LINEARIZATION:
REDUCING DISTORTION IN POWER AMPLIFIERS

BY: DR. ALLEN KATZ, APRIL 2009
• 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)
Ac \cos(\omega ct + M \cos[\omega mt]) = 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 SUBASSMMLY 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

Greater Output Power

- AMP
- LAMP

“SAME” Distortion

Power Out

Efficiency

Greater Efficiency

- AMP
- LAMP

“SAME” Distortion

- AMP
- LAMP
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
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 (NETWORK)

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

*INDIRECT FEEDBACK

- OPERATES ON ENVELOPE
- VERY LIMITED BW \(<\frac{1}{4\Delta t_S}\)
- 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.

\[
\begin{align*}
GL(P_{\text{outL}}) & - GL_{ss} = - [GA(P_{\text{inA}}) - GA_{ss}] \\
\Phi L(P_{\text{outL}}) & - \Phi L_{ss} = - [\Phi A(P_{\text{inA}}) - \Phi A_{ss}] \\
\end{align*}
\]

\[
\begin{align*}
GL(P_{\text{inL}}) & = GL_{ss} + GA_{ss} - GA(P_{\text{inL}} + GL(P_{\text{inL}})) \\
\Phi L(P_{\text{inL}}) & = \Phi L_{ss} + \Phi A_{ss} - \Phi A(P_{\text{inL}} + GL(P_{\text{inL}})) \\
\end{align*}
\]

- \(\Phi L\) 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
• 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
• CAN PRODUCE CURVES OF ANY SHAPE
• NORMALLY PROCESS AT BASEBAND
• CAN USE EITHER G AND $\Phi$ OR I AND Q
• MUST SAMPLE AT $> 2 \times$ CORRECTION BW FOR G AND $\Phi$
• BUT ONLY $> \text{CORRECTION BW FOR I AND Q}$
• CORRECTION BW (CBW) $>> 3 \times \text{BW OF SIGNAL}$
• MUST USE MANY BITS FOR HIGH CANCELATION ($< 6 \text{ dB}$/)
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: \( SR = CBW = N \times BW \)
  * 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 OBTAINT 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.
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 DIFF.

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

\[ C/I \text{ total} = C/ \sum \sqrt{I_{3}^{2} + I_{5}^{2} + I_{7}^{2} + \ldots} \]

Total C/I preferred to C/I\(_3\)

C/I\(_{\text{min}}\) 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.

C/I (MIN) IN dB

OUTPUT POWER BACKOFF IN dB

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 \( P_{pk} = 2NP_{av} \)

- 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
PROVIDES SIGNIFICANT REDUCTION IN SPECTRUM
EVEN NEAR SAT

> 2 dB POWER INCREASE
REDUCTION IN SPECTRAL REGROWTH PROVIDED BY LINEARIZATION OF A TWTA

![Graph showing reduction in spectral regrowth provided by linearization of a TWTA. The graph plots OPBO in dB on the x-axis and Carrier to Noise Ratio on the y-axis. Two lines are shown: LTWTA and TWTA. The LTWTA line shows a 15 dB reduction compared to the TWTA line at certain OPBO values.]
ETSI STANDARDS

• THE EUROPEAN TELECOMMUNICATIONS STANDARDS INSTITUTE (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) DATAGRAMS WITHIN A DIGITAL VIDEO BROADCAST (DVB) WAVEFORM (EN 301 192).
• PROVIDES AN OPEN FRAMEWORK FOR DELIVERING INTERNET SERVICES OVER SATELLITE.
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 uncoded 16QAM (in multicarrier environment through TWTA) vs Output backoff

LINEARIZER PROVIDES A HUGH ADVANTAGE
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

BER of FEC & Reed-Solomon coded 16QAM (in multicarrier environment through TWTA) vs Output backoff

Output Backoff of TWTA (dB)

LINEARIZER PROVIDES > 2 dB ADVANTAGE AT QEF
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

CENTER 1.30000GHZ

*RBW 100kHz *VBW 10kHz

SPAN 20.00MHz

SWP 50.0ms

*ATTEN 10dB
RL -20.2dBm 10dB/
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
- 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.
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.

Gain transfer response of MZM link at 8 GHz with and without linearization.
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
<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>IMD Improvement (dB)</th>
<th>IIP3 Improvement (dBm)</th>
<th>SFDR3 Improvement (dB·Hz$^{2/3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>13.3</td>
<td>6.65</td>
<td>4.43</td>
</tr>
<tr>
<td>6</td>
<td>20.0</td>
<td>10.0</td>
<td>6.67</td>
</tr>
<tr>
<td>8</td>
<td>23.6</td>
<td>11.8</td>
<td>7.87</td>
</tr>
<tr>
<td>10</td>
<td>17.9</td>
<td>8.95</td>
<td>5.97</td>
</tr>
<tr>
<td>12</td>
<td>12.3</td>
<td>6.15</td>
<td>4.10</td>
</tr>
</tbody>
</table>

**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.

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

• 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.
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 $F_e = \frac{F_\Delta}{2}$

TRANSFER CHARACTERISTICS CHANGE WITH $F_e$
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
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

30 MHz CARRIER SPACING

C/IN dB

Linearizer with Caps
Linearizer without Caps
No Linearizer with Caps
No Linearizer without Caps
Linearized (1MHz Average)
Non-Linearized (1 MHz Average)
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.


