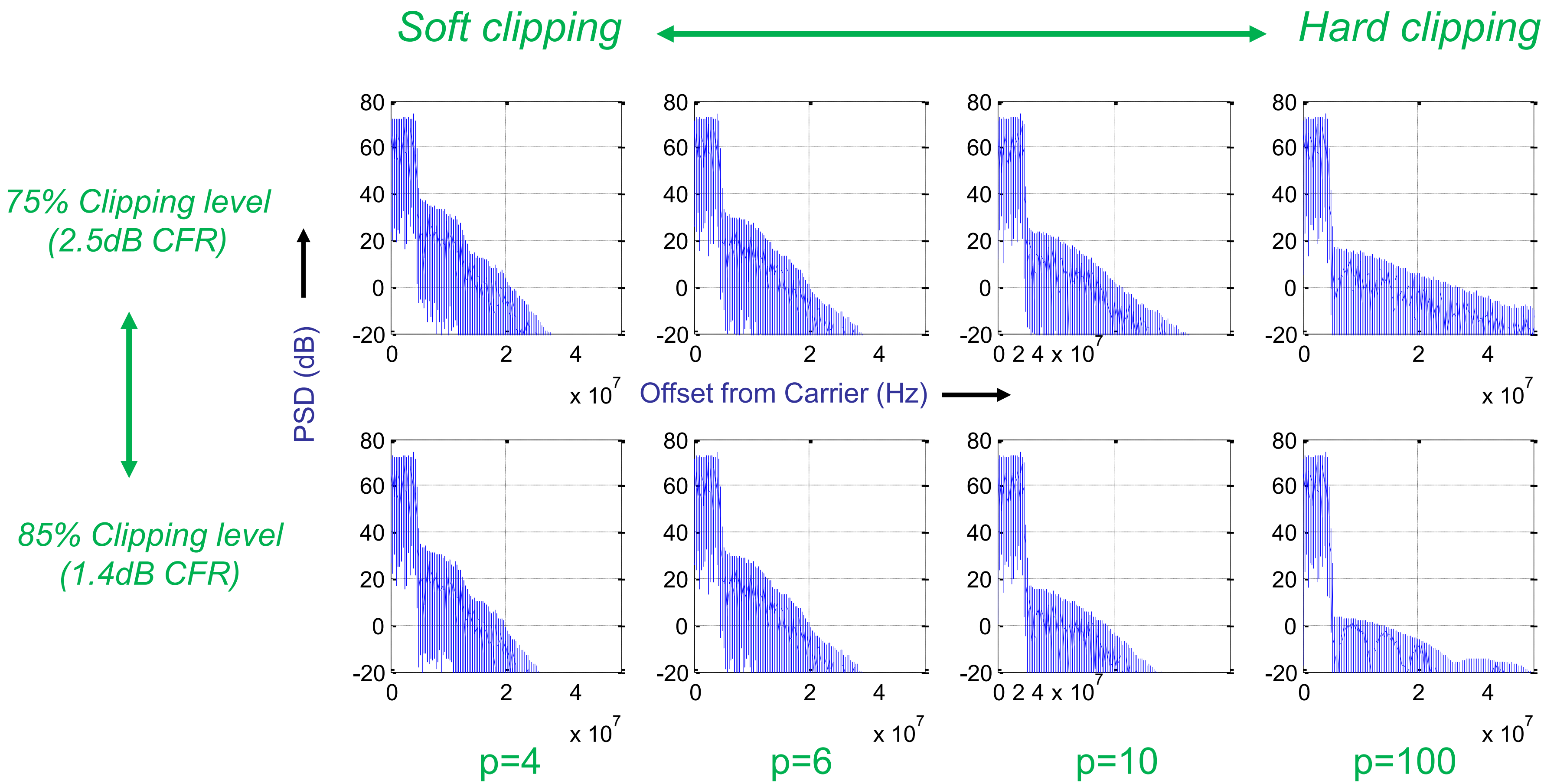


Output Signal Statistics



Controlled use of CFR allows Increased mean power and efficiency for given PA device periphery

'Software Defined PA'
RF Spectrum



Shaping Table based CFR allows dynamic configuration of PA's Power / ACPR / Efficiency characteristics

