# LINEARIZATION:

# **REDUCING DISTORTION IN POWER AMPLIFIERS**

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## OUTLINE

- WHY LINEARIZE
- TYPES OF LINEARIZERS
- THEORY/IDEAL LIMITER
- PREDISTORTION LINEARIZERS
- PHOTONIC LINEARIZERS
- PERFORMANCE EVALUATION
- RESULTS
- MEMORY EFFECTS
- CONCLUSIONS





# IN PAST MOST AMPS USED FOR SC FM MOD SIGNALS

#### - NL PRODUCTS ELIMINATED WITH LP FILTER -OPERATER AT SATURATION (MAX PWR & EFF)

TODAY MULTI-CARRIER AND COMPLEX MODULATED SIGNALS COMMON WHEN MORE THAN ONE CARRIER - DISTORTION PRODUCED (IM)





# TO REDUCE DISTORTION TO AN ACCEPTABLE LEVEL

# -MUST OPERATE AMPLIFIER AT REDUCED POWER LEVEL (BACKOFF FROM SATURATION)





# DISTORTION ALSO PRODUCED BY CHANGE IN PHASE WITH POWER LEVEL



Pin 2.5 dB/DIV

 $\begin{array}{l} \mathsf{n} = \ \infty \\ \mathsf{Ac} \ \mathsf{cos}(\omega\mathsf{ct} + \mathsf{M} \ \mathsf{cos}[\omega\mathsf{mt}]) = \mathsf{Ac} \ \Sigma \mathsf{J}_{\mathsf{n}}(\mathsf{M}) \ \mathsf{cos}([\omega\mathsf{c} + \mathsf{n}\omega\mathsf{m}]\mathsf{t}) \\ \mathsf{n} = - \ \infty \end{array}$ 





### FOR A DIGITALLY MODULATED CARRIER DISTORTION PRODUCES SPECTRAL REGROWTH





### LINEARIZATION ---

#### SYSTEMATIC PROCEDURE FOR REDUCING DISTORTIONS

#### USUALLY EXTRA COMPONENTS ADDED TO AN AMPLIFIER

# WHEN CONFIGURED IN A SUBASSMBLY OR *BOX* KNOWN AS A **LINEARIZER**

#### THREE COMMON FORMS:

- 1) FEEDFORWARD
- 2) FEEDBACK
- 3) PREDISTORTION

+ TECHNIQUES TO IMPROVE EFFICIENCY USING NL PAs



## **CHOICE OF LINEARIZATION**

- LEVEL OF LINEARITY (DISTORTION REDUCTION) NEEDED.
- BANDWIDTH REQUIRED (SIGNAL AND OPERATIONAL).
- COST/COMPLEXITY CONSTRAINTS.





### LINEARIZERS HAVE BEEN USED WITH

# TWTAs and KLYSTRONS

# •BIPOLAR SSPAs (CLASS A, AB, B)

# •FET SSPAs (GaAs, MOS, LDMOS)

# •PHOTONIC (DIRECT, MZM, PIN)





### LINEARIZERS ALLOW HPAs TO OPERATE CLOSER TO SAT





# **FIRST RULE:**

# YOU CAN'T LINEARIZE AN AMPLIFIER THAT IS ALREADY LINEAR!

#### WANT TO OPTIMIZE EFFICIENCY AND SATURATED POWER, NOT LINEARITY

EXCELLENT RESULTS CAN BE OBTAINED WITH CLASS A-B AND B AMPS BOTH FET AND BIPOLAR





## **IDEAL AMPLIFIER CHARACTERISTIC**

### WANT CONSTANT GAIN AND PHASE





### IMPROVEMENT DEPENDS ON ACCEPTABLE DIST LEVEL

#### SATELLITE --

•IMD PRODUCTS ADD TO THERMAL NOISE IF C/I = CNR THEN CNR DEGRADES BY 3 dB

•WANT C/I > CNR + 10 dB FOR NEGLIGIBLE DEG. (< .5 dB) IF CNR = 16 dB THEN C/I = 26 dB

•IF C/I = CNR + 6 THEN CNR = CNR DEG. BY 1 dB

#### CELLULAR --

 INTERFERENCE FROM TX TO ADJACENT RX A PROBLEM --CAN NEED C/I > 35 ~ 70 dB.

