Intelligent Transmitters and Power Amplifiers for Next Generation Wireless Communications

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RADIO & DIGITAL DESIGN

Outline

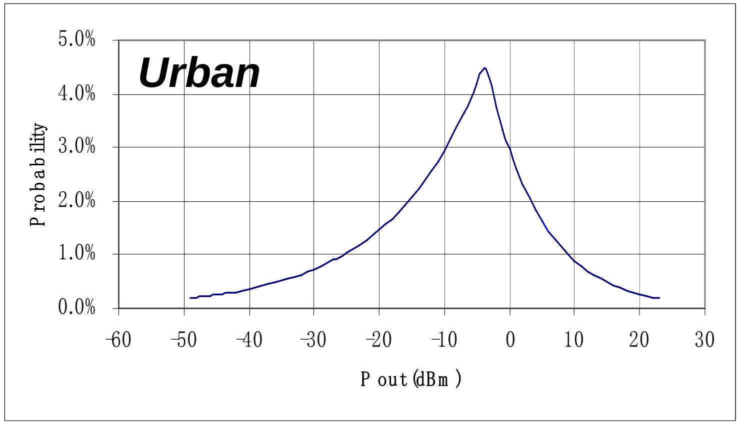
- ***Overview of Wireless Standards***
- ***Power Supply Modulation Techniques***
- ***System Limitations and Design Considerations of Power supply Modulation Approaches***
- ***Examples of Power Supply Modulation Applications: BiCMOS 2.4 GHz WiFi PA and GaN WCDMA Base Station***

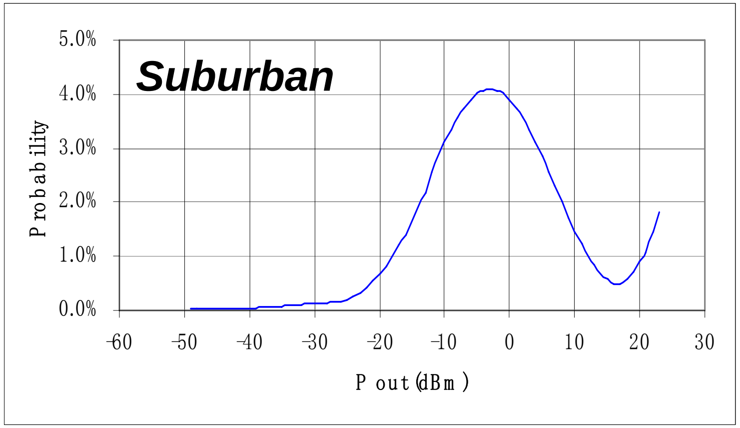
Signal Characteristics of Popular Wireless Standards

System	Peak-Average Ratio (dB)	Peak-Minimum Ratio (dB)	Power Control Dynamic Range (dB)	Bandwidth (MHz)	Access Type
GSM	0	0	30	0.2	TDMA
CDMA 2000	4-9	∞	80	1.25	CDMA
EDGE	3.2	17	30	0.2	TDMA
CDMA ONE	5.5-12	∞	73	1.25	CDMA
UMTS	3.5-7	∞	80	5	CDMA
WiMax	8-10	∞	50	1-20	TDMA
802.11 a/g	8-10	∞	25	20	TDMA

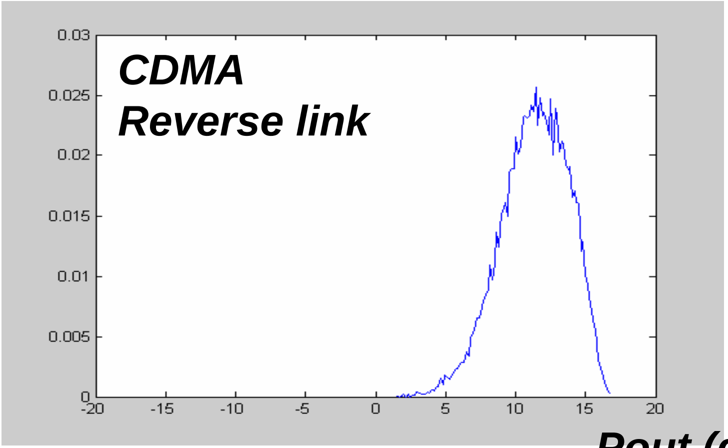
Critical Problem: Power Amplifiers are Efficient Only at Peak Output Power!

***Slow variations*-msec scale**
Fading and changing distance from base station

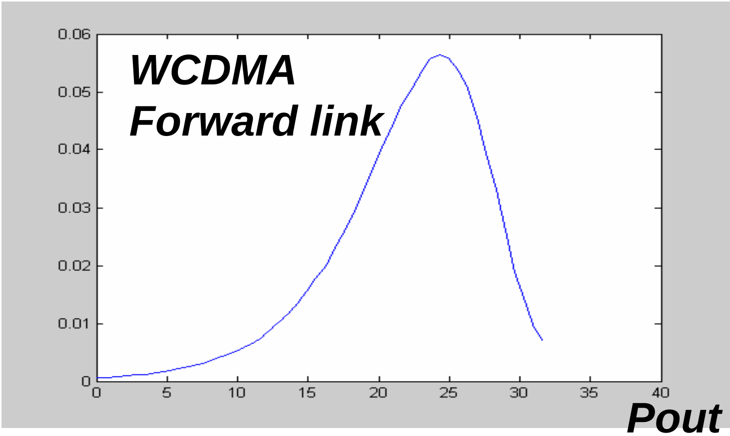




***Fast Variations*-μ sec scale**
Modulation characteristics

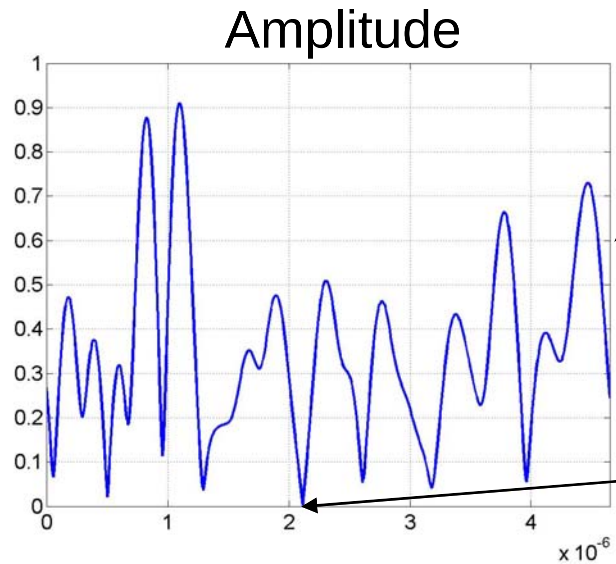


Pout (dBm)



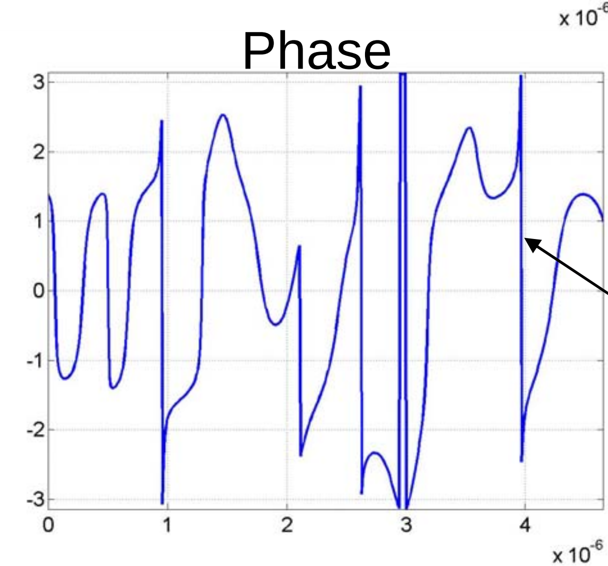
Pout (dBm)

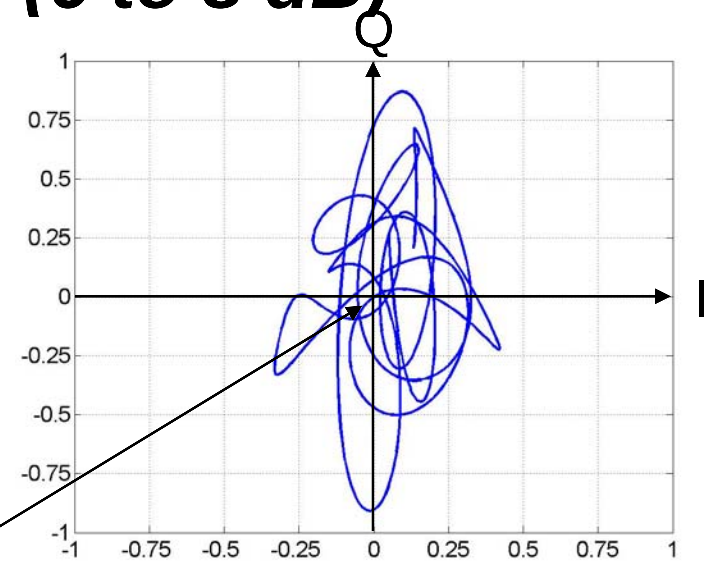
CDMA Base Station Signal Characteristics



High envelope peak factor (6 to 8 dB)

Zero Amplitude

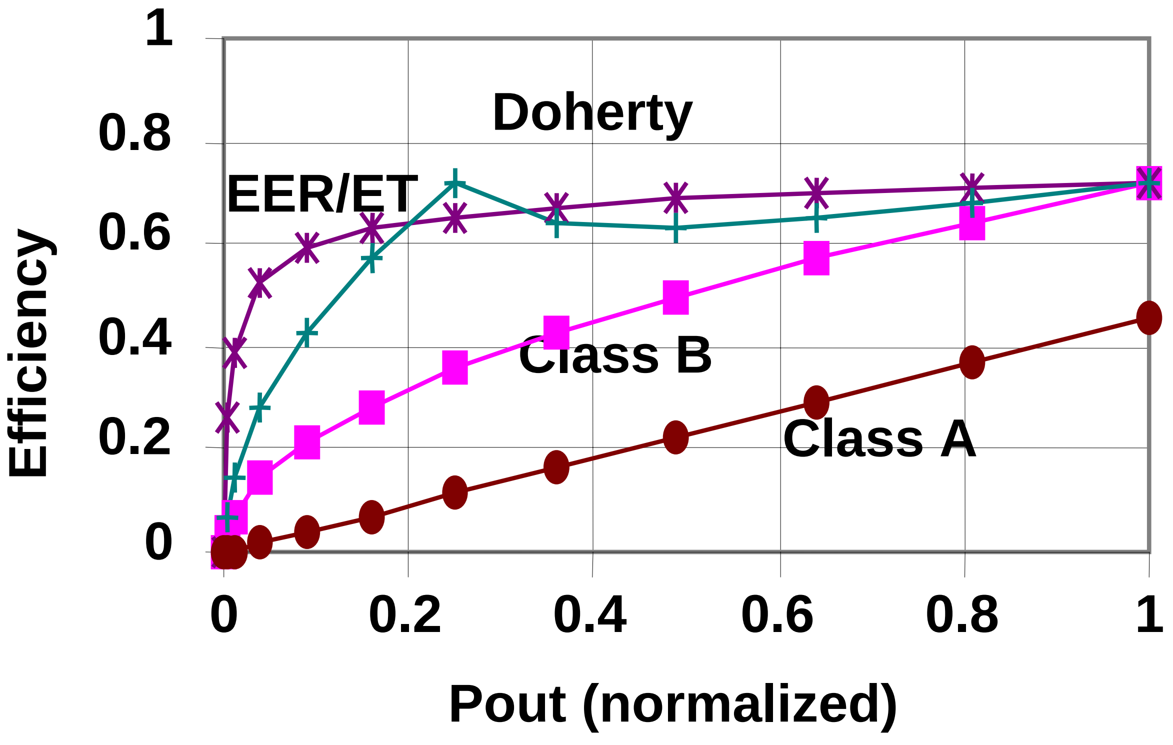




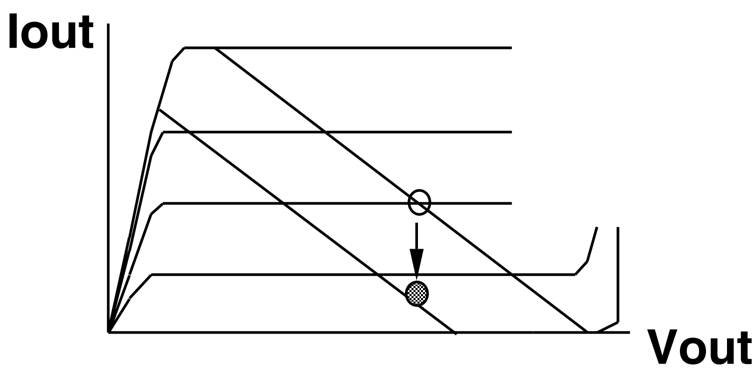
Rapid phase variations when CDMA signal crosses near the origin of the IQ diagram

Amplifier Architectures for Improved Average Efficiency

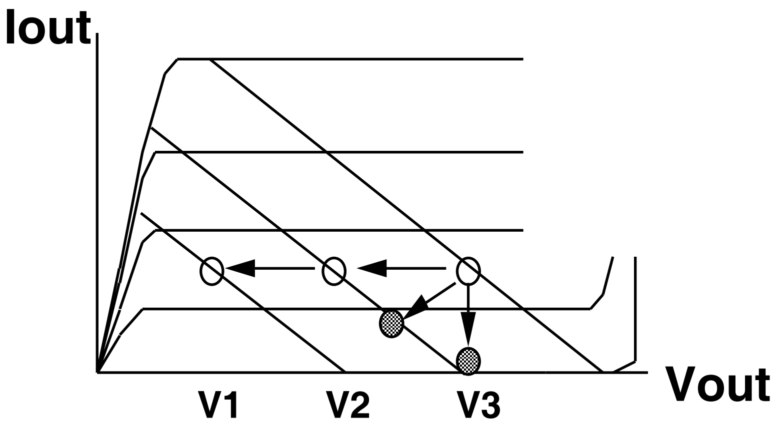
Efficiency averaged over conditions of usage dominated by behavior at *low power*



