Non Linear Distortion and Dynamic Range Issues in the Design Of Microwave Electronics for Communication and Remote Sensing Systems

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Short course on:

RF electronics for wireless communication and remote sensing systems

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Summary

• **Brief Overview of Wireless Systems**

• **Wireless T/R Front End Design Issues**

• **Non linear distortion, noise and dynamic-range issues in building blocks of wireless communication and remote sensing systems.**

• **Trade-off issues between nonlinear distortion, output power and power added efficiency in the design/optimization of microwave power amplifiers**

• **Basics of new generation electron devices for low-distortion, high-dynamic-range microwave circuit design.**
Wireless Systems Overview (I)

Wireless Cellular Telephone Network (Typ. Freq. : 950, 1800, 2100 MHz)

- (2G) **GSM** (mod. GMSK) - **EDGE** (mod. GMSK/8-PSK)

- (3G) **UMTS** (mod. QPSK)
  - e.g. W-CDMA provides HSPA up to 7Mbs
  - Freq. Band 5MHz

- (3GPP) **LTE** (mod. QPSK, 16-QAM, 64-QAM)
  - expected cell data rates of over 300 Mbps
  - Freq. Band up to 20 MHz

- (4G) IP-based, Software Defined Radio (SDR), Cognitive Radio (CR)
Wireless Cellular Telephone Network

- Downlink (from BTS to Handset)
- Uplink (from Handset to BTS)

Different specs and technologies used for uplink and downlink...

e.g. QPSK - $S/N_{req} = 5dB$
    \[ P_{out} = 23 \text{ dBm} \]

- Uplink (UL)

- Downlink (DL)

- 16-QAM - $S/N_{req} = 11dB$
  \[ P_{out} = 43 \text{ dBm} \]

Base Terminal Station (BTS)

Fig. from Ref.[1]
Wireless Local/Personal Area Network (WLAN/ WPAN)

**WiFi**
- OFDM with subcarriers mod. PSK or QAM)
- based on the IEEE 802.11 standards
- Data rate up to 54 Mbit/s
- Freq.: 2.4 GHz, 5 GHz, Bandwidth up to 22 MHz

**WiMax**
- based on the IEEE 802.16 standard
- Multi-user channel access techniques such as OFDMA
- Peak data rates of 144 Mbit/s in downlink and 35 Mbit/s in uplink (802.16e)
- Freq. 2.3–2.5 GHz and the 3.4–3.5 GHz, Bandwidths up to 20 MHz

MIMO channels available (multiple TX/RX antennas, spatial diversity)
Wireless Sensor Networks

- Spatially distributed autonomous sensors
- Equipped with a radio transceiver or other wireless communications devices
- Small dimensions, low-power consumption, low data rate, secure networking
- Typically based on the IEEE 802.15.4 standard (WPAN)

  e.g. ZigBee in ISM radio bands and 2.4GHz
Back-Haul – Terrestrial and Satellite Communications

• **Point-to-Point** Terrestrial or via-Satellite Microwave Radio Links (e.g. connecting Base Stations)
  
  – dedicated high-capacitive terrestrial radio links at 38 GHz (mod. PSK/QAM)

• **Point-to-Multipoint** Microwave Access Technologies (broadband, fixed wireless, point-to-multipoint technology)
  
  – WiMax
  – Local Multipoint Distribution Service (LMDS) at 28-29 GHz (PSK/QAM)
Wireless Systems Overview (V)

Not only networks…

**Satellite Remote Sensing and Communication**

- Synthetic Aperture Radars
- Altimeters and radiometer applications
- Radioastronomy
- Satellite Radio Links for video, audio and data broadcasting (DVB-S/S2) and Internet Access at 12GHz (downlink) and 18 GHz (uplink) (mod. BPSK, 16APSK and 32APSK)

Frequency Bands: C – X – Ku and beyond…
Reliability issues…
Basic Building Blocks of RF Front-Ends