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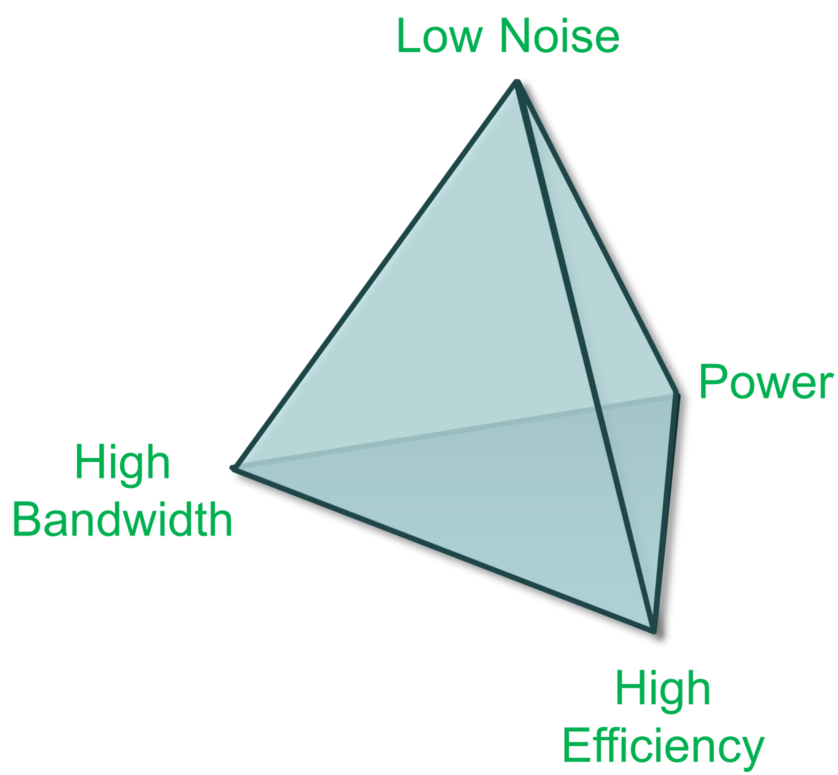
  - CFR shaping
- Envelope Amplifier Design Requirements
  - Sources of Impairment
  - Integrated Modulator
  - Distributed Modulator

Envelope Amplifier Requirements



High Bandwidth

(e.g 4ch WCDMA, 20MHz LTE, 2x 10MHz WiMAX)

- Envelope Bandwidth ~3x RF Bandwidth
- Cannot be achieved with 'switcher only' architecture

Low Noise / Distortion

- Required to meet ACPR specifications
  - Many factors to consider
  - Requires high Tracking Accuracy

High Efficiency

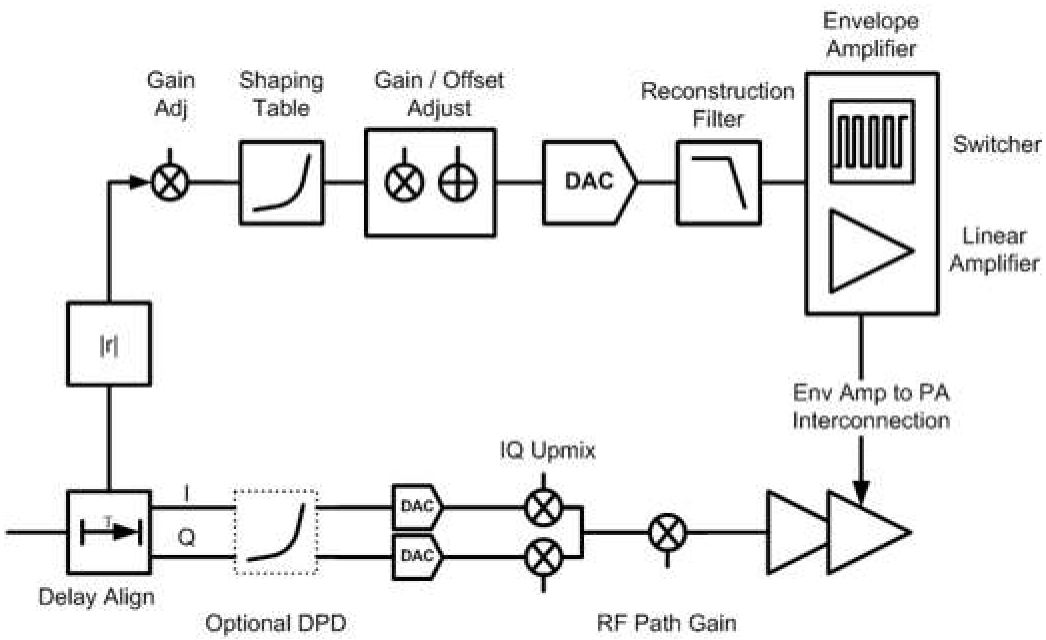
- Must consider combined PA / modulator efficiency
- Linear supply would be pointless