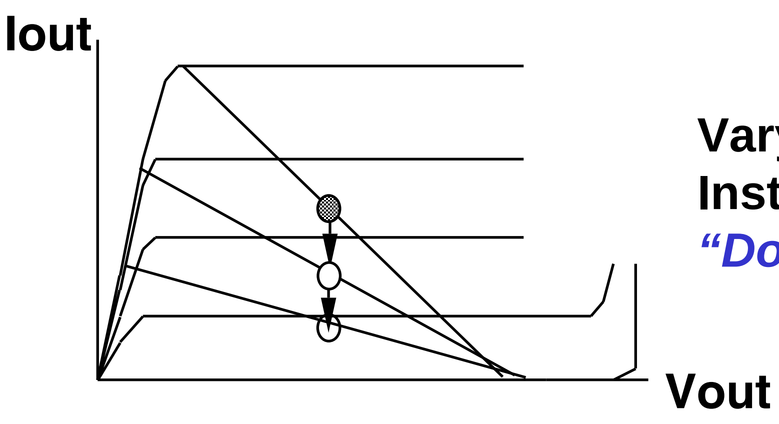
Strategies for Efficiency Improvement Over Wide Power Range



Vary bias current according to Instantaneous power
"Dynamic biasing"

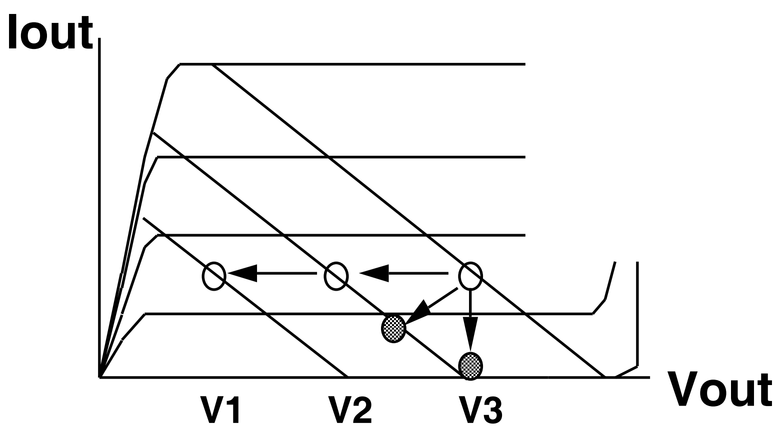


Vary bias current and voltage according to Instantaneous power
"Envelope tracking and EER"

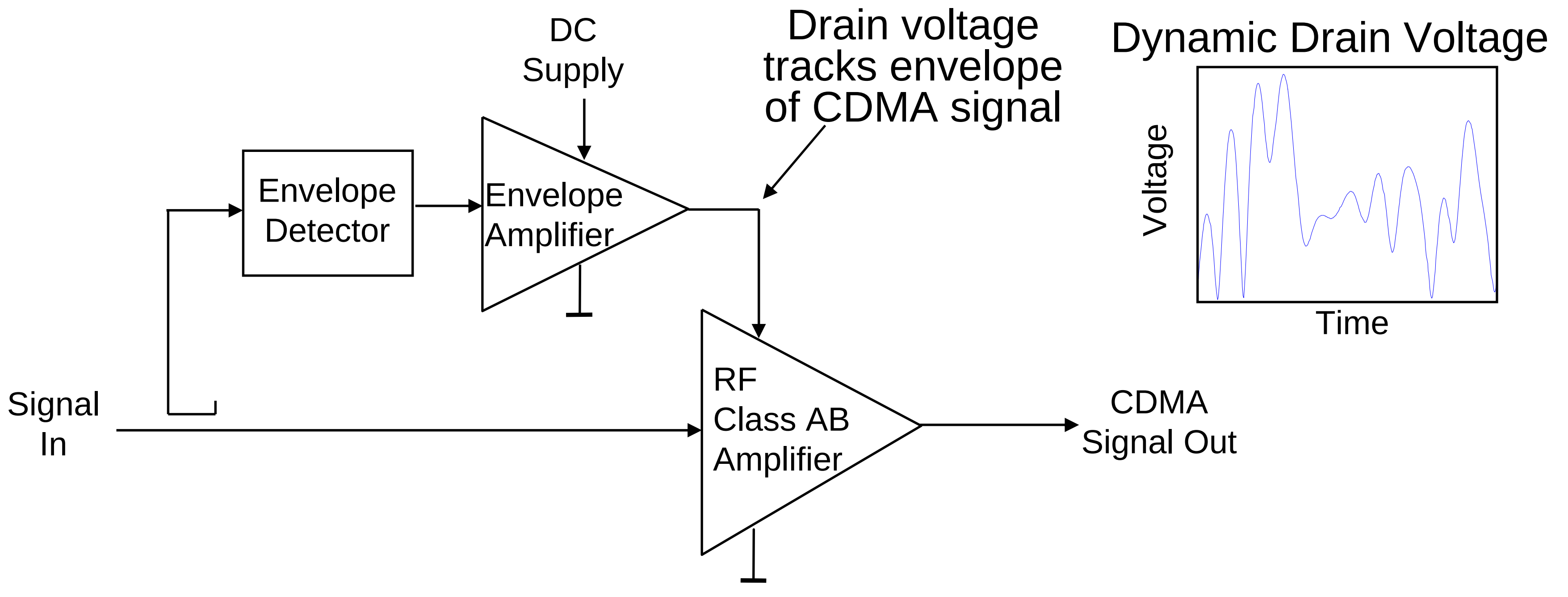


Vary load impedance according to Instantaneous power
"Doherty and Chereix"

Envelope Tracking (ET) Technique

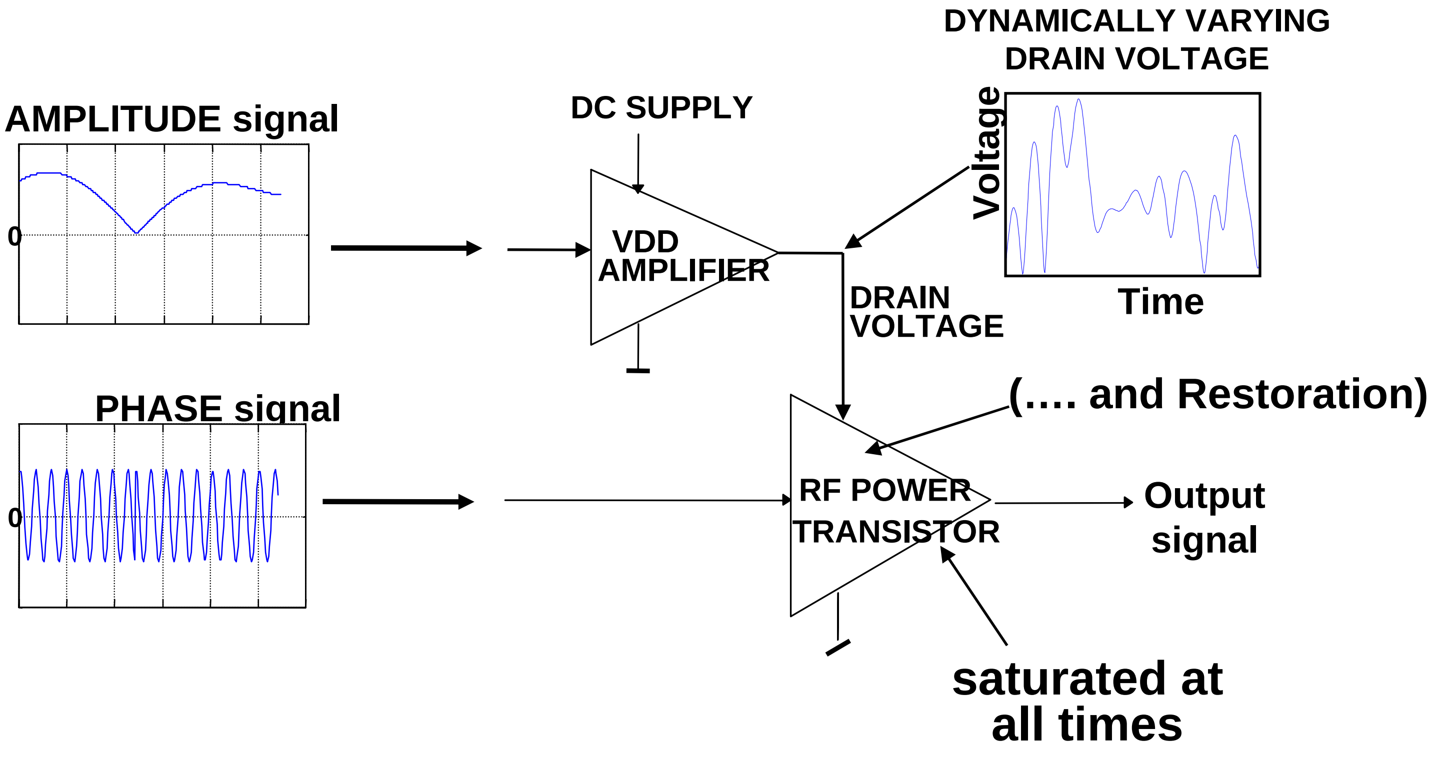


- ***Maximizes PA efficiency by keeping RF transistor closer to saturation for all envelope amplitudes***
- ***Envelope Amplifier provides dynamic drain voltage***



In Envelope Tracking, PA is Class AB.
Input signal contains envelope and phase information.

Envelope Elimination and Restoration (EER) Technique

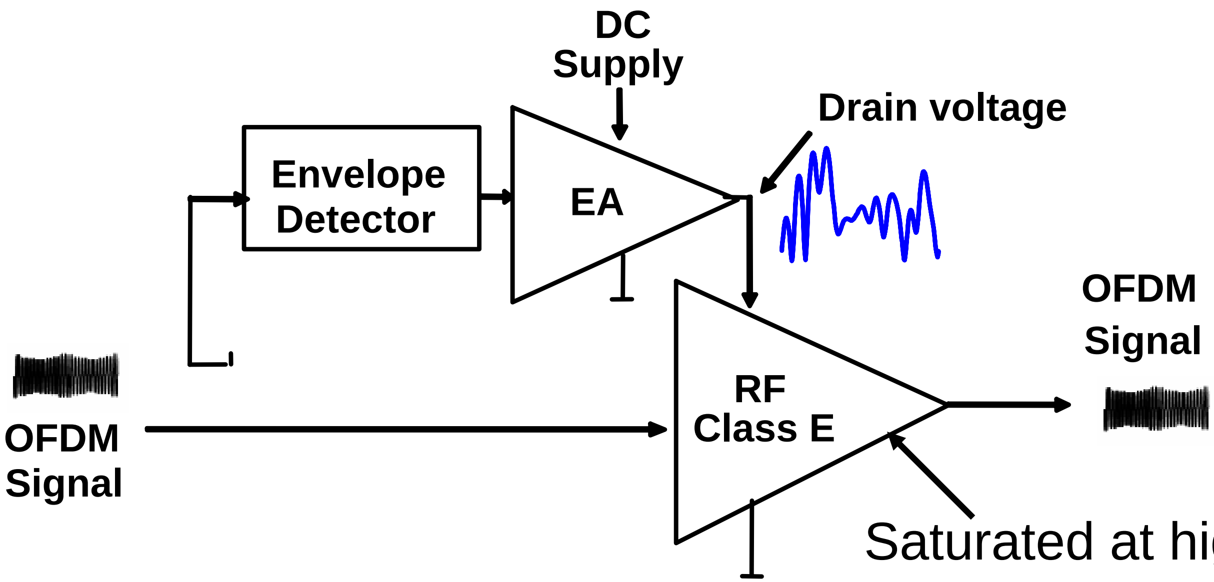


- ***Maximizes PA efficiency by keeping RF transistor in switching mode (saturation) for all envelope amplitudes***
- ***Envelope Amplifier provides exact amplitude information and re-modulated to RF phase signal at the RF PA***

Comparison Between EER and ET

	EER	ET
Efficiency	Highest	High
Envelope Path Bandwidth	Wider than Baseband	Wider than Baseband
RF Path Bandwidth	Much Wider than RF BW	Same as RF BW
Time Calibration	Very precise time alignment	Modest time alignment

"Hybrid" WBEER Technology



Saturated at high output power
Nearly saturated at low output power

Benefits of envelope in the RF input signal: (vs. classical EER)

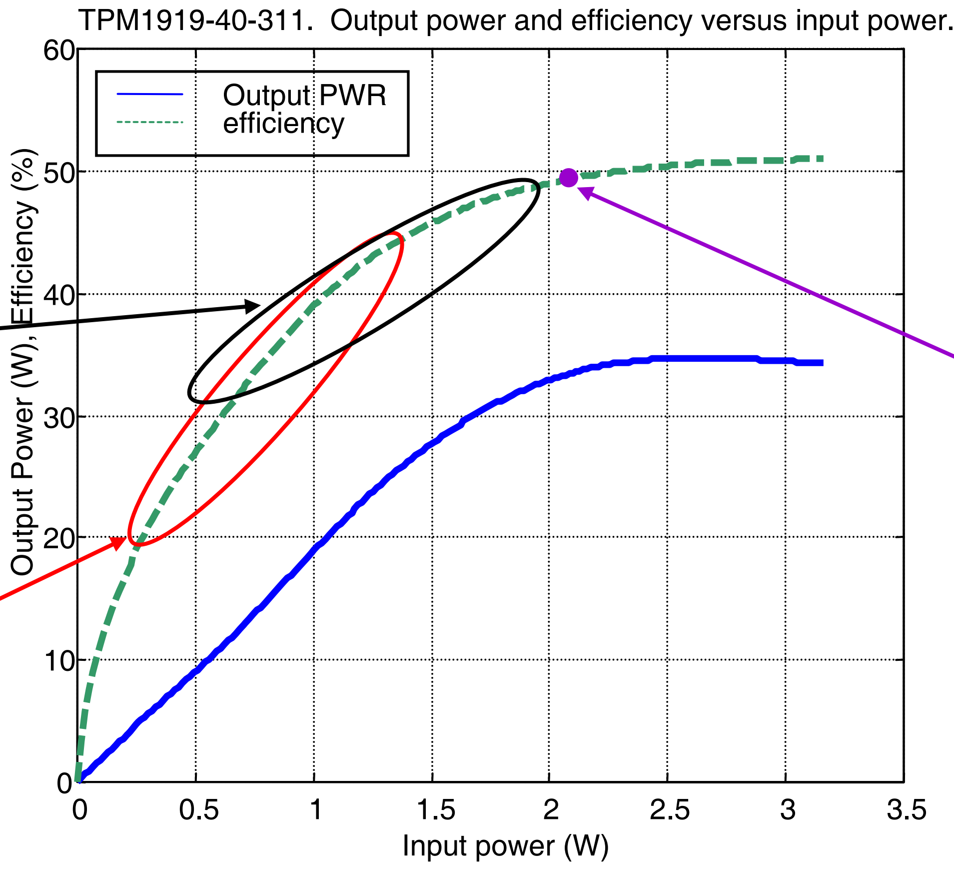
1. Higher gain at low output power;
2. Narrower bandwidth requirement for envelope amplifier;
3. Lower sensitivity to time-mismatch;
4. Lower bandwidth requirement for RF path
   – no limiter required, or narrow bandwidth of the DAC

Why Does EER/ET Improve Efficiency?