•FOR DIGITAL MOD, 16QAM ... 8PSK NEED HIGH C/I TO KEEP BER DOWN.





### **FEEDFORWARD**



•RELATIVELY COMPLEX

•NOT WORKABLE AS STAND-ALONE UNIT

•NOT EFFECTIVE FOR OPBOs < 6 dB

•MOST USEFUL FOR VERY HIGH LINEARITY APPLICATIONS



### MINIMUM FEEDFORWARD OPBO FOR IMD CANCELATION (20 dB)



#### DEPENDS ON: 1) AUX AMP SIZE, 2) OUTPUT COUPLER COEF.



## **FEEDBACK LINEARIZATION**

#### \*FEEDBACK (NETWORK)

- NARROW BAND
- STABILITY PROB
- REDUCED GAIN
- DIFF TO ADJ

#### **\*INDIRECT FEEDBACK**

-OPERATES ON ENVELOPE -VERY LIMITED BW  $< 1/(4\Delta t_S)$ -CAN BE POLAR OR CARTESIAN







### CARTESIAN FEEDBACK ELIMINATES THE NEED FOR PHASE CORRECTION CIRCUITRY





# PREDISTORTION



•RELATIVELY SIMPLE CIRCUITRY

•EASILY IMPLEMENTED AS A STAND-ALONE UNIT

•WIDE BAND (>20% – MULTI OCT/GHz BW ACHIEVED)

•MOST POPULAR FOR MICRO/MILLIMETER WAVE



# LINEARIZER GAIN DEPENDS ON INPUT TO HPA

• THE GAIN OF THE LINEARIZER (GL) MUST INCREASE BY THE SAME AMOUNT THE HPA'S GAIN (GA) DECREASES.

• 
$$GL(P_{outL}) - GL_{ss} = -[GA(P_{inA}) - GA_{ss}] | P_{outL} = P_{inA}$$

• 
$$\Phi L(P_{outL}) - \Phi L_{ss} = - [\Phi A(P_{inA}) - \Phi A_{ss}] | P_{outL} = P_{inA}$$

• 
$$GL(P_{inL}) = GL_{ss} + GA_{ss} - GA(P_{inL} + GL(P_{inL}))$$

$$\Phi L(P_{inL}) = \Phi L_{ss} + \Phi A_{ss} - \Phi A(P_{inL} + GL(P_{inL}))$$

•  $\Phi$ L DEPENDS ON THE GL AND CANNOT BE SET IDENPENDENTLY





#### AN IDEAL LINEARIZER MUST PROVIDE A GAIN EXPANSION THAT APPROACHES INFINITY NEAR SATURATION



 $dG/dP =>\infty$  as Pin => Sat





# FORMS OF PREDISTORTION LINEARIZERS



#### 3. IN LINE





#### **BASIC DSP PREDISTORTION (PD) LINEARIZER**



- Every input level has a corresponding output level
- Correction (mag & phase) in look up tables (LUT) depends on input level
- LUT often adaptively updated for slow changes over time





# **DIGITAL PREDISTORTION**



- CAN PRODUCE CURVES OF ANY SHAPE
- NORMALLY PROCESS AT BASEBAND
- CAN USE EITHER G AND  $\Phi$  OR I AND Q
- MUST SAMPLE AT > 2 X CORRECTION BW FOR G AND  $\Phi$
- BUT ONLY > CORRECTION BW FOR I AND Q
- CORRECTION BW (CBW) >> 3 x BW OF SIGNAL
- MUST USE MANY BITS FOR HIGH CANCELATION (<6 dB/)