- Power Amplifier (PA) – provides signal power amplification just before the transmitting antenna
- Low Noise Amplifier (LNA) – provides amplification just after the receiving antenna by introducing minimal S/N degradation
- Mixer – provides up and down frequency conversion of signals
- Local Oscillator – provides sinusoidal waveform for carrier generation
- Frequency Synthesizer – Provides stable and programmable carrier generation and recovery
- Linear Filters and Phase Shifters – for band and channel selection, image rejection, IQ modulation, etc.
- Duplexer - allows using a single antenna for TX/RX
Duplexing

- Single antenna for RX and TX
- Time Division Duplexing (TDD) vs. Frequency Division Duplexing (FDD)
- RX has to be isolated from high power generated by HPA (otherwise: LNA desensitisation)

![Diagram showing RX and TX with TDD and FDD configurations]

Fig. 1: Duplexing Diagrams from Ref. 2
The mixer ideally executes a perfect multiplication of two input signals \( v_A, v_B \)

\[
v_{out}(t) = A \cdot v_{LO}(t) \cdot v_S(t)
\]

The Mixer provides **Frequency Conversion**

\[
v_{LO}(t) = V_{LO} \cos \omega_{LO} t \quad v_S(t) = V_S \cos \omega_S t
\]

\[
v_{out}(t) = \frac{A}{2} V_{LO} V_S \cos (\omega_{LO} + \omega_S) t + \frac{A}{2} V_{LO} V_S \cos (\omega_{LO} - \omega_S) t
\]

- Up-conversion
- Down-conversion

• Actual Mixers suffer from noise and distortion
Example of a Microwave T/R Front-End

Lucent Tech. GSM Transceiver

Fig. from Ref. 2
Typical Trends in T/R Front-End Architectures

- ADC and DAC progressively shift towards the antenna (Software Defined Radio)
- Reconfigurable building blocks (“frequency-agile” RF components and systems)

- Digital RF circuits
- Analog RF circuits with digital control (e.g. with use of RF-MEMS)

- High-efficiency PA schemes (Doherty Amplifiers, Class-S Amplifiers, Envelope Tracking,...)

Linearity ??? PA Linearization techniques

Fig. from Ref. 1

A. Santarelli - Non linear distortion and dynamic range issues in the design of microwave electronics for communication and remote sensing systems – 14th July, 2010
Limiting Factors of Nonlinear RF Building Blocks

Nonlinear RF building blocks of T/R Front Ends (PA, LNA, Mixer, Oscillator and Frequency Syntethasizer) are basically limited in performance by

- Broad-band and Parametric **Noise**
- Nonlinear **Distortion**
- Component **Dynamics** cannot be neglected at microwaves
- **Power consumption** (energetic efficiency, self-heating, reliability)
- Transmission of Wide-Band signals leads to critical requirements for the Receivers in terms of robustness against **strong Interfering Signals**
- **Flexibility and Reconfigurability**
Two basic kinds of noise exist in electrical components:

- **Broad-Band (Additive) Noise**
  (e.g. Thermal, Diffusion/Shot-Noise)
  - Due to fluctuations of carrier velocity
  - Broad-Band White Power Spectral Density (PSD)

- **Parametric (Modulating) Noise**
  (e.g. 1/f Flicker Noise, G-R Noise)
  - Due to fluctuations of carrier population
  - Low Frequency-Generated (LFG) Noise
  - “Colored” PSD
  - Converted to RF by multiplicative mixing phenomena

![PSD Plot](image)
Effects of Noise on T/R Front-End Performance

Broad-Band Noise

• Sensitivity (and dynamic range) reduction of the Low Noise Amplifier
• Noise Figure degradation due to strong adjacent interfering signals

Phase Noise

• Phase Noise of the locally generated oscillation: carrier generation with inherent spurious “noisy” modulation
• Same problem both in the Transmitter and in the Receiver (Carrier Recovery)
• No benefit from increasing signal power since phase noise side-band amplitude also increases proportionally (non additive, but modulation noise)
Distortion in Nonlinear Components (focus on PA)

Which description for the PA?