- ***RF Transistors achieve maximum efficiency when their output power is saturated:***

ET Operating Range

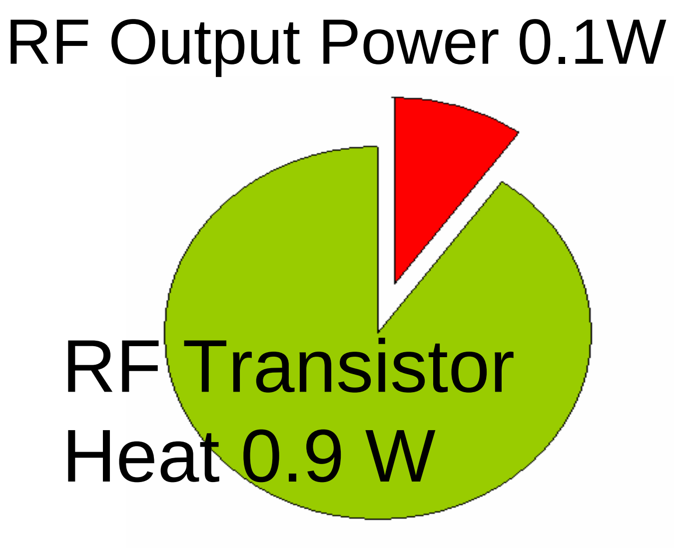
Traditional PA Operating Range



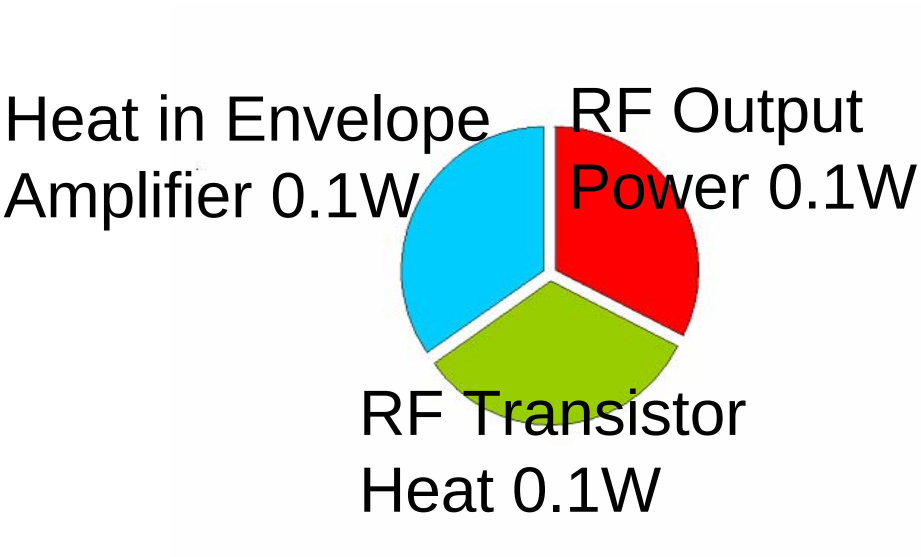
PD + EER Operating Point

Motivation of EER/ET PA – Improve Transmitter Efficiency

OFDM 802.11g signal : PAR: 9~10 dB, BW = 20MHz.



10% Class AB PA

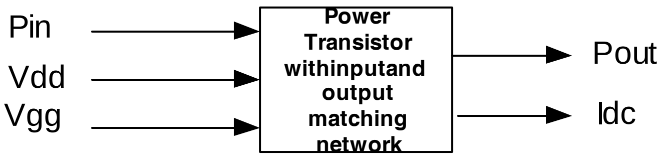


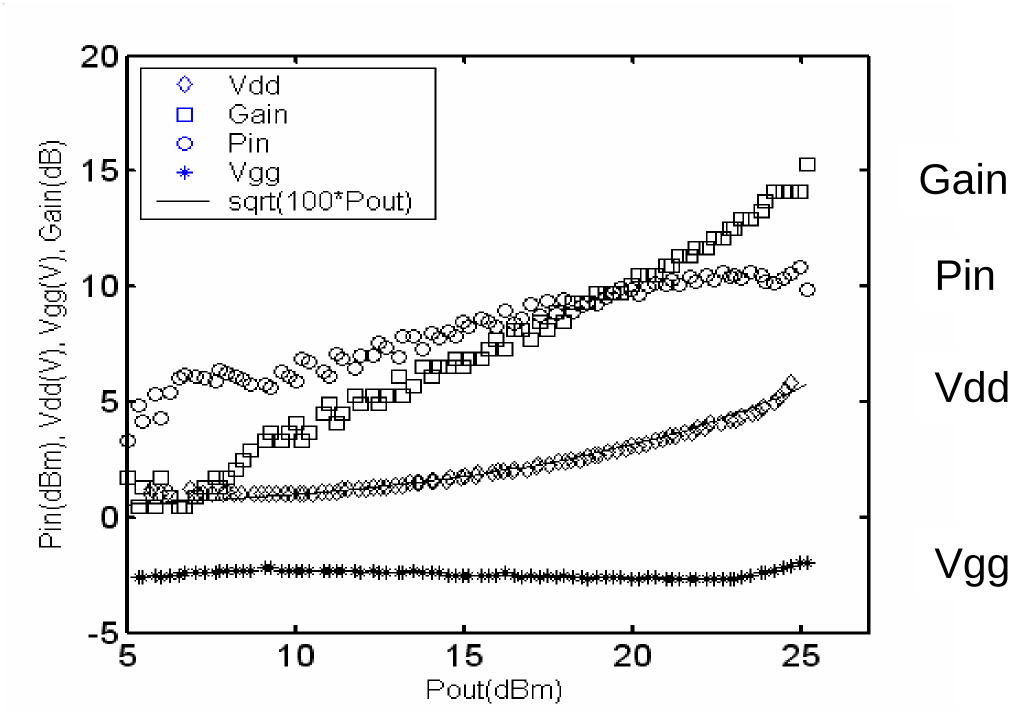
30% EER PA

- High overall efficiency improves battery life
- High drain efficiency improves RF transistor life

Black Box Model of ET/EER PA

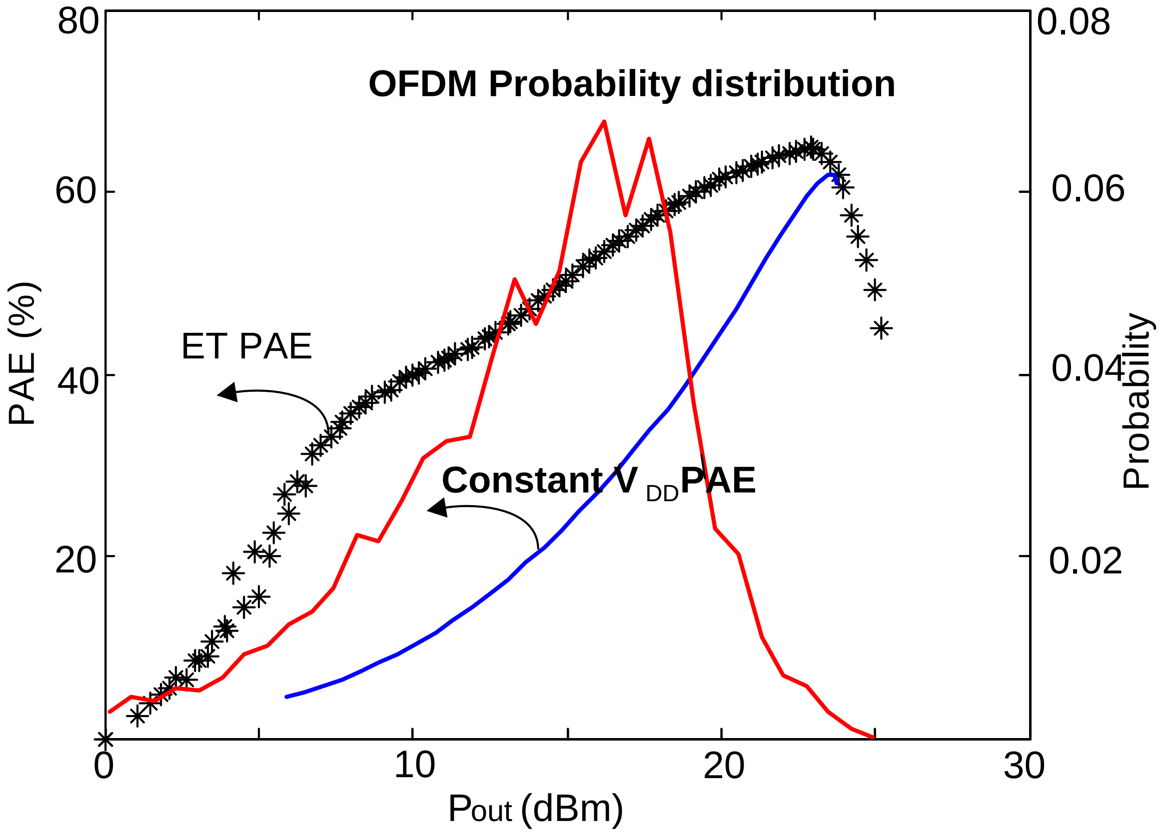
Pout = f1 (Pin, Vdd, Vgg)
Idc = f2 (Pin, Vdd, Vgg)





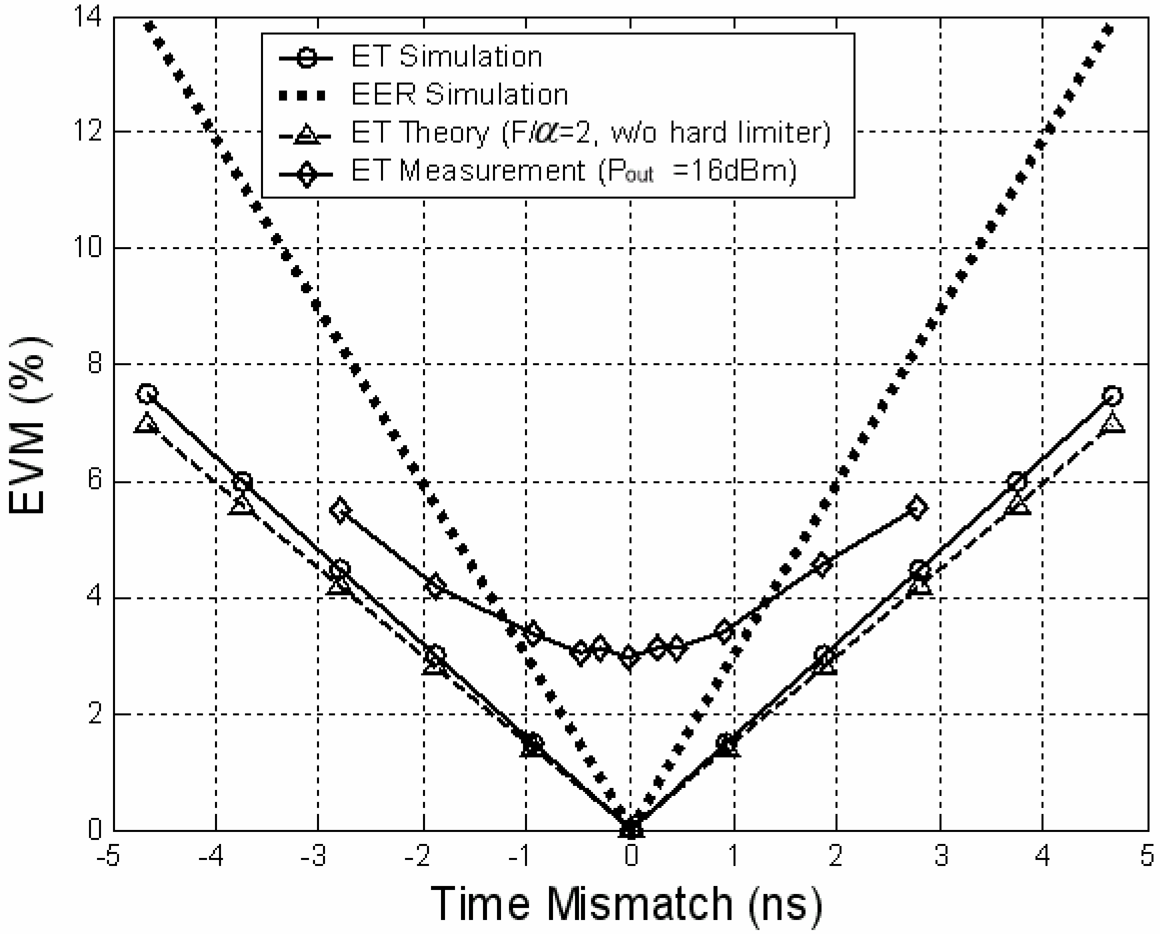
Measured Results: Adjust the independent controllable variables of Pin, Vdd, and Vgg to get the **highest PAE** at each point of the output power

Envelope Tracking vs. Class-AB



High average efficiency over a wide range of output power for ET**.**
ADS simulation, Class AB PA is GaAs MESFET transistor.