Power

- Must maintain BW and Noise at increased power levels

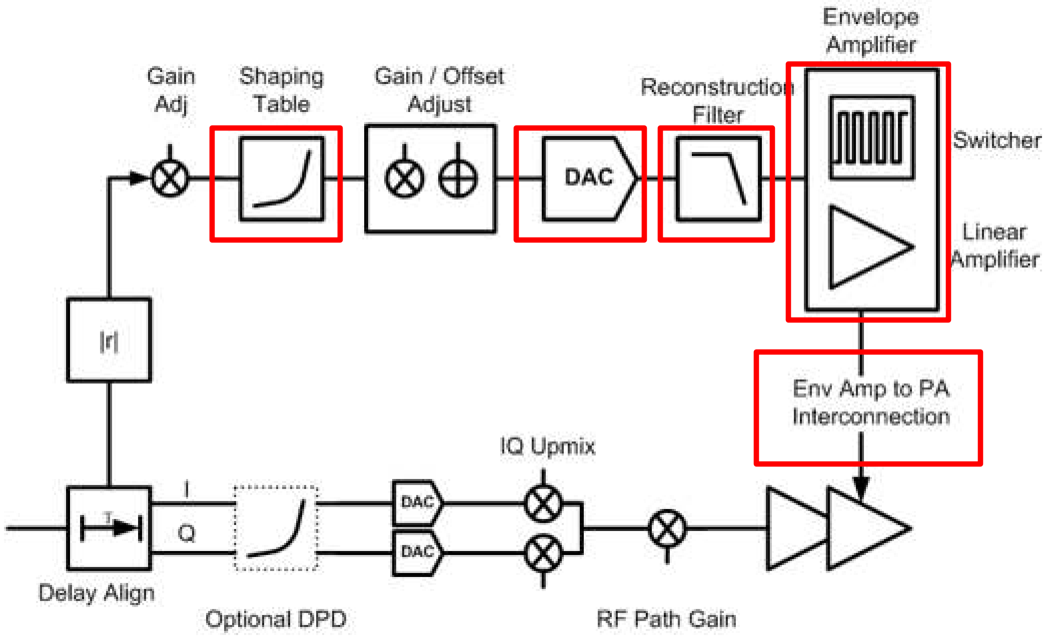
ET Impairment Categories

- System (Env & RF paths)
  - RF/Env Delay match
  - RF/Env Gain match
  - PA AM/AM and AM/PM
- RF Path
  - Noise
    - Thermal
    - Quantisation
  - Linearity
  - PA Memory effects
    - Bias
    - Thermal
- Envelope Path



Envelope Path Impairments

- Shaping Accuracy
- Tracking Accuracy
  - Noise
    - DAC Quantisation
    - Env Amp Thermal
    - Switcher breakthrough
    - Linear Amp PSRR
  - Frequency Response
    - Amplitude
    - Group Delay flatness
  - Env Amp Distortion
    - Harmonic
    - Crossover
  - Env Amp to PA Interaction
    - Env Amp Output Impedance
    - PA Interconnect Impedance
    - PA Non Linear Load Impedance