At microwave frequencies (presence of reactive phenomena) the Power Amplifier is nonlinear with memory

**Linear With Memory:**
\[ y(t) = \int_0^{T_M} h(\tau) x(t - \tau) d\tau \]

**Nonlinear Memory-less:**
\[ y(t) = f[x(t)] = \alpha_1 x(t) + \alpha_2 x^2(t) + \alpha_3 x^3(t) + \ldots \]

**Nonlinear with Memory:**
\[
\begin{align*}
y(t) &= \int_0^{T_M} h_1(\tau_1) x(t - \tau_1) d\tau_1 + \\
&+ \int \int h_2(\tau_1, \tau_2) x(t - \tau_1) x(t - \tau_2) d\tau_1 d\tau_2 + \\
&+ \int \int \int h_3(\tau_1, \tau_2, \tau_3) x(t - \tau_1) x(t - \tau_2) x(t - \tau_3) d\tau_1 d\tau_2 d\tau_3 + \\
&+ \ldots
\end{align*}
\]

VOLterra Series
A Simplified Description of PAs

- Volterra kernels $h_1(\tau_1)$, $h_2(\tau_1, \tau_2)$, $h_3(\tau_1, \tau_2, \tau_3)$, … completely characterize the amplifier nonlinear dynamic response

- Volterra series can be practically used only for weak non-linearity, since kernels measurement at microwave frequencies is difficult

- Modified Volterra Series descriptions exist. They are based on modified kernels and are more suited for practically dealing with weak and strong nonlinearities

However…

Simplified Analysis

- For a simplified analysis of nonlinear distortion in power amplifiers a purely memory-less power amplifier is assumed in the following
Nonlinear Distortion Characterization

Nonlinear Distortion has been traditionally characterized by means of:

- Harmonic Distortion
- Gain compression (Pout vs. Pin, Power Gain vs. Pin)
- Intermodulation Distortion
- AM/AM and AM/PM plots (Complex Gain vs. Pin, Describing Function Approach)

More recently-introduced FoM for dealing specifically with Wireless Systems:

- NPR (Noise Power Ratio)
- EVM (Error Vector Magnitude)
- ACPR/ACLR (Adjacent Channel Power/Leakage Ratio
- …
Harmonic Distortion (I)

Single-Tone Sinusoidal Excitation

$y(t) = f[x(t)] = \alpha_1 x(t) + \alpha_2 x^2(t) + \alpha_3 x^3(t) + \ldots$

Input PA Excitation: $x(t) = X \cos(\omega_0 t)$

PA Output: $y(t) = f[x(t)] = X_{AC-DC} + \sum_{k=1}^{\infty} X_k \cdot \cos(k \omega_0 t)$

Spectral re-growth at Harmonic (angular) Frequencies: $k \omega_0 t$
Harmonic Distortion (II)

- Very simple but scarcely meaningful for microwave communications
- Out-of-band harmonics only (output filtering possible)
- Results can be too optimistic (selective output matching networks = harmonic filtering)
- Non realistic input test signal (constant amplitude carrier, no modulation, zero bandwidth)

Fig. from Ref. 3
Harmonic Distortion (III)

Typical Plots

Transducer Power Gain vs. Pin

- $P_{out1dB}$
- $P_{in1dB}$

1dB (3dB) Compression Point

Pout versus Pin

- $P_{out} [\text{dBm}]$
- $P_{in} [\text{dBm}]$

$1\text{dB} (3\text{dB})$ Compression Point
Intermodulation Distortion (I)

Two-Tone Sinusoidal Excitation

![Diagram of two-tone sinusoidal excitation](image)

**Scalar Measurement**

**PA Memory-less Model:**

\[ y(t) = f[x(t)] = \alpha_1 x(t) + \alpha_2 x^2(t) + \alpha_3 x^3(t) + \ldots \]

**Input PA Excitation:**

\[ x(t) = X \cos(\omega_1 t) + X \cos(\omega_2 t) \]

**PA Output:**

\[ y(t) = f[x(t)] = X_{AC-DC} + \sum_{m,n} X_{m,n} \cdot \cos(m\omega_1 t + n\omega_2 t) \]