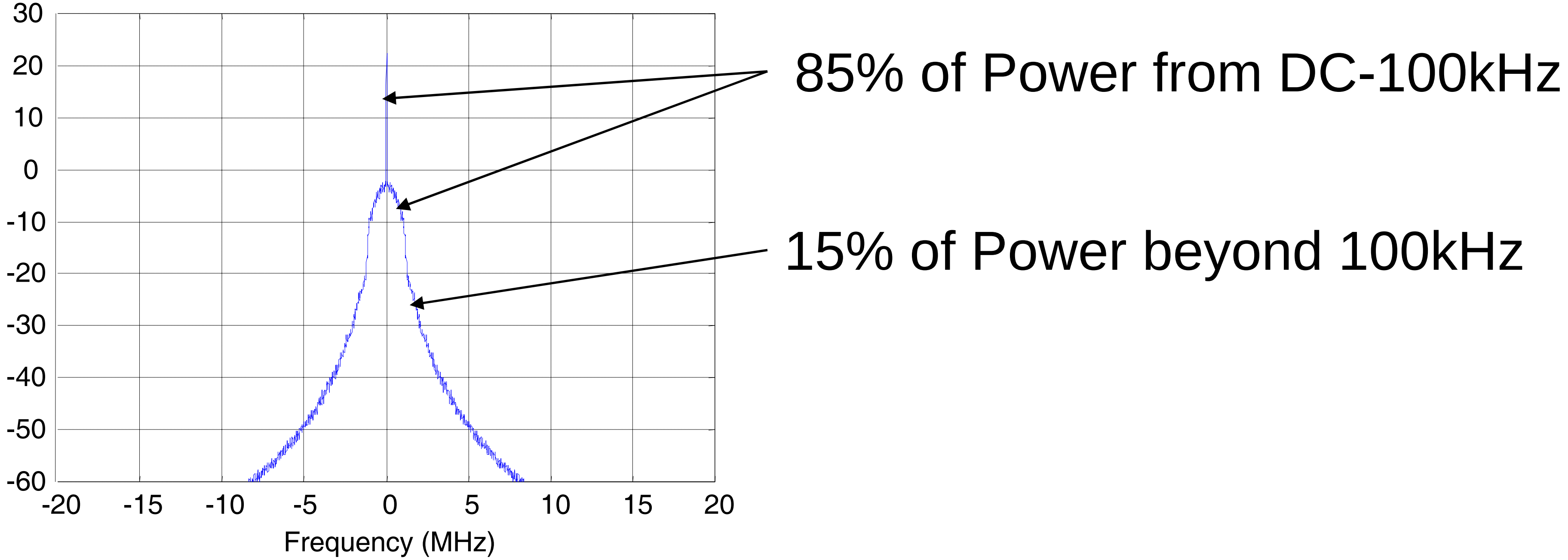
EER Is More Sensitive to Time Mismatch than ET



- Theory, simulation, and measurement agree with well.

Envelope Amplifier

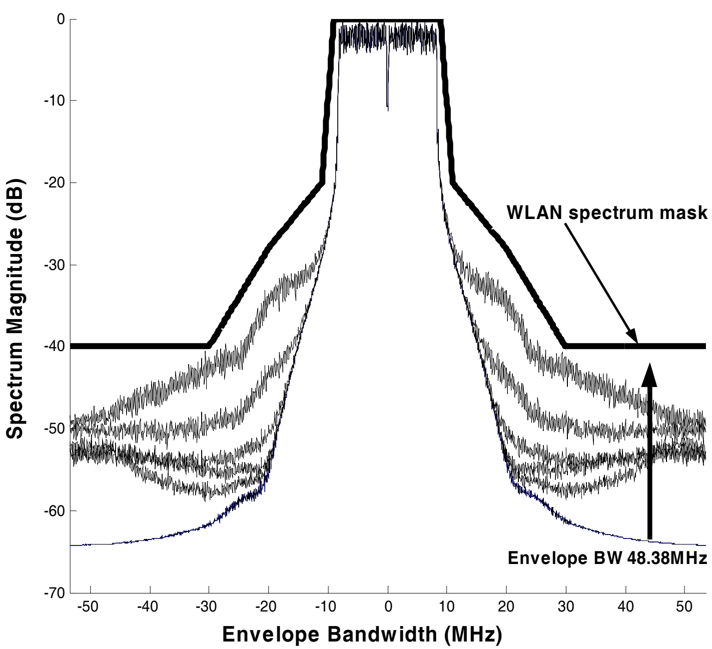
- ***Envelope Signal Power Spectral Density, IS-95 signal***



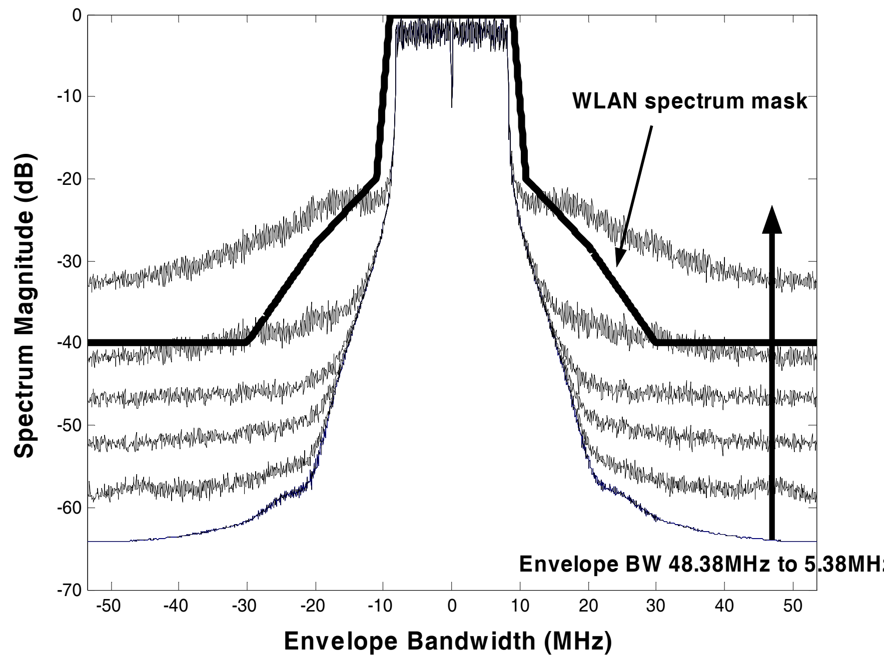
- ***Amplitude Spectrum Suggests Design Topology***
  - ***Supply DC and low frequency power from a very efficient source***
  - ***Supply high frequency power from a high fidelity source***

Wideband High-Efficiency Envelope Amplifier

ET Amplifier Requirements



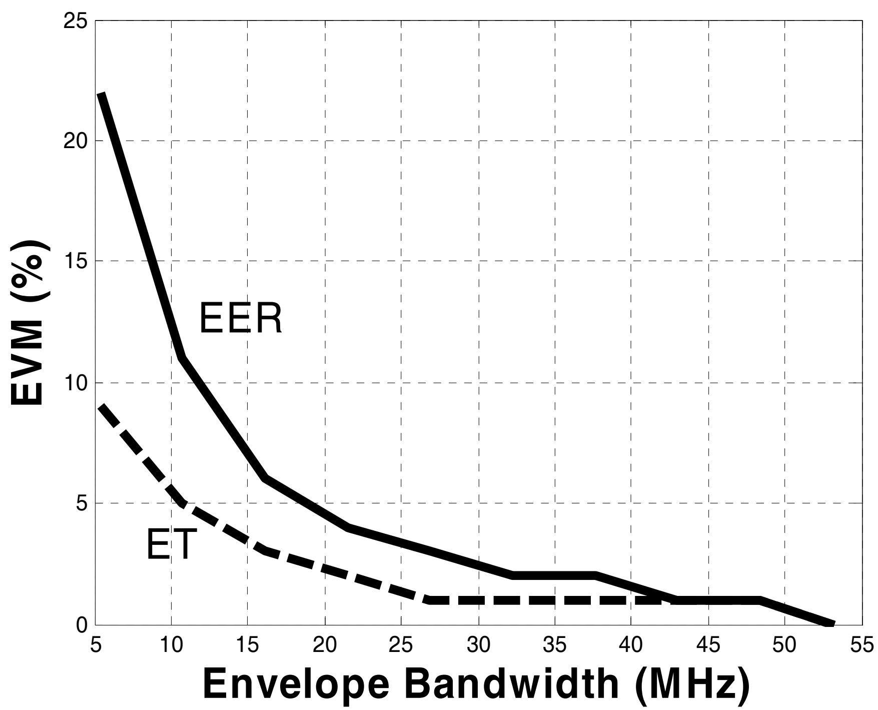
EER Amplifier Requirements



Envelope amplifier bandwidth requirements are more modest for ET amplifiers

Wideband High-Efficiency Envelope Amplifier

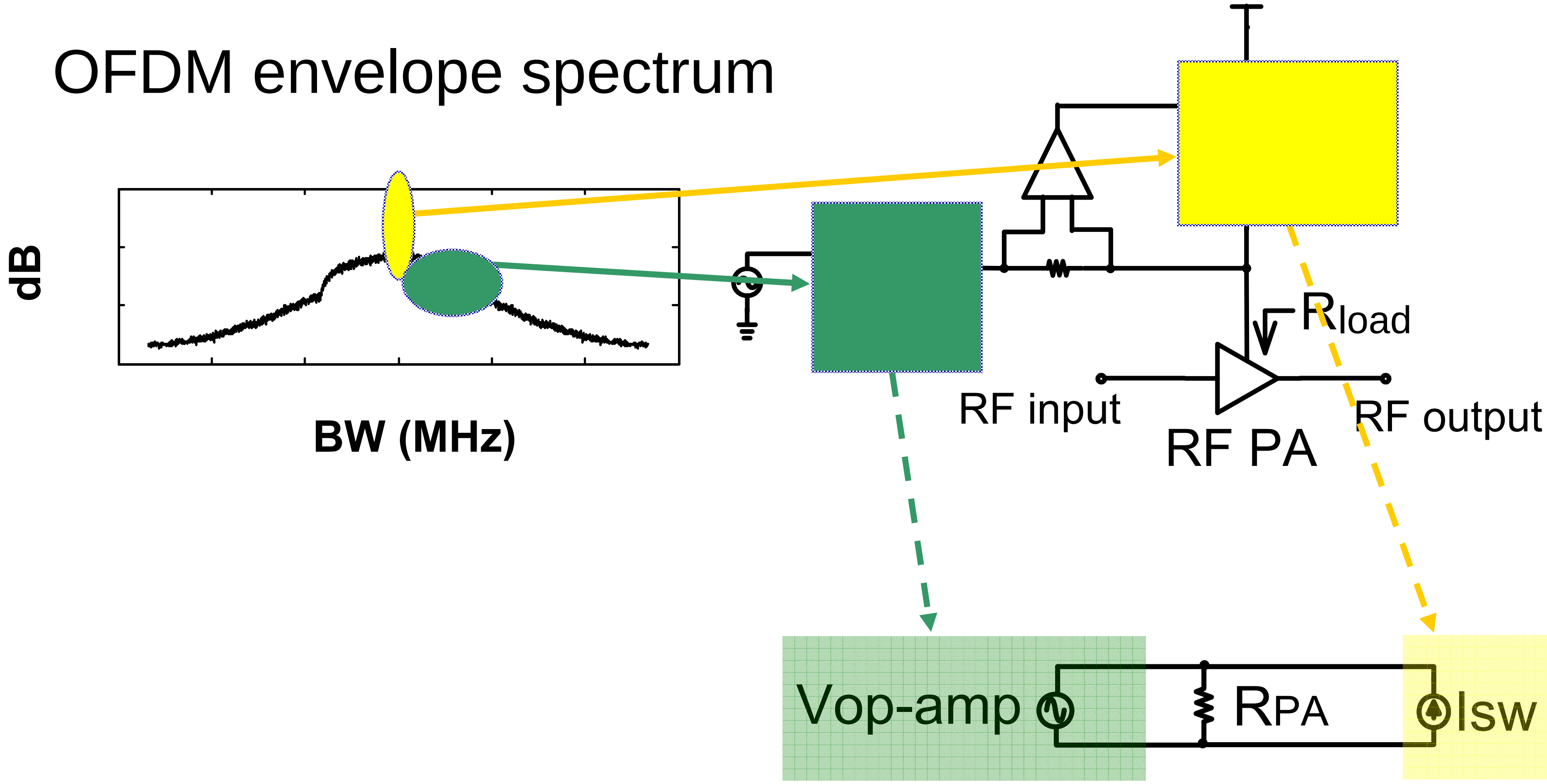
Simulations of ET and EER envelope amplifier BW requirements for 802.11 OFDM Signal



Envelope amplifier bandwidth requirement: 30MHz for EVM < 3%.

Envelope Amplifier Design

OFDM envelope spectrum



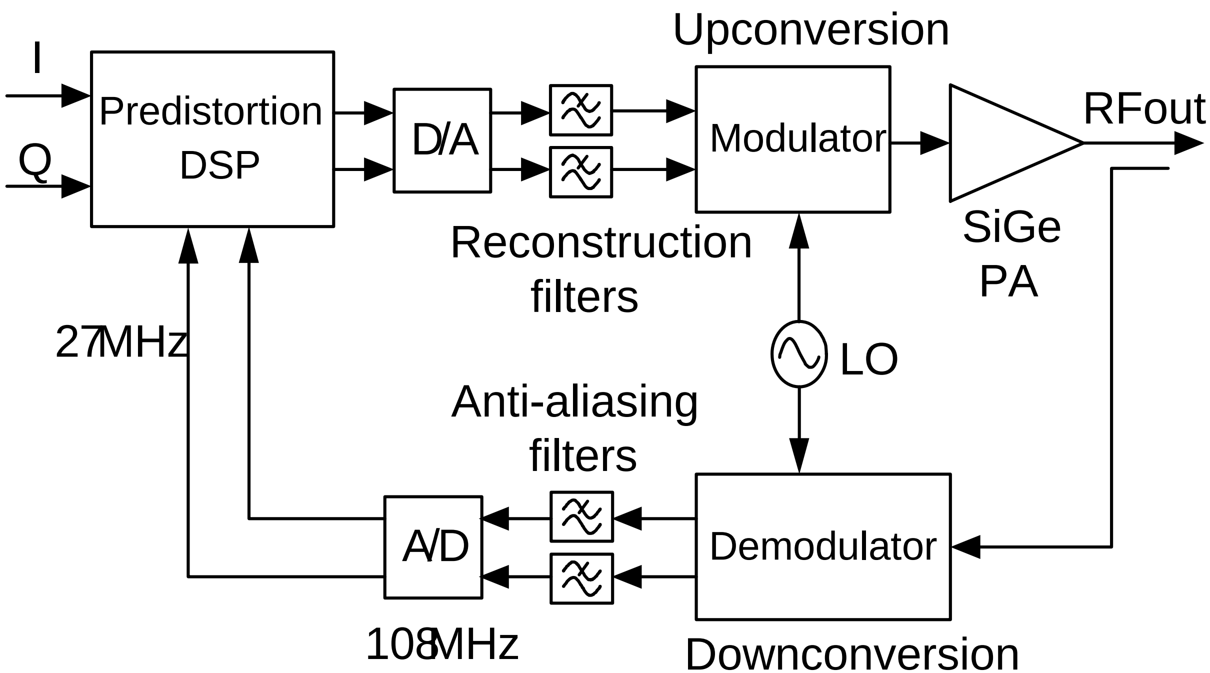
The overall envelope amplifier efficiency is
a combination of switcher and linear stage efficiency.