## **DIGITAL ADAPTIVE PREDISTORTION**



#### **CORRECTION BW MUST BE >> SIGNAL BW**





## **DIGITAL ADAPTIVE PREDISTORTION**



#### ADAPTIVE SYSTEMS CORRECT AT << ENVELOPE RATE





# **DIGITAL PREDISTORTION**

#### ADVANTAGES:

- \* ACCURATE CORRECTION OVER WIDE DYNAMIC RANGE AND FOR IRREGULAR NON MONOTONIC CHARACTERISTICS
- \* EASY TO MODIFY AND UPDATE
- \* SIMPLE TO IMPLEMENT AS ADAPTIVE SYSTEM

#### • **DISADVANTAGES**:

- \* CORRECTION BANDWIDTH LIMITED BY SAMPLING RATE: SR = CBW = N X BW
- \* COST CAN BE HIGHER THAN ANALOG
- \* POWER CONSUMPTION CAN BE HIGH \* WIDE BW SYSTEMS DIFFICULT TO IMPLEMENT





### TECHNIQUES TO IMPROVE EFFICIENCY USING NL PAs

- MANY WAYS TO ACCOMPLISH.
- CLASSICAL "KHAN METHOD" DEMODS ENVELOPE AND LIMITS SIGNAL. THEN REMODULATES AT OUTPUT PA.
- LINC SYSTEMS USE OBTAIN LINEAR AMPLIFICATION BY COMBINING TWO NON-LINEAR PAs.
- LOAD MODULATION AND OUTPHASING (DOHERTY – ONE EXAMPLE)





# EER – ENVELOPE ELIMINATION AND RESTORATION



IF ELIMINATE ENVELOPE, SIGNAL CAN BE AMPLIFIED IN NL PA OPERATED AT OR NEAR SATURATION.





### LINC – LINEAR AMPLIFICATION WITH NON-LINEAR COMPONENTS



CAN OBTAIN ANY AMPLITUDE FROM THE SUM OF 2 CONSTANT AMPLITUDE SIGNALS OF VARIABLE PHASE

> LEGE TERSEY

## **PERFORMANCE EVALUATION**

#### MAGNITUDE & PHASE IMPORTANT INDICATORS OF PERFORMANCE

#### **\*\* OBTAIN WITH POWER SWEEP**



#### SEPARATION OF 1 dB COMPRESSION AND SATURATION PROVIDES GAGE FOR COMPARISON





# C/I (CARRIER TO IMD) MEASUREMENT

• MANY DIFFERENT STANDARDS MAKE COMPARISON DIF.

• DATA USUALLY PRESENTED REL TO BACKOFF FROM SAT.

• SAT POINT SHOULD BE SINGLE CARRIER SAT. 2 CARRIER SAT ABT 1 dB LOWER, NOISE ABT 1.5 dB.

• CAN NOT USE COMPRESSION POINT FOR REFERENCE. 1 dB = SAT - D

 BOTH IPBO AND OPBO USED ... IPBO CAN BE MISLEADING. BEST TO REFER TO OPBO

 OUTPUT LEVEL IS WHAT'S IMPORTANT!





### **OFTEN RESULTS PRESENTED FOR C/I3 ONLY**

With Linearizers, not uncommon for 5th order terms to be greater than 3rds or of same order



C/I total = C/ 
$$\Sigma$$
 |3 <sup>2</sup> + |5 <sup>2</sup> + |7 <sup>2</sup> + ...