**Spectral re-growth at Harmonic (angular) Frequencies:**

\[ m\omega_1 t + n\omega_2 t \]

*Small Tone Spacing:*\n
\[ \Delta \omega = \omega_2 - \omega_1 \ll \omega_0 \]
Intermodulation Distortion (II)

\[ w(t) = \alpha_1 X \cdot [\cos(\omega_1 t) + \cos(\omega_2 t)] + \]
\[ + \frac{3}{4} \alpha_3 X^3 \cdot [\cos((\omega_1 - \Delta \omega)t) + \cos((\omega_2 + \Delta \omega)t)] + \]
\[ + \text{out-of-band terms} + \]
\[ + \text{in-band higher order (odd)} \]

In mild large-signal operation intermodulation distortion is mainly due to 3\(^{rd}\) order non-linearity

\[ \alpha_3 = \frac{1}{6} \frac{d^3 f}{dx^3} \]
Intermodulation Distortion (III)

Carrier to Interference Ratio (CIR)

\[ \text{IMD}_3 = \frac{C}{I} = \frac{P_1}{P_3} \text{ [dBc]} \]

- \( P_3 \) 3\textsuperscript{rd}-order IMD product (in-band: co-channel distortion)
- \( P_5 \) 5\textsuperscript{th}-order IMD product (out-band: adjacent channel distortion)
Intermodulation Distortion (IV)

A closer look to the two-tone excitation...

\[
\begin{align*}
\omega_0 &= \text{central carrier frequency} \\
E_x(t) &= \text{complex modulation envelope} \\
x(t) &= \text{GOOD SIGNAL FOR NONLINEAR TESTING}
\end{align*}
\]

\[
x(t) = \text{Re}\left\{E_x(t) \cdot e^{j\omega_0 t}\right\}
\]

\[
E_x(t) = X_1 \cdot e^{-j\frac{\Delta\omega}{2} t} + X_2 \cdot e^{j\frac{\Delta\omega}{2} t}
\]

\[E_x(t)\text{ has variable amplitude and phase:}\]

\[
0 \leq |E_x(t)| \leq |X_1| + |X_2|
\]

\[
0 \leq \angle E_x(t) \leq 2\pi
\]

- Co-channel and Adjacent Channel Distortion Evaluation
- Input test signal with non-zero bandwidth (amplitude and phase modulation)
- Quite simple measurement set-up
- Scalar Measurement
Third-Order Intercept Point (IP3)

Alternative way of expressing the PA distortion specification

\[ OIP3 = \frac{3 \cdot P_1 - P_3}{2} \]

High-linearity amplifier:

\[ \frac{P_3}{P_1} = -30 \div -40 \text{ dBC} \]
Describing Function Model of PAs

Modulated input signal: 

\[ x(t) = \text{Re}\left\{E_x(t) \cdot e^{j\omega_0 t}\right\} \]

Output signal (neglecting out-of-band harmonics, but including both co-channel and adjacent channel interference): 

\[ y(t) = \text{Re}\left\{E_y(t) \cdot e^{j\omega_0 t}\right\} \]

\( E_x(t), E_y(t) \) are slowly time-varying when modulated signal bandwidth BW<<\( \omega_0 \)

QUASI-STATIC AMPLIFIER DESCRIPTION

No memory on signal modulation envelopes but PA complex response considered at \( \omega_0 \)

\[ E_y(t) = G\left[\omega_0, |E_x(t)|\right] \cdot E_x(t) \]

G is a complex Describing Function only dependent on \( |E_x(t)| \) since PA is a time-invariant non-linear system.
can be measured (vector voltmeter) or computed (HB) under amplitude-swept sinusoidal excitation

\[ G = |G| \cdot e^{j\angle G} \]

- \( G [\omega_0, |E_x(t)|] \) completely describes the nonlinear amplifier response to any signal \( x(t) \) with relatively small bandwidth \( BW \ll \omega_0 \)
- **SCALAR GAIN COMPRESSION (1dB) NOT SUFFICIENT!**
  - no AM/PM conversion;

Complex Describing Function

\[ G = \frac{E_y}{E_x} \]
Adjacent Channel Power Ratio (ACPR)

Quantifying PA performance in the final application

\[
ACPR = \frac{\int_{Bin} PDF_y(f) \cdot df}{\int_{B_{out}} PDF_y(f) \cdot df}
\]

Fig. from Ref. 5

Different definitions of $B_{in}$ and $B_{out}$ depending on the Ref. Std.