Linearization Technique Comparison

Linearization Techniques	***Linearization Performance***	***Compensation Bandwidth***	***Cost***	***Comments***
Feedforward	*Good*	*Wide*	*High*	*Not for stand-alone unit*
Feedback	*Moderate*	*Narrow*	*Moderate*	*Stability; Reduced gain*
Analog Predistortion	*Low*	*Wide*	*Low*	*Simple implementation; Reduced gain*
Digital Predistortion	*Moderate*	*Wide*	*Moderate*	*Easy to integrate and control; Depends on DSP*

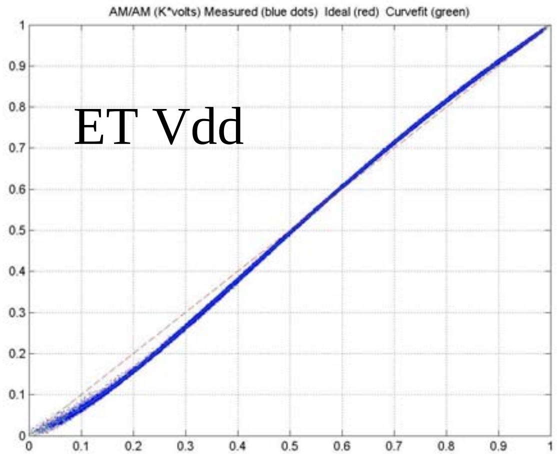
➡ **Digital predistortion becomes promising with the widespread application of DSP to PAs.**

Principle of Adaptive Digital Predistortion

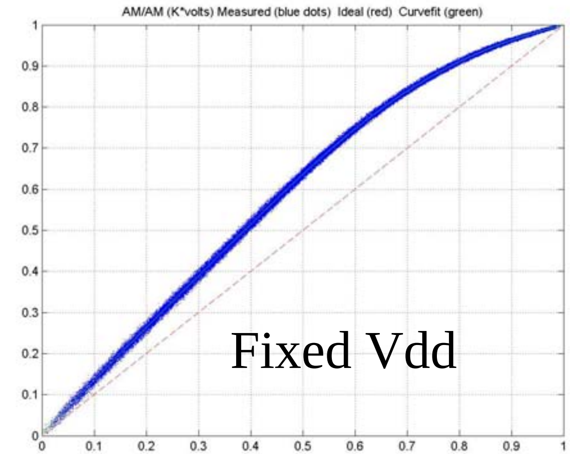


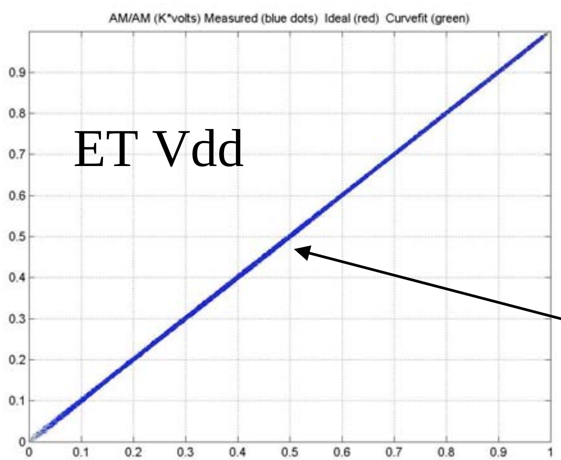
- ***Digital predistortion creates an "inverse" PA nonlinearity in the DSP.***
- ***Issues: bandwidth expansion; DSP memory table size and updating.***
- ***Predistortion works well for ET and Hybrid EER, but is less effective for classic EER.***

AM/AM Distortion, ET Vdd vs Fixed Vdd, EDGE Example



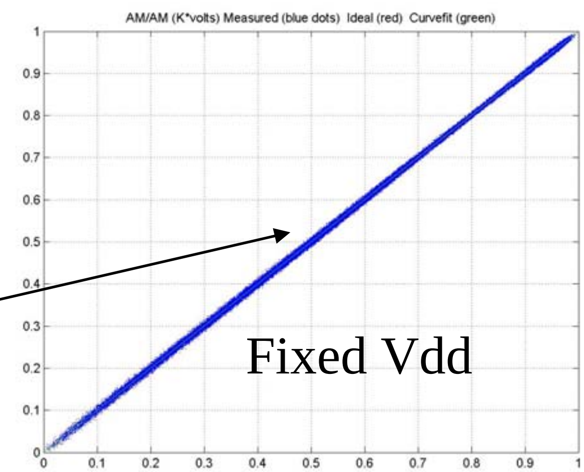
Before Pre-Distortion



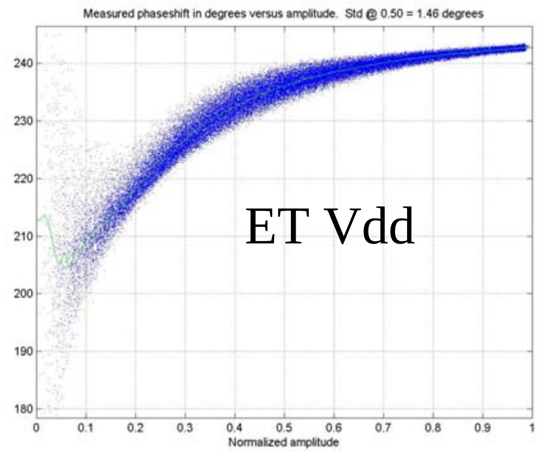


After Pre-Distortion

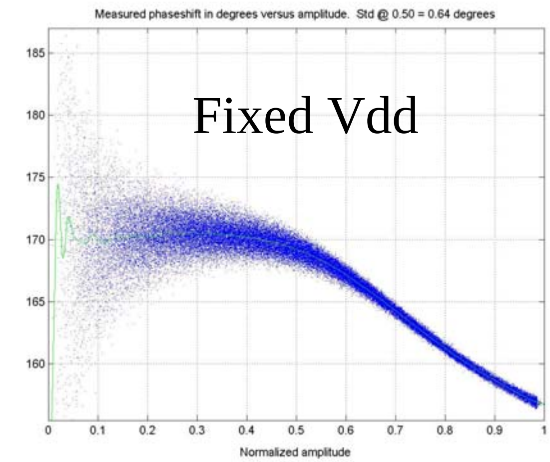
ET has Lower Memory Effects,
.005rms vs 0.02rms

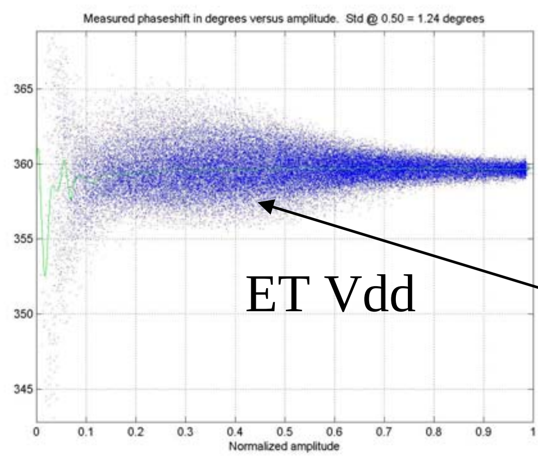


AM/PM Distortion, ET Vdd vs Fixed Vdd, EDGE Example



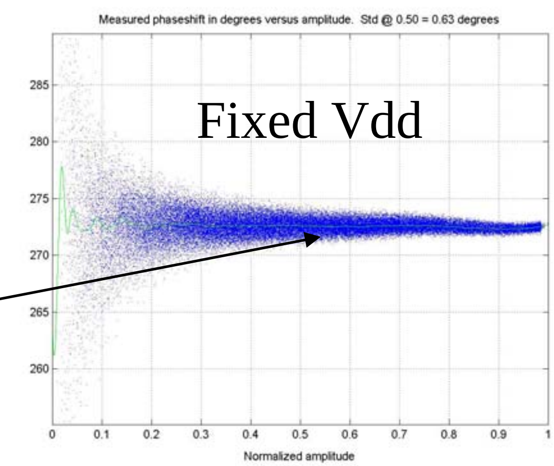
Before Pre-Distortion





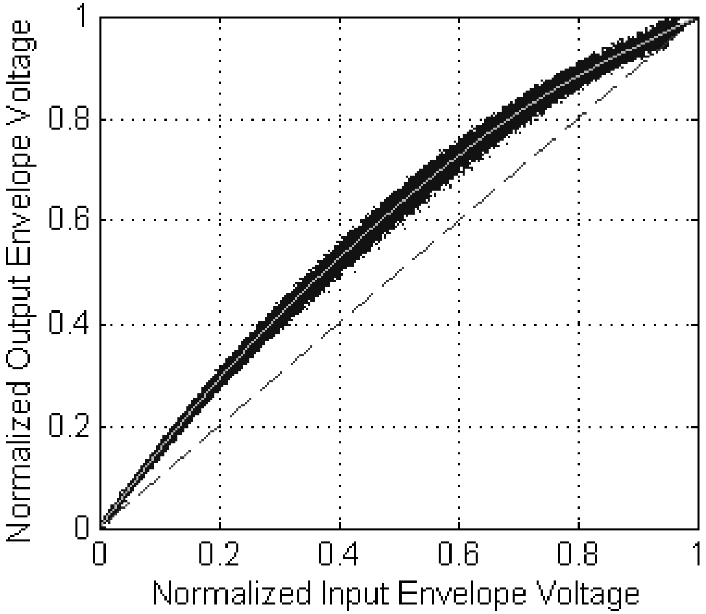
After Pre-Distortion

ET has Higher Memory Effects,
1.24deg vs 0.63deg

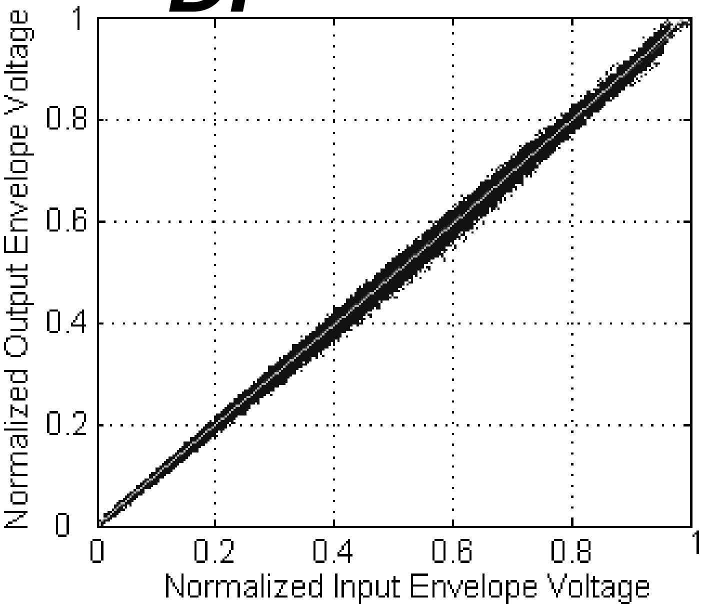


Digital Predistortion of SiGe PA

- ***AM-AM before DP***

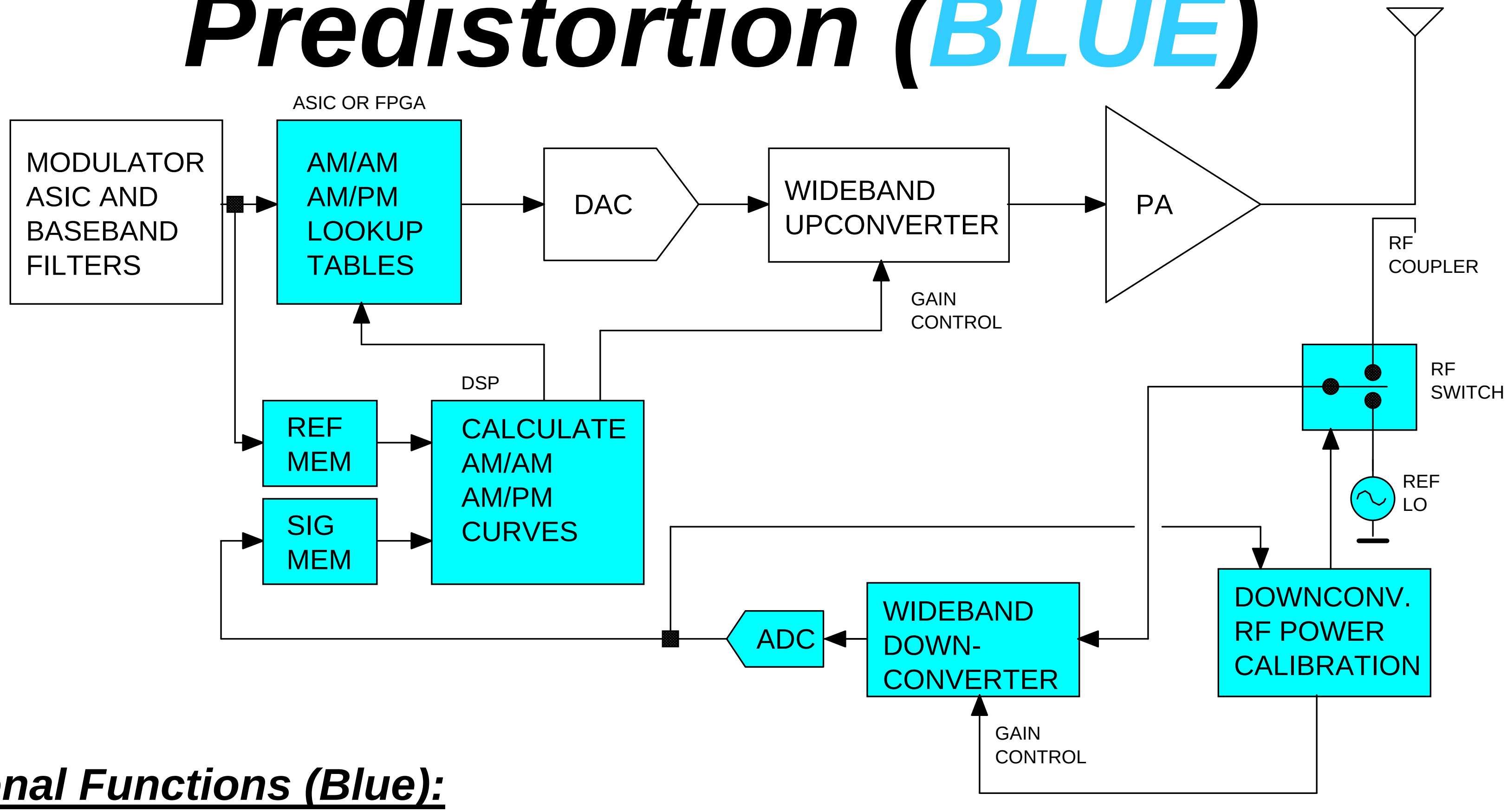


- ***AM-AM after DP***



- ***Memory effects are very small in SiGe HBT PAs.***
- ***Pre-Distortion Tables are generated using a training sequence, whose statistical properties approximate the desired signal.***