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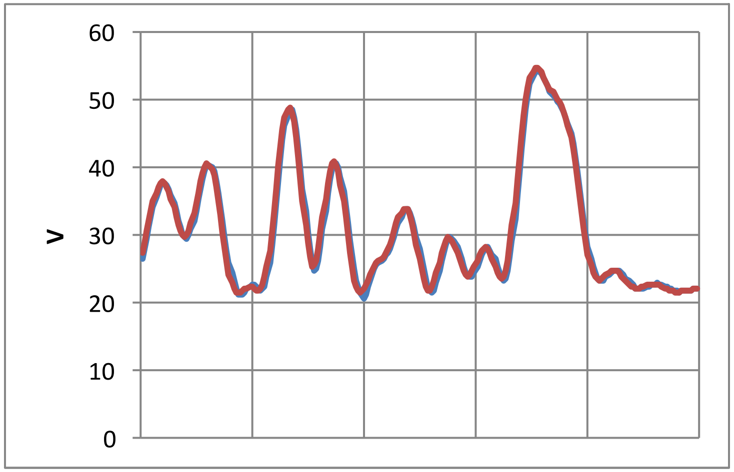
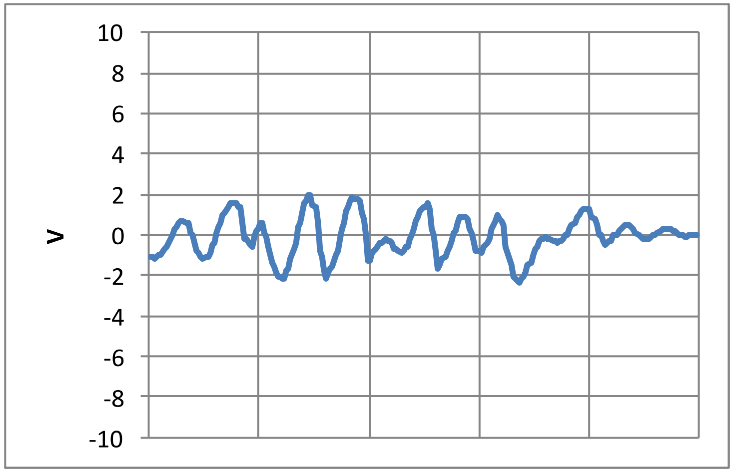
Tracking Accuracy Explained

- The difference between ideal and measured supply waveform after removal of DC offset, gain and timing errors
- Analogous to EVM for modulated signals
    - Tracking error analysis is useful diagnostic tool: RMS, Peak, Spectrum

Residual modulator tracking error



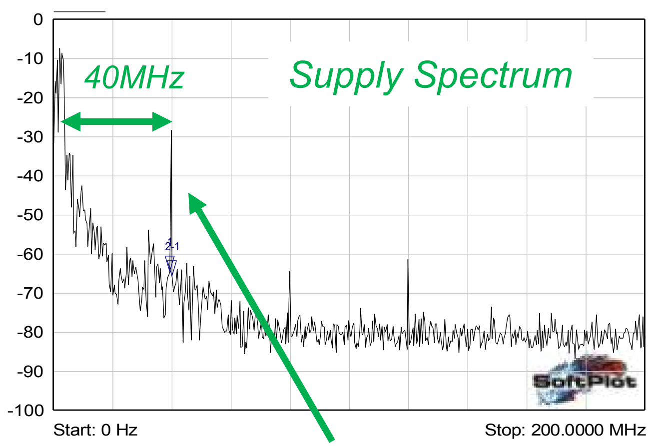
Ideal and measured waveforms



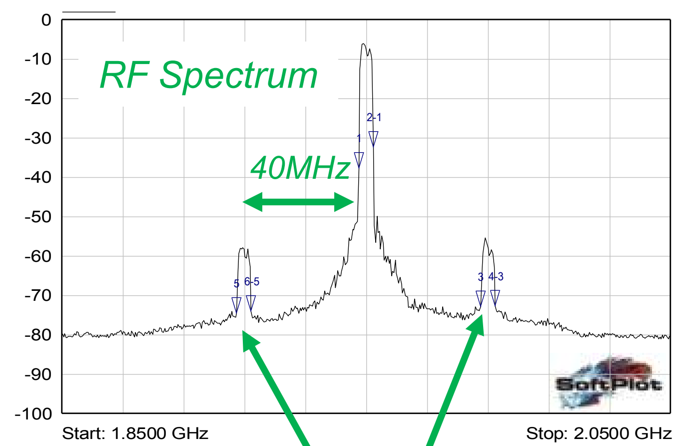
Tracking Error

Supply 'Noise' – RF Conversion

- PA in compression – Supply Noise & Distortion modulates RF carrier
- PA can be considered as mixer
  - O/P spectrum is convolution of Supply and PA input Spectra
- Conversion factor (Supply Sensitivity) for noise on supply to RF sidebands is similar to ideal AM modulator (mixer)