<table>
<thead>
<tr>
<th>Type</th>
<th>NB CDMA IS-95 (rev link)</th>
<th>WB CDMA (one approach)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main channel measurement BW</td>
<td>1.23 MHz or 30 kHz</td>
<td>3.84 MHz</td>
</tr>
<tr>
<td>Adj. channel location (from carrier)</td>
<td>± 885 kHz</td>
<td>± 5 MHz</td>
</tr>
<tr>
<td>Adj channel measurement BW</td>
<td>30 kHz</td>
<td>3.84 MHz</td>
</tr>
<tr>
<td>Alt channel location (from carrier)</td>
<td>± 1.98 MHz</td>
<td>± 10 MHz</td>
</tr>
<tr>
<td>Alt channel measurement BW</td>
<td>30 kHz</td>
<td>3.84 MHz</td>
</tr>
</tbody>
</table>
Noise Power Ratio (NPR)

- Used initially for characterizing multi-carrier power amplifiers
- A broad-band Additive Gaussian White Noise (AGWN) source is used to simulate the presence of many carriers of random amplitude and phase
- Band-pass Filtering approximately equal to the Channel Bandwidth
- Equivalent to: \((C+I)/I\)

Fig. from Ref. 6
Error Vector Magnitude (EVM)

- PA Specifications often given in terms of peak and rms value of the EVM
### Specs. of various Wireless Systems (example)

#### ACPR

<table>
<thead>
<tr>
<th>STANDARD</th>
<th>Offset 1</th>
<th>Offset 2</th>
<th>BW (kHz)</th>
<th>Integration Filter</th>
<th>EVM (peak/rms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NADC [13]</td>
<td>±30 kHz</td>
<td>±60 kHz</td>
<td>32.8 kHz</td>
<td>RRC</td>
<td>25%/12%</td>
</tr>
<tr>
<td></td>
<td>−26 dBC</td>
<td>−45 dBC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PHS [14]</td>
<td>±600 kHz</td>
<td>±900 kHz</td>
<td>37.5 kHz</td>
<td>RRC</td>
<td>25%/12%</td>
</tr>
<tr>
<td></td>
<td>−50 dBC</td>
<td>−55 dBC</td>
<td></td>
<td>α=0.50</td>
<td></td>
</tr>
<tr>
<td>EDGE [15]</td>
<td>±400 kHz</td>
<td>±600 kHz</td>
<td>30 kHz</td>
<td>None</td>
<td>22%/7.0%</td>
</tr>
<tr>
<td></td>
<td>−58 dBC</td>
<td>−66 dBC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TETRA [16]</td>
<td>25 kHz</td>
<td>50 kHz</td>
<td>25 kHz</td>
<td>RRC</td>
<td>30%/10%</td>
</tr>
<tr>
<td></td>
<td>−60 dBC</td>
<td>−70 dBC</td>
<td></td>
<td>α=0.35</td>
<td></td>
</tr>
<tr>
<td>IS-95 CDMA [17]</td>
<td>885 kHz</td>
<td>1980 kHz</td>
<td>30 kHz</td>
<td>None</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>−45 dBC</td>
<td>−55 dBC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W-CDMA (3G-PP) [18]</td>
<td>5.00 MHz</td>
<td>10.0 MHz</td>
<td>4.68 MHz</td>
<td>RRC</td>
<td>25%/N/A</td>
</tr>
<tr>
<td></td>
<td>−33 dB</td>
<td>−43 dB</td>
<td></td>
<td>α=0.22</td>
<td></td>
</tr>
</tbody>
</table>

Fig. from Ref. 8
Energetic Efficiency

\[ \eta = \frac{P_{out}^{RF}}{P_{in}^{DC} + P_{in}^{RF}} \]