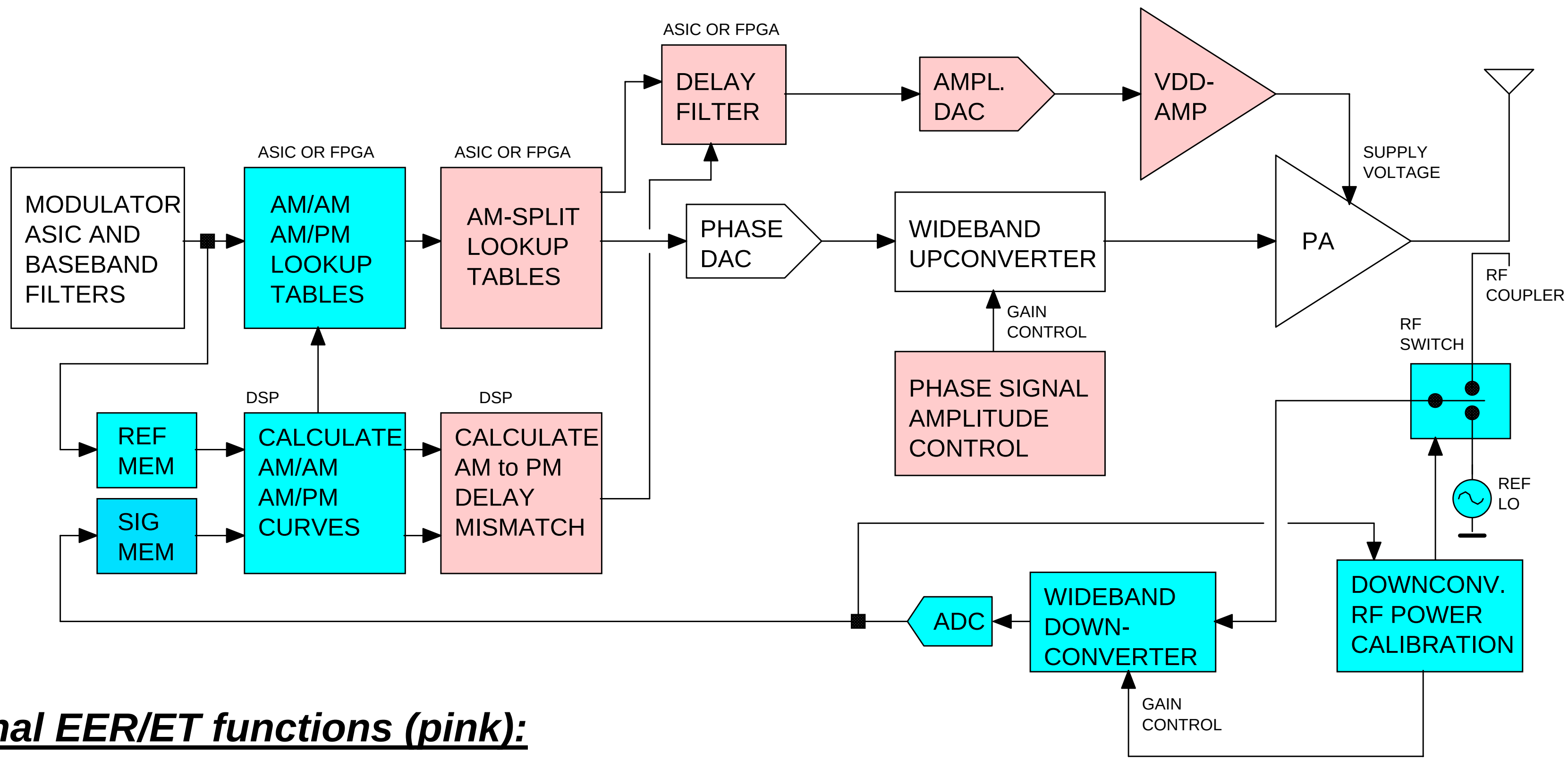
Transmitter with Digital Predistortion (BLUE)



<u>Additional Functions (Blue):</u>

- ***Reference and Signal memory stores a sequence of desired and actual signal***
- ***Data enables DSP to calculate AM/AM and AM/PM correction tables.***
- ***This is done ongoing, without interrupting the signal.***
- ***Between pre-distortion updates, ref LO is switched in to calibrate gain of the down-converter.***

Transmitter Lineup with PA and Pre-distortion (BLUE) AND EER/ET (PINK)



<u>Additional EER/ET functions (pink):</u>

- ***AM-Split block splits AM between Amplitude and Phase signal as per the Bandwidth reduction algorithm.***
- ***Control loop with delay filter to match delay in AM path with upconverter SAW delay.***
- ***VDD-amp amplifies Amplitude sig to be used as supply voltage to final RF transistor.***
- ***Control loop maintain appropriate power level on Phase signal.***

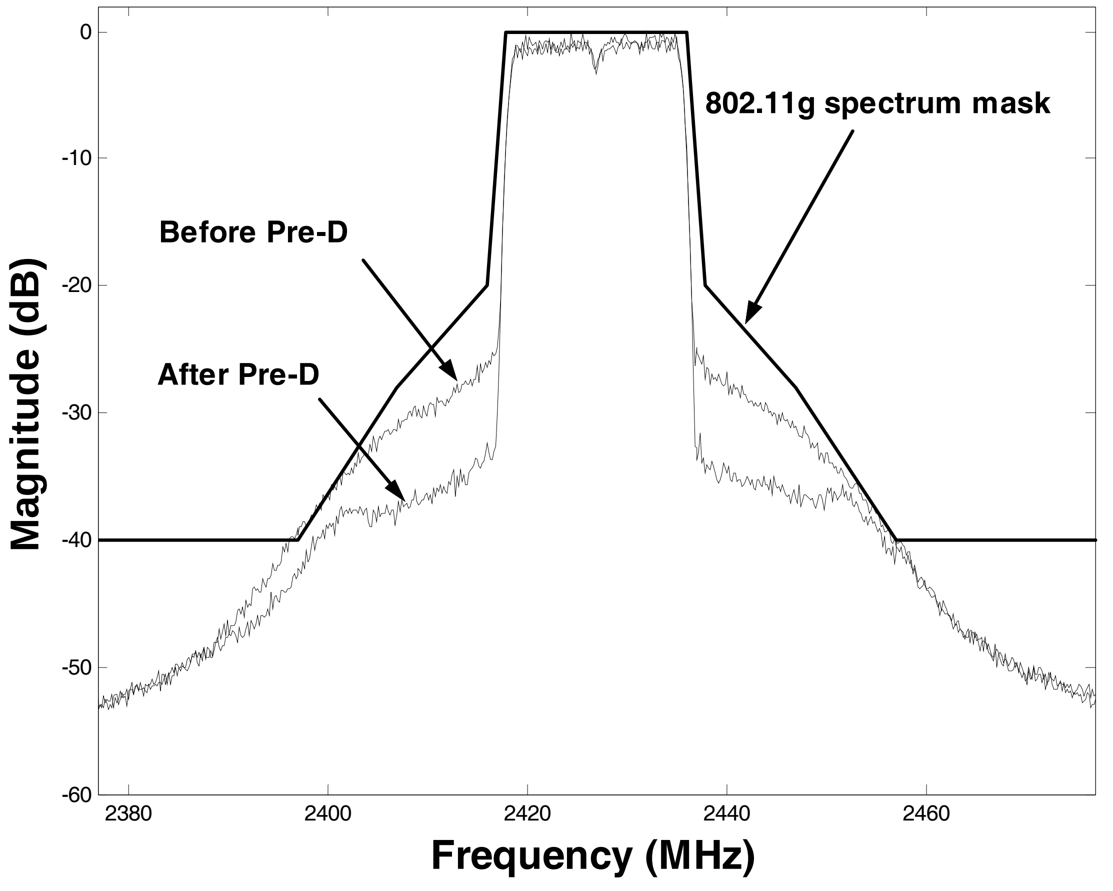
Measured Wideband EER Performance

802.11g (OFDM) signal

	EER Amplifier	Class AB Amplifier
Pout	19 dBm	20 dBm
Gain	6.5 dB	10 dB
Drain/collector efficiency	66 %	13.7 %
RF transistor PAE	51 %	12.3 %
Envelope amplifier efficiency	55 %	-
Overall drain/collector efficiency	36 %	13.7 %
Overall PAE	28 %	12.3 %
EVM	2.8 %	1.6 %

- ***Compared with traditional Class AB PA, efficiency is improved by approximately 2 times***

Measured Spectrum Before and After Pre-distortion

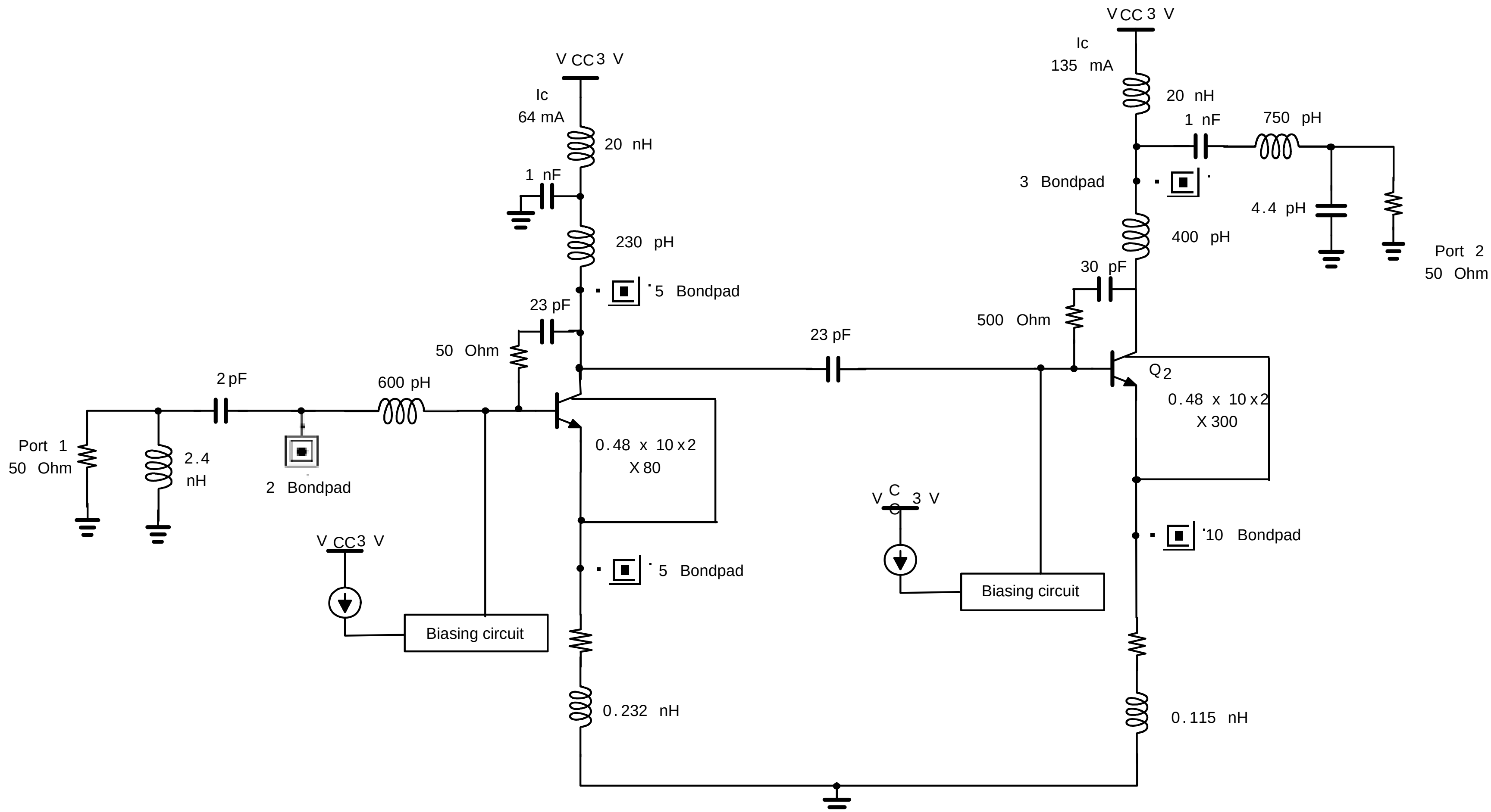


- ***Pre-distortion is implemented to linearize the nonlinear ET PA.***
- ***ACPR is improved by approximately 10dB.***