40MHz 'test tone' added to Envelope Amplifier O/P (whilst amplifying 5MHz WCDMA signal)



Corresponding RF sidebands

Measured Supply Sensitivity

An ideal AM modulator is described by: $y(t) = [A + M\cos(\omega_m t)]\sin(\omega_c t)$

where modulation index $h = \frac{M}{A}$

This can be re-expressed in terms of carrier and LSB and USB components

$$y(t) = A\sin(\omega_c t) + R[\sin((\omega_c + \omega_m)t) + \sin((\omega_c - \omega_m)t)]$$

where for an ideal AM modulator $R = \frac{M}{2}$

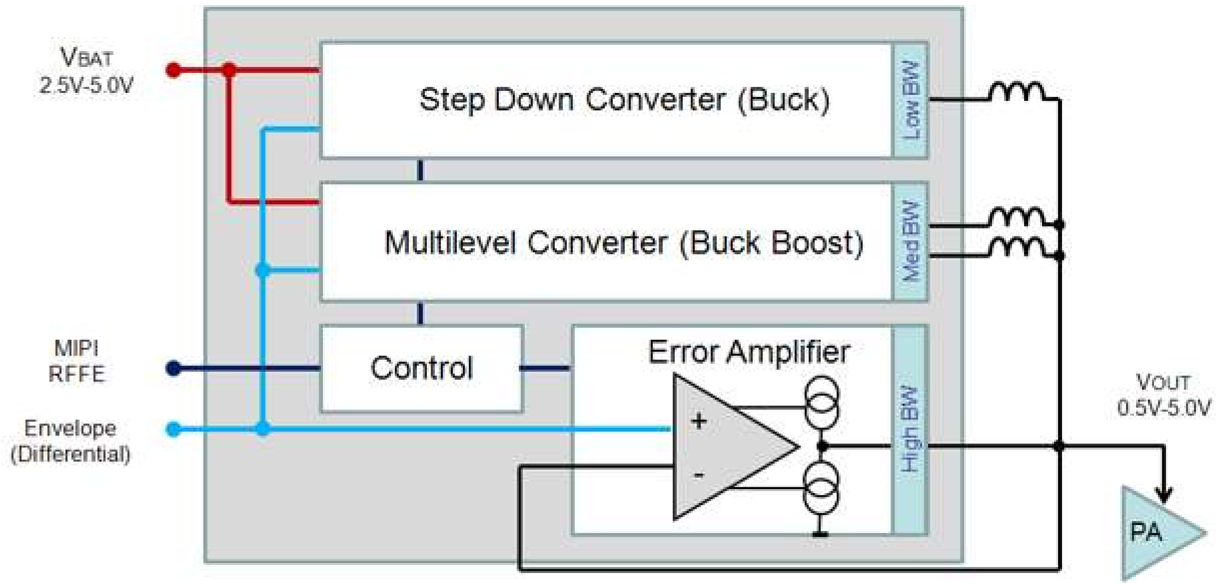
Average DC drain voltage	2.62V
Measured 40MHz injected tone level	17.3mV rms
Calculated RF sideband level for ideal AM modulator	-49.6dBC
Measured RF sideband level	-51dBC
PA Supply Sensitivity (dB)	-1.4dB
PA Supply Sensitivity (%)	85%

$\frac{\Delta V_{env}}{V_{env}}$ (first two rows)

$\frac{\Delta V_{rf}}{V_{rf}}$ (measured RF sideband level)