Power Added Efficiency

\[ PAE = \frac{P_{out}^{RF} - P_{in}^{RF}}{P_{in}^{DC} + P_{in}^{RF}} \]

In the presence of an modulated signal, efficiency becomes a function of the instantaneous signal envelope amplitude:

\[ \eta = \frac{\overline{P}_{out}^{RF}}{\overline{P}_{in}^{DC} + \overline{P}_{in}^{RF}} \]

where, for instance:

\[ \overline{P}_{out}^{RF} = \int P(E_y) \cdot E_y \, dE_y \]

\[ p(E) \] Probability Density Function of the Envelope Amplitude

Fig. from Ref. 8
**Thermal Aspects (PA Self-Heating)**

Power dissipated into the device:
(time-dependent quantity due to the inst. variations of the Env. Amplitude)

\[ P_D = P_{in}^{DC} + P_{in}^{RF} - P_{out}^{RF} = P_{out}^{RF} \cdot \left( \frac{1}{\eta} - 1 \right) \]

Internal Device Temperature:
(thought as spatially averaged along the FET channel)

\[ T = T_B + R_\theta \cdot P_D \]

- High-Efficiency is needed for limiting the Internal Device Temperature
- Peak and Average Internal Device Temperature must be kept under tolerable limits for reliability
- Proper design of the assembly structures for optimal heat extraction (package)
Linearity vs. Efficiency Trade-off

In many power amplifier (e.g. class-A/AB) the maximum efficiency is obtained for peak output power corresponding to a maximum of tolerable distortion.

Whenever the instantaneous input signal envelope amplitude corresponds to input power lower than PEP the efficiency dramatically drops.

Constraints on PA distortion often lead to choose: PEP << Pin1dB (BACK-OFF)

Figs. from Ref. 8
Peak to Average Ratio (PAR)

- High-spectral-efficiency modulation schemes are characterized by large PARs (or crest factor)

- The same happens when a large number of independently modulated sub-carriers are added to form the signal to be transmitted (such as with OFDM)

- PA average energetic efficiency may become extremely low in the presence of large PARs combined with power back-off

- Dedicated PA solutions needed (e.g. Doherty Amplifier)

\[
PAR = \frac{\hat{E}_v(t)_{peak}}{\hat{E}_v(t)_{rms}}
\]

\[\hat{E}_v \] Complex envelope of the modulated signal

<table>
<thead>
<tr>
<th>Mod. (examples)</th>
<th>PAR (typ.) [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>QPSK</td>
<td>3.5-4</td>
</tr>
<tr>
<td>64-QAM</td>
<td>7.7</td>
</tr>
<tr>
<td>W-CDMA (DL carrier)</td>
<td>10.6</td>
</tr>
<tr>
<td>OFDM</td>
<td>12</td>
</tr>
</tbody>
</table>
Effects of Noise and Distortion in LNA and Mixers

Weakest signal detected limited by:

Noise Floor
(Broad-band noise)

Noise Floor Input \( [dBm] = 30 + 10 \log(kTB) + NF_{dB} \)

Strongest Signal limited by:

Nonlinear Distortion
(e.g. P1dB, P3dB)

Spurious Free Dynamic Range (SFDR)
(upper power limit corresponds to 3\(^{rd}\)-order Intermodulation Product equal to the Noise Floor)

DR IS CRITICAL IN WIDEBAND WIRELESS SYSTEMS DUE TO LINEARITY CONSTRAINTS AND STRONG INTERFERING ENVIRONMENT
The Doherty Power Amplifier (I)

- Two PAs combined
  - Carrier PA (class-B)
  - Peaking PA (class-C)
- Only Carrier PA is working for small input signal envelope amplitude (e.g. $P_{in} < \alpha \cdot PEP$ with $0.25 < \alpha < 0.5$)
- Max. efficiency of the Carrier PA is achieved at $P_{in} = \alpha \cdot PEP$ (ideally 78.5%)
- Both PAs contribute output power for $P_{in} > \alpha \cdot PEP$
- Equivalent load impedances vary with increasing envelope amplitude ($Z_{L\text{Carrier}} \downarrow$, $Z_{L\text{Peaking}} \uparrow$) implementing a sort of "active load-pulling" mechanism
- Both PAs deliver 50% of output power at $PEP$
The Doherty Power Amplifier (II)