Total C/I preferred to C/I3

C/Imin is a good compromise





### IMD TERMS CAN BE NON-SYMMETRICAL

#### DUE TO MEMORY EFFECTS (AM/AM AND AM/PM)

#### UPPER & LOW ODD ORDER AM/AM TERMS IN PHASE

#### UPPER & LOW ODD ORDER AM/PM TERMS OUT OF PHASE





#### A LINEARIZER IMPROVES LINEARITY OF A CLASS A SSPA





#### LINEARIZATION OF A CLASS A SSPA PROVIDES ONLY

#### A 0.5 dB POWER INCREASE FOR A C/I OF 26 dB, BUT A 2.5 dB POWER INCREASE FOR A C/I OF 50 dB





#### LINEARIZATION OF LESS LINEAR CLASS AB SSPA

#### **PROVIDES > 1.5 dB POWER INCREASE FOR C/I OF 26 dB.**




## WITH A TWTA A C/I = 26 dB CAN OBTAIN > 3 dB POWER INCREASE



WITH MULTIPLE CARRIERS THE IMPROVEMENT IS EVEN GREATER!



# **MULTIPLE CARRIERS (N>2)**

• EXERCISE OVER RANGE Ppk = 2NPav

• NO SIMPLE RELATIONSHIP BETWEEN C/I FOR 2 AND N CARRIER CASE





## **NPR - NOISE POWER RATIO**

MEASURE OF N-CARRIER C/I

WANT DEPTH OF GENERATOR NOTCH > 10 dB BELOW NPR OF INTEREST



## NPR PREDICTS AMPLIFIER PERFORMANCE WITH MANY CARRIERS



FOR C/I = 25 dB OBTAIN ALMOST 6 dB INCREASE IN POWER.





# NPR OF CLASS AB SSPA





## PROVIDES SIGNIFICANT REDUCTION IN SPECTRUM





# **EVEN NEAR SAT**



> 2 dB POWER INCREASE





## REDUCTION IN SPECTRAL REGROWTH PROVIDED BY LINEARIZATION OF A TWTA





# **ETSI STANDARDS**

- THE EUROPEAN TELECOMMUNICATIONS STANDARDS INSITUTE (ETSI) HAS PRODUCED STANDARDS FOR THE TRANSMISSION OF MPEG-2 TRANSPORT STREAMS OVER SATELLITES USING BEM.
  - QPSK (EN 300 421)
  - 8PSK and 16QAM (EN 301 210).
- PROVIDES A MECHANISM FOR ENCAPSULATING INTERNET PROTOCOL (IP) DATAGRAMIS WITHIN ADDIGTIAL VIDEO BROADCAST (DVB) WAWEFORWI (EN 3011 1992).
- PROVIDES AN OPEN FRAMEWORK FOR DELIVERING INTERNET SERVICES OVER SATIELLITTE.



## **MULTI-CARRIER QAM**

#### A TYPICAL DVB QAM SIGNAL REQUIRES ABOUT 2 MHz OF BW.



• A STANDARD 36 MHz SATELLITE TRANSPONDER CAN ACCOMMODATE AT LEAST 12 16QAM FDM SIGNALS.

• THIS FORMAT GREATLY INCREASES THROUGHPUT AND REVENUE AND IS IDEAL FOR INTERNET VIA SATELLITE.



# **MULTI-CARRIER QAM**

• IMD IS THE MAJOR PROBLEM. IT LIMITS THE BIT ERROR RATE (BER) OF DIGITAL SIGNAL.

• CODING USED TO INCREASE BER FOR A SMALL SACRIFIC IN BW EFFICIENCY.

• NO DATA AVAILABLE ON THE AFFECT OF DISTORTION ON MULTI-CARRIER QAM WITH OR WITHOUT CODING.

• A HARDWARE TEST PLATFORM WAS SET UP TO INVESTIGATE THE PERFORMANCE OF CODED FDM QAM THROUGH A LINEARIZED TWTA.



