LINEARIZATION:
REducing distortion in Power Amplifiers

OUTLINE

• WHY LINEARIZE
• TYPES OF LINEARIZERS
• THEORY/IDEAL LIMITER
• PREDISTORTION LINEARIZERS
• PERFORMANCE EVALUATION
• RESULTS
• CONCLUSIONS
IN PAST MOST AMPS USED FOR SC FM MOD SIGNALS

- NL PRODUCTS ELIMINATED WITH LP FILTER
- OPERATE 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

\[ Ac \cos(\omega t + M \cos(\omega_m t)) = Ac \sum_{n=-\infty}^{\infty} J_n(M) \cos((\omega_c+n\omega_m)t) \]

### 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

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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)

LINEARIZERS ALLOW HPAs TO OPERATE CLOSER TO SAT

- Greater Output Power
- Greater Efficiency

“SAME” Distortion
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 $C/I > 35 \sim 70$ dB.
- For digital mod, 16QAM … 8PSK need high C/I to keep BER down.

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**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/(4Δt_{ch})
- CAN BE POLAR OR CARTESIAN
CARTESIAN FEEDBACK ELIMINATES THE NEED FOR PHASE CORRECTION CIRCUITRY

• RELATIVELY SIMPLE CIRCUITRY
• WIDE BAND (>20% BW)
• MOST POPULAR FOR MICRO/MILLIMETER WAVE

PREDISTORTION

• RELATIVELY SIMPLE CIRCUITRY
• EASILY IMPLEMENTED AS A STAND-ALONE UNIT
• WIDE BAND (>20% BW)
• 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.

\[ GL(P_{out}) - GL_{ss} = -[GA(P_{inA}) - GA_{ss}] \mid P_{out} = P_{inA} \]

\[ \Phi_L(P_{out}) - \Phi_{Lss} = -[\Phi_A(P_{inA}) - \Phi_{A_{ss}}] \mid P_{out} = P_{inA} \]

\[ GL(P_{inl}) = GL_{ss} + GA_{ss} - GA(P_{inl} + GL(P_{inl})) \]

\[ \Phi_L(P_{inl}) = \Phi_{Lss} + \Phi_{A_{ss}} - \Phi_A(P_{inl} + GL(P_{inl})) \]

- \( \Phi_L \) depends on the GL and cannot be set independently.

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

\[ \frac{dG}{dP} \rightarrow \infty \text{ as } P_{in} \rightarrow \text{Sat} \]
FORMS OF PREDISTORTION LINEARIZERS

1. TRANSMISSION

2. REFLECTIVE

3. IN LINE

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
**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) \( \geq 3 \times \) BW OF SIGNAL
- MUST USE MANY BITS FOR HIGH CANCELATION (<6 dB/)

**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: $SR = CBW = N \times BW$
  - COST CAN BE HIGHER THAN ANALOG
  - POWER CONSUMPTION CAN BE HIGH
  - WIDE BW SYSTEMS DIFFICULT TO IMPLEMENT

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 DIFFICULT.
- DATA USUALLY PRESENTED REL TO BACKOFF FROM SAT.
- SAT POINT SHOULD BE SINGLE CARRIER SAT.
  2 CARRIER SAT ABOUT 1 dB LOWER, NOISE ABOUT 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

\[
C/I_{\text{total}} = C/I_{13}^2 + C/I_{15}^2 + C/I_{17}^2 + \ldots
\]

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)

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)

- NO SIMPLE RELATIONSHIP BETWEEN C/I FOR 2 AND N CARRIER CASE
- GREATER IMPROVEMENT (REDUCTION IN OPBO) FOR A GIVEN C/I AS N INCREASES
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**

![Graph showing NPR vs OPBO in dB]

- NPR in dB
- OPBO in dB

**PROVIDES SIGNIFICANT REDUCTION IN SPECTRUM**

![Graph showing spectrum reduction]

- REF LEVEL: 0.5 dBm
- TWT ONLY 4.0 dB B.O.
- 4.0 dB B.O. WITH LINEARIZER
- VBW 1 kHZ
EVEN NEAR SAT

> 2 dB POWER INCREASE

REDUCTION IN SPECTRAL REGROWTH PROVIDED BY LINEARIZATION OF A TWTA
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

OUTPUT BACKOFF IN dB

C/I IN dB

2-TONE

MANY-TONE (NPR)

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

![Graph showing C/I vs Carrier Spacing](image-url)
MAJOR CAUSE OF DEGRADATION --

INABILITY OF AMPLIFIERS TO FOLLOW RAPIDLY CHANGING ENVELOPE

ENVELOPE FREQUENCY \( F_e = \frac{F_\Delta}{2} \)

TRANSFER CHARACTERISTICS CHANGE WITH \( F_e \)

MEMORY EFFECTS

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

\[ V_o = f(V_{in}, \text{time}) \]

- 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.
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
SUMMARY

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