- Average efficiencies nearly doubled at equal ACPR
- Lower $\alpha$ are chosen for high-PAR signals
- Limitations exist with UWB signals due to freq. selective matching networks and transmission lines

Figs. from Ref. 8
Other Efficiency Enhancement Techniques

Techniques based on “Bias Modulation”

Envelope Elimination and Restoration (EER)
(Final PA stage operating in class-C/D/E/F)

Envelope Tracking (ET)
(Final PA stage operating in class-A/AB)

Limitations with UWB signals due to the limited bandwidth of the Bias Modulator (DC/DC converter)

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Figs. from Ref. 8
PA Linearization Techniques

Three main families of PA Linearization Techniques:

Example: (DIGITAL) PREDISTORTION

- FeedBack
- FeedForward
- Predistortion

Red: Unlin. PA
Blue: Linearized PA

Figs. from Ref. 8, 9
PA Design

• Conflicting requirements on output power, efficiency and high linearity
• Search for optimal values of source/load impedances, bias conditions, bias networks, non-linearity compensating structures, etc
• Device technology suitably chosen according to frequency, output power,…

DESIGN TOOLS

• Source/Load-pull device characterization
  (IMD, output power, power-added-efficiency plots)
• Numerical simulation with suitable non-linear transistor models and CAD tools
  (Harmonic Balance, Transient Simulation, Envelope Simulation)
Source/Load Pull PA Characterization

Plots of main FoM versus input/output reflection coefficients (impedances)
**Nonlinear Transistor Models**

**Physics-based models**: derived by physical principles applied to the device structure

- Direct link between technological process parameters (materials, geometry, doping profile, ...) and electrical response
- More suitable for device design/analysis

**Empirical Compact Models**: measurements based

e.g. Equivalent Circuits use of lumped circuital elements to describe measured characteristics

- Numerically efficient
- Widely used for MMIC and HMIC design
IC Technologies for T/R Front-Ends

Transistors may be available for:
Mixed Analog/Digital Integrated Circuits, MMIC Design, or in Package or Die for Hybrid Solutions

Wireless

• Base-Band Processing:
  CMOS

• RF Front-Ends in Handset and Portable Devices (Pout < 1W):
  SiGe HBT (BiCMOS Integrated Circuits), CMOS, BJT

• RF Front-Ends in Base-Stations (Pout ~ 10-100 W):
  Si-LDMOS, GaN-HEMT

Back-Haul, Satellite Links, Space
Radio-Astronomy, Radars (GHz<f<THz)

• GaAs-PHEMT, GaN-HEMT, GaAs-HBT, InP-PHEMT
## PAs for Handsets (Technology Overview - Dec ‘09)

<table>
<thead>
<tr>
<th>Year</th>
<th>Ref.</th>
<th>Techniques</th>
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<td></td>
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<td>WiBro</td>
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<td>38.2</td>
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<td>16.4% CDMA average efficiency</td>
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</table>

Fig. from Ref. 10

A. Santarelli - Non linear distortion and dynamic range issues in the design of microwave electronics for communication and remote sensing systems – 14th July, 2010

47
SiGe Heterojunction Bipolar Transistor (HBT)

- Similar to well-known BJT, but the Base region is implemented by SiGe instead of Si by creating hetero-junctions (H-J).
- Due to the specific properties of H-J, electron injection efficiency is strongly improved even in the presence of a heavily doped Base
- Very small parasitic effects (and Base resistance) obtained also thanks to the high Base doping
- Extremely good Transition Frequency (frequency at unity current gain with short-circuited output)
- Integration with Standard CMOS processes (BiCMOS)

Fig. 3: Evolution of $f_t$ for IBM SiGe HBT technologies.
Fig. from Ref. 11
BiCMOS (Si-CMOS+SiGe HBT) Technology