### **BER OF UNCODED DATA** QEF CAN NOT BE ACHIEVED



#### **BER OF 3/4 CONVOLUTIONAL FEC DATA** QEF STILL CAN NOT BE ACHIEVED





LINEARIZER PROVIDES ~ 3 dB ADVANTAGE

### **BER OF FEC/REED-SOLOMON CODED DATA**



### IDEAL LINEARIZER PERFORMANCE IS LIMITED BY SIGNAL PEAK-TO-AVERAGE CHARACTERISTICS (PAC)

#### PAC SETS MINIMUM BACKOFF OF PA! CANNOT IMPROVE BY LINEARIZATION. MUST USE PA WITH HIGHER POWER/EFFICIENCY





# DSP L/TWTA AT 3 dB OPBO – C/I > 50 dB





# IMD CANCELLATION> 30 dB





## **MULTI-TONE**





# WIDE BAND (100 MHz)



Digital linearization across 100 MHz using filters to correct for frequency memory effects



#### ANALOG PREDISTORTION CAN PROVIDE A VERY BROAD FREQUENCY RESPONSE



- USEFULL LINEARIZER CHARACTERISTICS < 2 GHz TO > 20 GHz.
- ~3 dB GAIN INCREASE FROM 6 TO 16 GHz.
- DECREASING PHASE CHANGE OF 5° TO 10°





#### 1 dB CP IS MOVED > 6 dB CLOSER TO SAT FROM 6 TO 16 GHz PHASE SHIFT IS REDUCED FROM > 30° TO < 10 ° OVER THIS BAND



### LINEARIZER'S PERFORMANCE WITH GaN PA

#### LINEARIZER PERFORMANCE WITH PHOTONIC LINK



- NON-LINEAR CHARACTERISTICS OF THE MODULATORS USED FOR THE TRANSMISSION OF SIGNALS OVER FIBER OPTIC LINKS ARE SIMILAR TO CHARACTERISTICS OF PAs
- WIDEBAND GaN LINEARIZER WAS TESTED WITH A MACH ZEHNDER MODULATOR (MZM) FIBER OPTIC LINK OVER 4 TO 12 GHz BAND
- FOR MZM LINKS, LITTLE OR NO NONLINEAR PHASE CHANGE IS PRODUCED AND THE LINEARIZER WAS THUS BIASED FOR MINIMUM PHASE CORRECTION



#### GAIN TRANSFER RESPONSE OF MZM LINK AT 8 GHz WITH AND WITHOUT LINEARIZATION



- MZM HAS FREQUENCY INDEPENDENT NON-LINEAR CHARACTERISTICS
- THE LINEARIZER MOVES THE 1 dB CP 5 dB CLOSER TO SATURATION
- SIMILAR RESULTS WERE ACHIEVED FROM 4 TO 12 GHz
- WITH NO SIGNIFICANT DEGRADATION OF THE LINK'S NEAR ZERO PHASE SHIFT



#### 2-TONE C/I OF NONLINEARIZED AND LINEARIZED LINK



BIG IMPROVEMENT IN C/I AT ALL LEVELS EXCEPT NEAR SAT> 10 dB OVER MUCH OF THE RANGE WITH A PEAK OF > 30 dB



#### IMD, IIP3 AND SFDR IMPROVEMENTS OF LINEARIZED LINK

Frequency	IMD	IIP3	SFDR3
(GHz)	Improvement	Improvement	Improvement
	(dB)	(dBm)	$(dB \cdot Hz^{2/3})$
4	13.3	6.65	4.43
6	20.0	10.0	6.67
8	23.6	11.8	7.87
10	17.9	8.95	5.97
12	12.3	6.15	4.10

SIGNIFICANT IMPROVEMENT IN LINEARITY PROVIDED OVER 1.5 OCTAVE FREQUENCY RANGE

SFDR INCREASED BY > 4 dB OVER THIS RANGE





# MEMORY EFFECTS (ME)

# SOURCES OF ME

- Frequency ME
- Drain/collector ME
- Gate/base ME
- Device related ME
- Thermal ME



# **MEMORY EFFECTS**

• Memory Effects are changes in a Power Amplifier's (PA) non-linear characteristics resulting from the past history of the input signal.

## Vo = f(Vin, time)

- Primary cause drain/collector and gate/base bias change.
- Thermal, device and frequency are also factors.
- Standard predistortion linearizers depend on a stable non-linear response, and can be particularly degraded by memory effects.