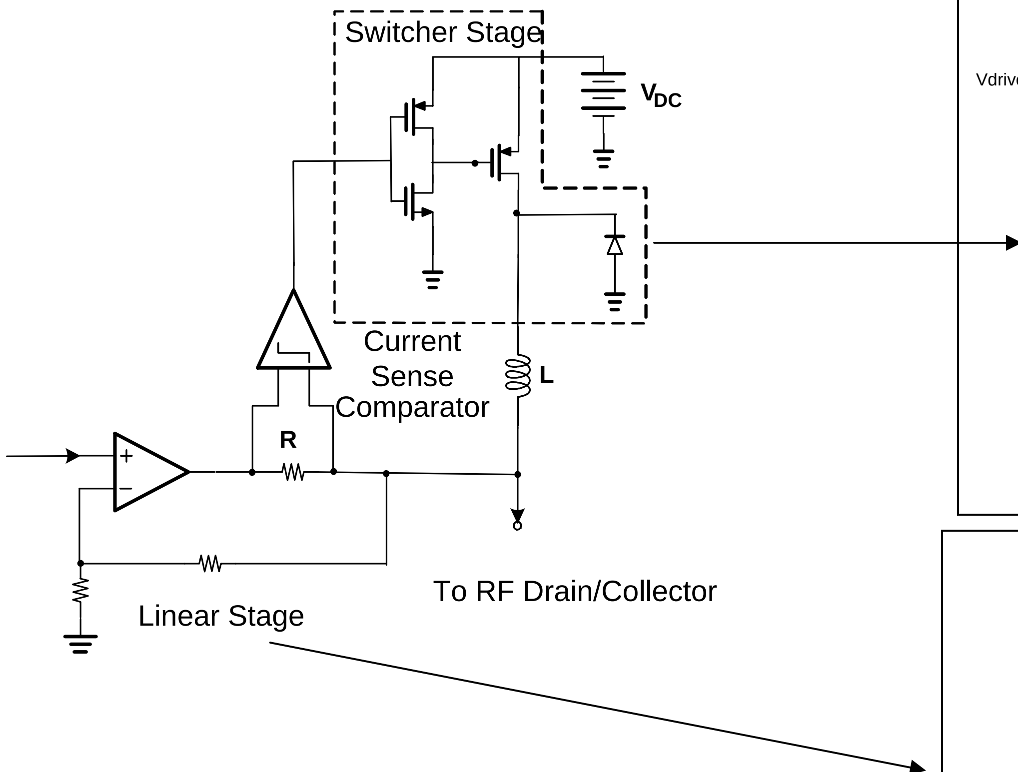
Examples of Power Supply Modulation Implementations

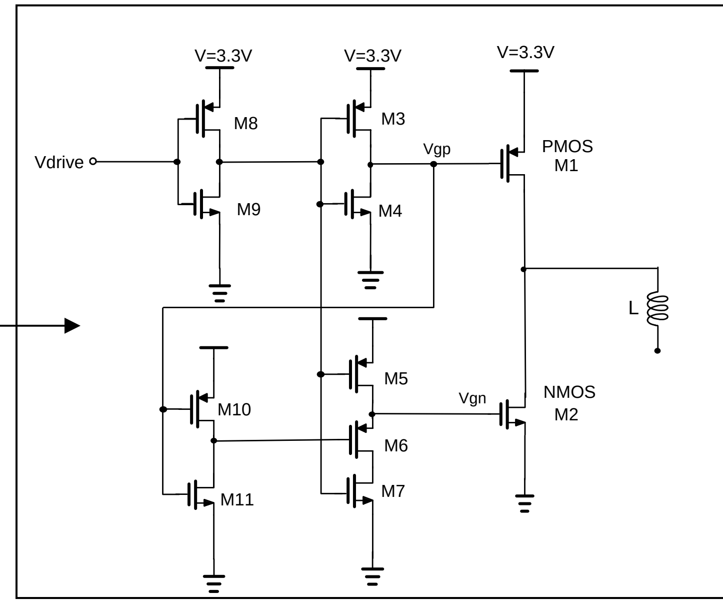
- ***BiCMOS RF IC 2.4 GHz WiLAN Power Amplifier Design***
  - ***Technology: IBM SiGe BiCMOS 7WL***
  - ***RF PA IC Design***
  - ***Envelope Amplifier IC Design***
- ***WCDMA Base Station Power Amplifier***
  - ***Technology: GaN HEMT***

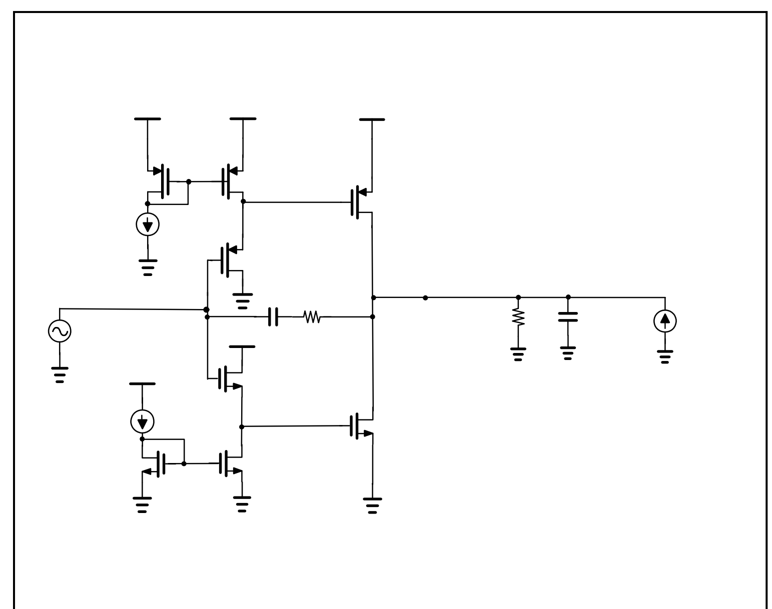
Two Stage RF PA IC Design



Wideband Envelope Amplifier



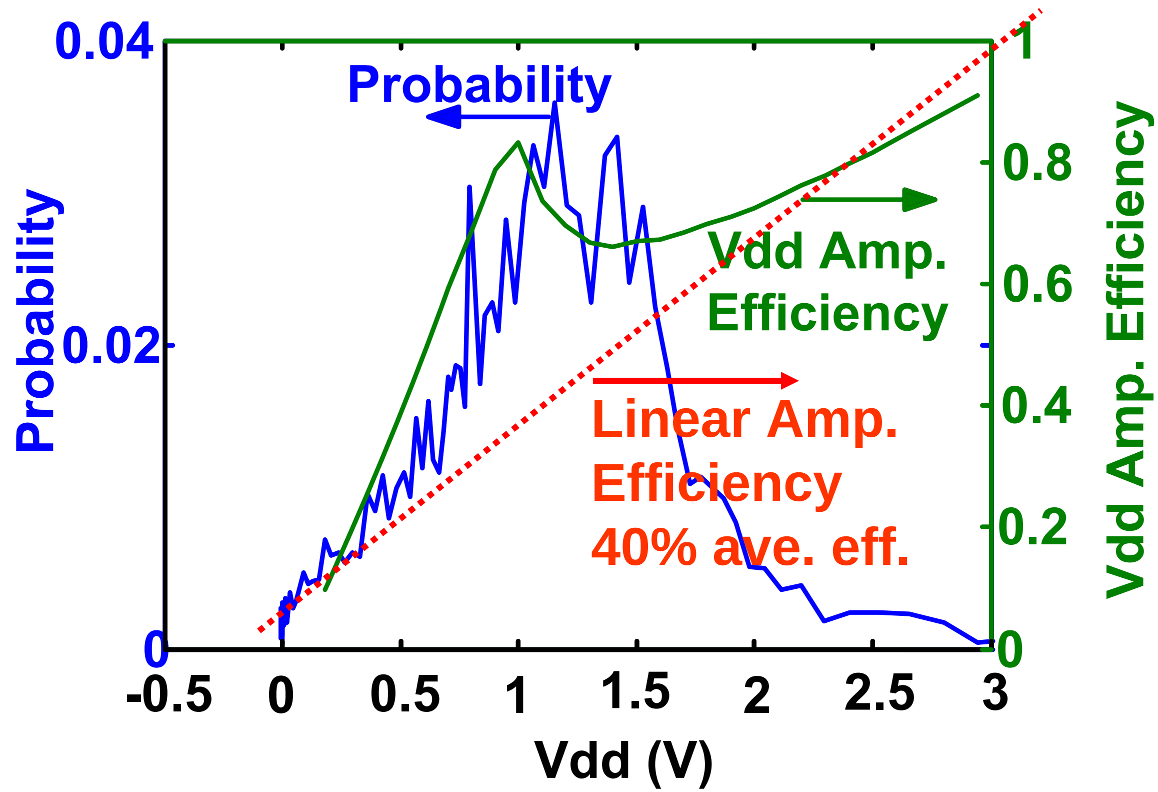




The overall envelope amplifier efficiency is a combination of switcher and linear stage efficiency.

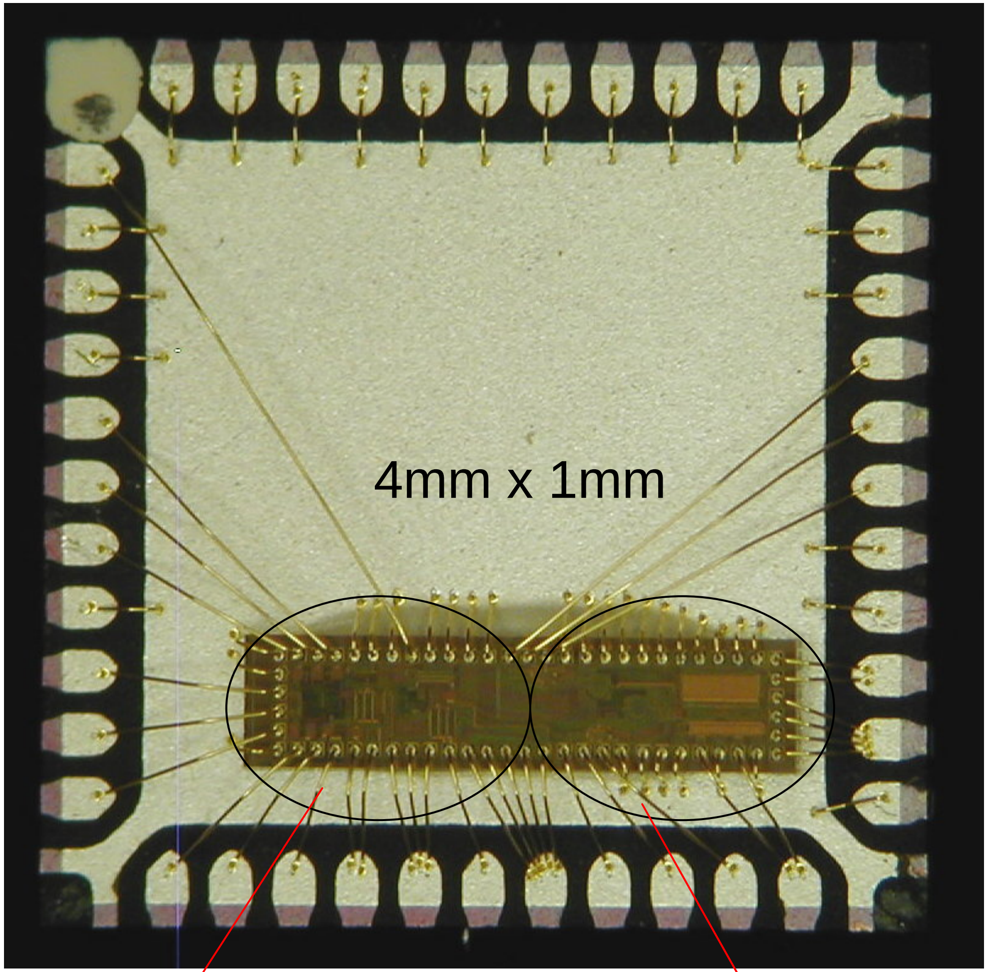
Envelope Amplifier Design

Simulated average IC envelope amplifier efficiency: 70%



Envelope Amplifier Efficiency Curves Matches the PDF of OFDM signal.

Package of ET Amplifier



Envelope Amplifier

2.4 GHz Two stage PA

Summary of Measured IC Performance

- **RF PA**
  - **Two Stage Integrated**
  - **2.4GHz SiGe HBT**
  - **3V power supply**
  - **29 dBm output power**
  - **Gain 15 dB.**
  - **Peak PAE 43%.**

- **Vdd Amplifier**
  - **BW ~ 20MHz**
  - **Gain 3 dB**
  - **Peak output power: 1.8W**
  - **Output voltage: 0.5 ~ 2.75V**
  - **Peak output current: ~600 mA**
  - **Switch frequency: ~ 5MHz**
  - **Ave. Efficiency: ~ 63%**

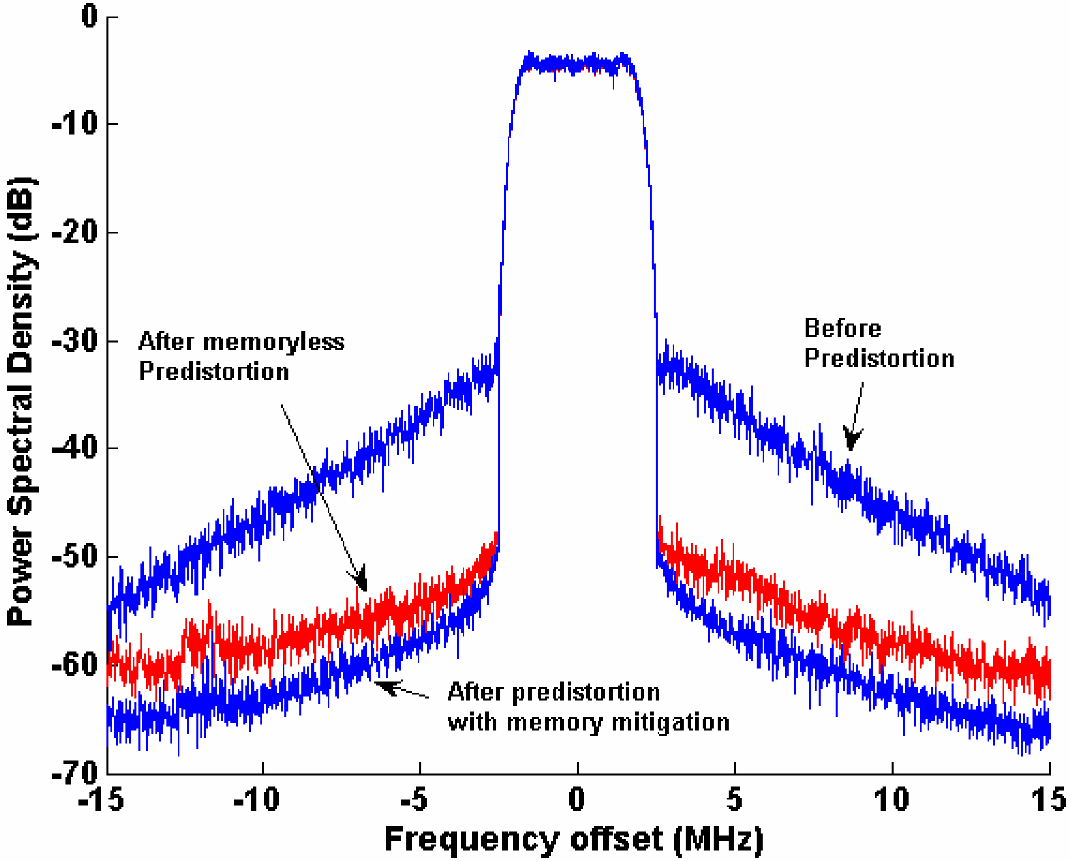
- **ET/EER IC for 2.4GHz OFDM Average output power 20 dBm**
  - **Average gain ~ 13 dB**
  - **Average efficiency 28%**
  - **OFDM Pout = 20 dBm**
  - **EVM<5%**