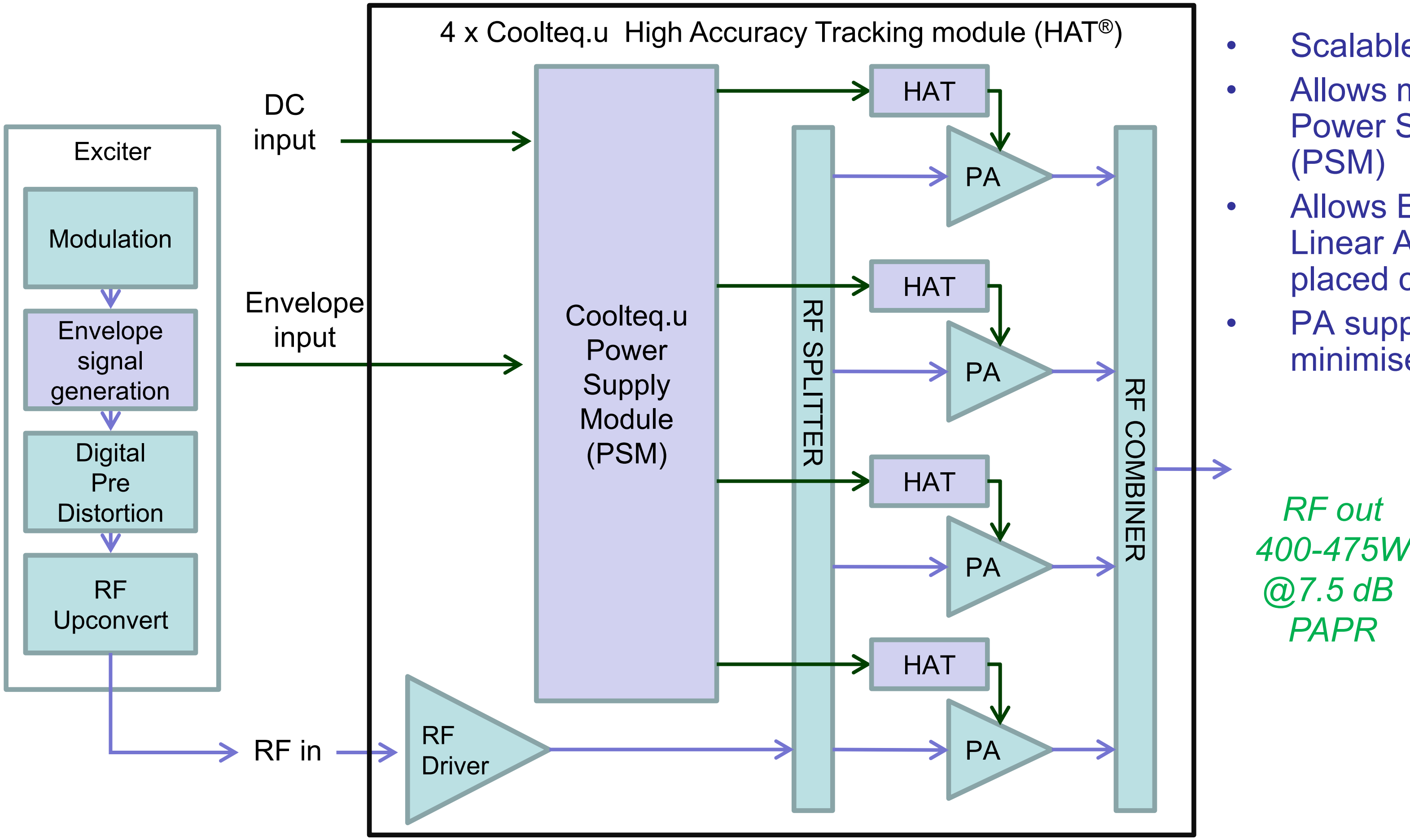
$\frac{\Delta V_{rf} / V_{rf}}{\Delta V_{env} / V_{env}}$ (PA supply sensitivity)

Integrated Modulator Example –Coolteq.L



- Boost and Buck capable
  - Battery depletion resilience
  - Increased PA peak Power
- Slow switching Buck converter provides LF power
- Fast switching multilevel converter provides HF power
- Error Amplifier ‘cleans up’ output

Distributed Modulator Example - Coolteq.u



- Scalable O/P Power
- Allows multiple PAs per Power Supply Module (PSM)
- Allows Envelope path Linear Amplifier to be placed close to PA
- PA supply impedance minimised

Conclusions

- Understanding of PA characteristics key to achieving good ET performance.
- Careful selection of shaping table contents allows optimisation key ET system performance metrics
- ET is a simple concept, but attention must be paid to multiple potential sources of impairment to realise full potential

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