# FREQUENCY MEMORY EFFECTS



#### GAIN VS. INPUT POWER IS AFFECTED BY FREQUENCY

#### PHASE VS. INPUT POWER IS AFFECTED BY FREQUENCY

- Standard predistorter look-up tables have the same correction for every frequency
- Real PA non-linearities do change with frequency



# **TWO KINDS OF BANDWIDTH**

1) STATIC BANDWIDTH - ABILITY OF LIN MAG/PHASE TRANSFER RESP TO EQUALIZE AMP AT ALL FREQ OF INTEREST

> - MEAS WITH 2 CLOSE SPACED TONES AT ALL FREQ OF INTEREST

2) DYNAMIC BANDWIDTH - ABILITY OF LIN MAG/PHASE TRANSFER RESP TO FOLLOW ENVELOPE OF SIGNALS

- MEAS WITH 2-TONE SIGNAL IN WHICH THE SPACING OF THE TONES IS INCREASED





## THE LINEARITY OF AMPLIFIERS DEGRADE WITH INCREASING CARRIER SPACING





# **MAJOR CAUSE OF DEGRADATION --**

#### INABILITY OF AMPLIFIERS TO FOLLOW RAPIDLY CHANGING ENVELOPE



#### ENVELOPE FREQUENCY $F_e = F_{\Delta}/2$

### TRANSFER CHARACTERISTICS CHANGE WITH Fe





### RF ENVELOPE (GREEN) IS ~ 140° OUT OF PHASE WITH DRAIN RIPPLE (YELLOW)



IMDs caused by the PA non-linearity subtract from the ripple induced IMDs





# **BIAS (DRAIN) INDUCED ME**



A low impedance network at envelope frequencies across the drain and effective power supply decoupling can minimize memory effects



### IMPROVEMENT IN C/I RESULTING FROM ADDED LOW INDUCTANCE DRAIN CAPACITORS (RESONATE AT 12 MHz)



### **OUTPUT BACKOFF IN dB**





## **SUMMARY**

LINEARIZERS INCREASE HPA POWER CAPACITY AND EFFICIENCY FOR MULTI-CARRIER AND COMPLEX DIGITAL SIGNALS

NEW LINEARIZER DESIGNS HAVE GREATLY ENHANCED PERFORMANCE

SSPAs - BENEFIT GREATEST FOR CLASS B AND AB 2 X POWER INCREASE IN HIGH LIN APPLICATIONS

TWTAS - 4 X POWER INCREASE AND DOUBLE EFFICIENCY







#### **FEEDFORWARD:**

LINEARIZATION IS MOST VALUABLE WHEN VERY HIGH LIN REQUIRED.

#### **INDIRECT FEEDBACK:**

WORKS WELL, BUT LIMITED IN BANDWIDTH.

#### **PREDISTORTION:**

ADVANTAGES SIMPLICITY, WIDEBAND, VIABLE BOTH LOW AND HIGH LIN. DSP CAN PROVIDE VERY HIGH LIN.




## FOR MORE INFORMATION

- 1. A. Katz, "Linearization: Reducing Distortion in Power Amplifiers," IEEE Microwave Magazine, pp. 37-49, December 2001.
- 2. Vuolevi and Rahkonen, "Distortion in RF Power Amplifiers", Artech House, 2003.
- 3. S. Cripps, "Advanced Techniques in RF Power Amplifier Design", Artech House, 2002.
- 4. A. Katz and R. Gray, "The Linearized Microwave Power Module," MTT-S International Microwave Symposium Digest, June, 2003.
- 5. A. Katz, "Performance Of Multi-carrier 16QAM Over a Linearized TWTA Satellite Channel," AIAA 20th International Communications Satellite Systems Conference Proceedings, Montreal, May 2002.
- P. Kenington, "Methods Linearize RF Transmitters and Power Amps, Part 1, "Microwaves & RF Magazine," pp. 103-116, December 1998, Part 2, pp. 79-89, January 1999.