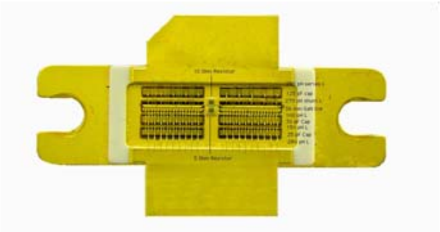
Comparison of Published Envelope Amplifier Performance

Envelope Amplifier (authors)	Applied System	Applied Signal	Envelope Bandwidth	Efficiency
Hannington	WBET	CDMA	1MHz	65%-74%
Staudinger	Average ET	CDMA	20kHz	90%
Sahu	Average ET	CDMA	20kHz	65%
Jau-Horng Chen	WB "Hybrid" EER	CDMA	2MHz	80%
Narisi Wang	WBEER	-	-	-
Raab	WBEER	-	5MHz	-
This work	WB "Hybrid" EER	WLAN OFDM	20MHz	> 55%

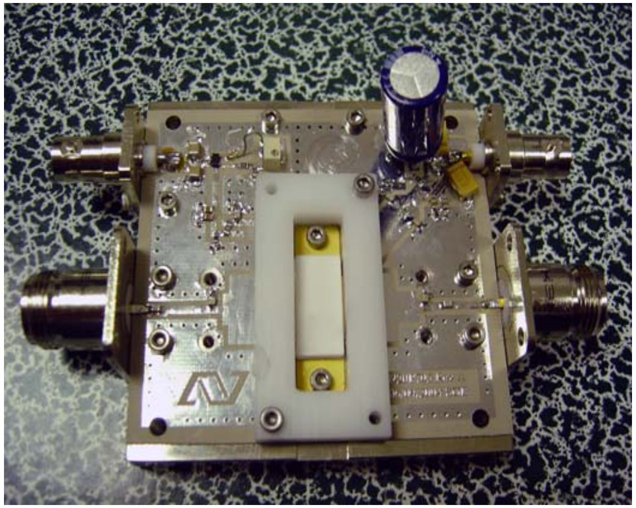
WCDMA with ET System

>50% Efficiency (including Vdd amplifier) with
<1% EVM after Memory digital predistortion



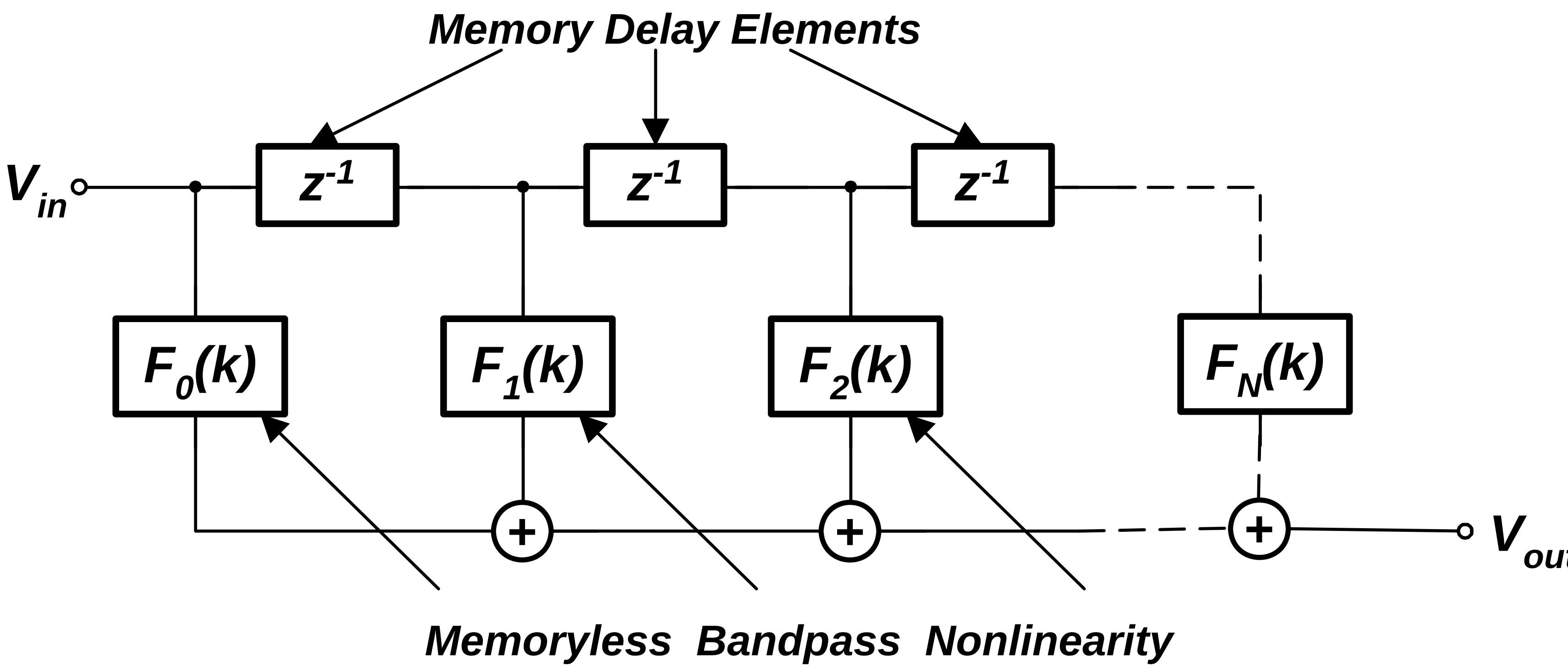


Nitronex NPT21120
Two 36mm GaN devices



Presented at CSIC, Oct. 31st, 2005, Palm Springs, CA

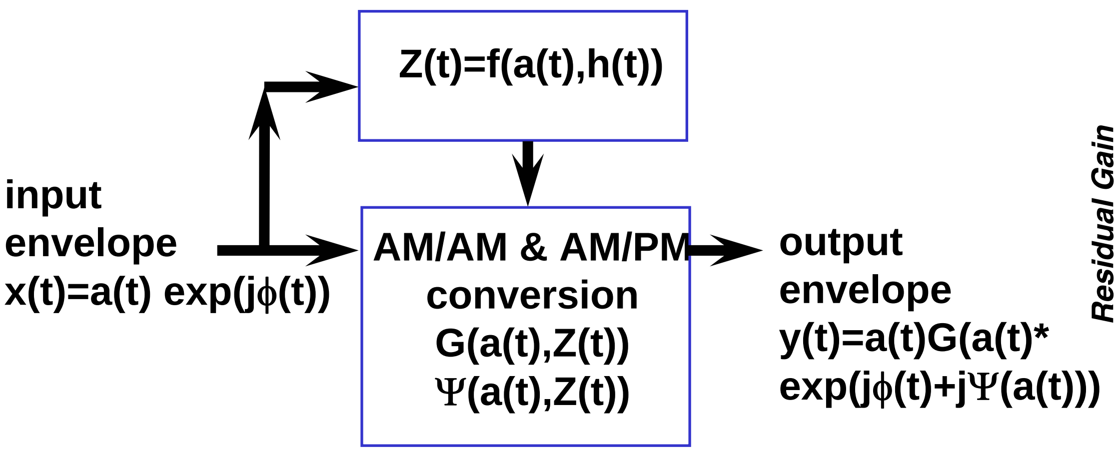
Memory Effects in Nonlinear Amplifiers

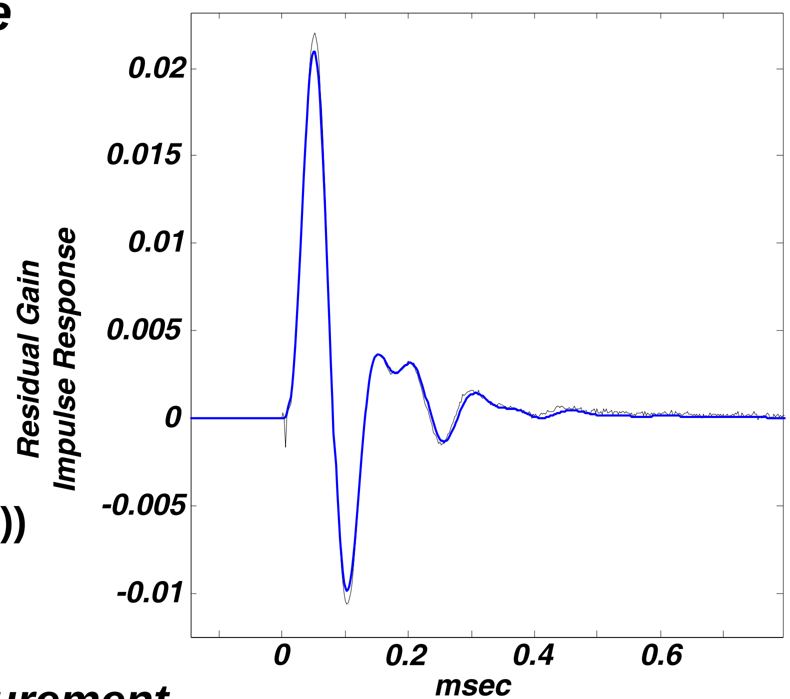


- *Memory Delay Elements can have variable length*
- *Delays are typically 10 usec to 100 msec*

Memory Effects in Nonlinear Amplifiers

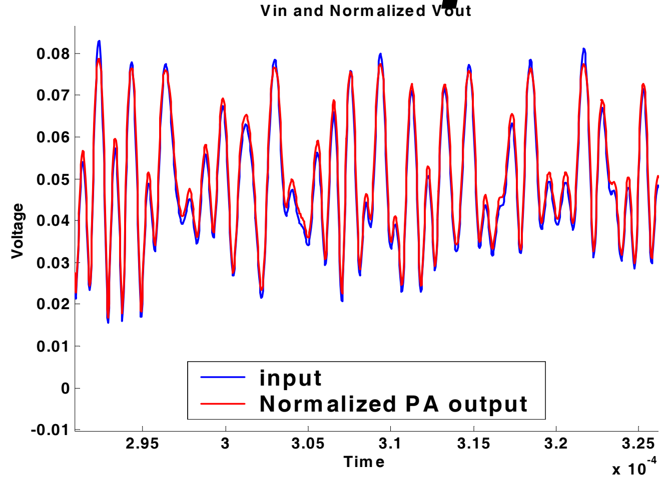
Gain and phase depend on additional parameter, *Z*
but this parameter may <u>not</u> be accessible





Extract gain residue, h, from square wave measurement
Extract pole/zero model for gain residue
and apply as modulation on Z(t).

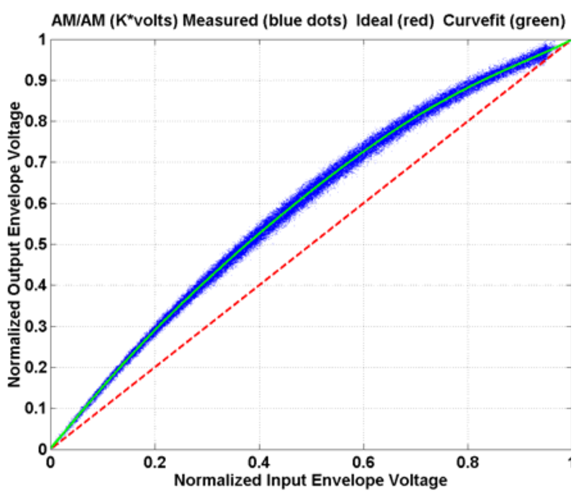
Time Domain Response of Power Amplifiers



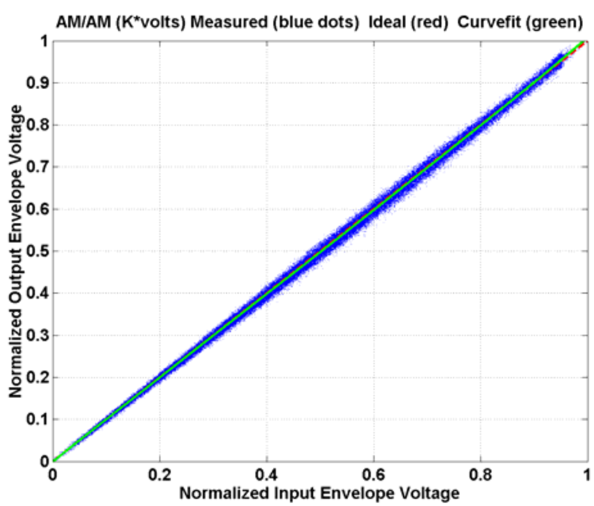
Input and output waveforms vs time (HSDPA signal)

Vout vs Vin

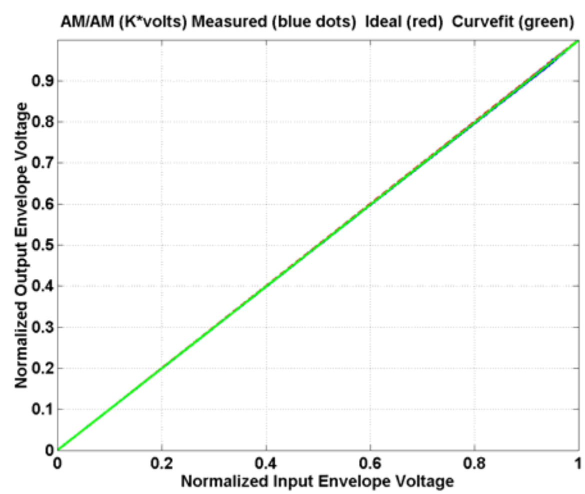
No correction



Memoryless correction



Full correction (with memory effect)



Summary

- ***Mobile station power amplifier are required to operate over a wide range of powers. The traditional PA suffers from the low average efficiency.***

- ***EER/ET can improve the efficiency over wide dynamic range: for WLAN 802.11g signal, efficiency is improved by roughly a factor of two.***

- ***EER/ET is suitable for integration in one single chip to realize low cost mobile station PA.***

- ***DSP is required to maintain high linearity and control the time – mismatch cancellation.***

Acknowledgements

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