- Analog, RF and Digital Circuit Integrated into a single IC Process
- Most suited technology for the Software Defined Radio
- SiGe-HBT offers very low-noise (both 1/f and broad-band)
- Highly reliable

Fig. from Ref. 12 (NEC) 0.18-um RF SiGe BiCMOS
High Power MOSFETs – Si-LDMOS

- Wide low-doped Drift Drain region for high Break-Down Voltage
- Wide channel widths (distributed structures) for High Drain Currents
- Output Power: tens/hundreds of Watt
High Electron Mobility Transistors (HEMT)

- Hetero-Junction (H-J) between AlGaN and GaN layers
- N-Channel confined in a very shallow, almost bi-dimensional region into the intrinsic-GaN
- Extremely high mobility of carriers in the intrinsic GaN
- Devices obtained with high Break-down voltages (~100V), high power densities (5W/mm)
- SiC or Sapphire substrates
- Quite expensive but extremely promising technology

Fig. 3: Photograph of the developed AlGaN/GaN HEMT with a gate width of 5.52mm. Chip size: 2.7mm × 0.6mm × 0.1mm

Fig. from Ref. 13
### A GaN Foundry Example: TriQuint

#### 0.25-mm Gallium Nitride 3MI Process Details

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<th>Element</th>
<th>Parameter</th>
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<td>mA/mm</td>
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<td></td>
<td>$G_m$</td>
<td>300</td>
<td>mS/mm</td>
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<tr>
<td></td>
<td>$V_{bd}$</td>
<td>-70</td>
<td>V</td>
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<td></td>
<td>$V_P$</td>
<td>-4</td>
<td>V</td>
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<td></td>
<td>$F_1$ (peak)</td>
<td>32</td>
<td>GHz</td>
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<tr>
<td></td>
<td></td>
<td>1200</td>
<td>pF/mm$^2$</td>
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<td>Capacitors over vias</td>
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<td>September 2009</td>
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<td>TaN resistors</td>
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<td>50</td>
<td>Ohms/sq</td>
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<tr>
<td>Vias</td>
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<td>Substrate thickness</td>
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<td>μm</td>
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<tr>
<td>Wafer diameter</td>
<td></td>
<td>3 (76.2)</td>
<td>inches (mm)</td>
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#### Features

- 0.25-μm amplifier transistors
- High Q passives
- 3 MIM capacitance densities
- TaN resistors
- High-density interconnects
- 3 metal layers
- Air bridges
- Substrate vias
- Silicon Carbide substrate for excellent thermal conductivity
- Protective Overcoat
- Operation up to $V_d = 40$ V
- Gain: >10 dB @ 18 GHz; >17 dB @ 4 GHz
- 5-7 W/mm
- 50% - 75% PAE

Fig. from Ref. 14
## GaAs-based Technologies (Example: UMS)

### GaAs PHEMT

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<td>HBT</td>
<td>HBT</td>
<td>MESFET</td>
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<td>0.25μm</td>
<td>0.25μm</td>
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<td>Ids (gm max)</td>
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<td>500mA/mm</td>
<td>450mA/mm</td>
<td>600mA/mm</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td>V&lt;sub&gt;BES&lt;/sub&gt; / V&lt;sub&gt;BCE&lt;/sub&gt;</td>
<td>&gt; 6V</td>
<td>&gt; 4.5V</td>
<td>&gt; 12V</td>
<td>&gt; 18V</td>
<td>&gt; 8V</td>
<td>&gt; 16V</td>
<td>&gt; 35V</td>
<td>&gt; 14V</td>
<td>&gt; 14V</td>
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<td>15GHz</td>
<td>3THz</td>
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<td>V&lt;sub&gt;pinch&lt;/sub&gt;</td>
<td>- 0.8V</td>
<td>- 0.7V</td>
<td>- 0.9V</td>
<td>- 0.9V</td>
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<td>- 4.0V</td>
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<td>640mS/mm</td>
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### GaAs HBT

*Fig. from Ref. 15*
# GaAs-based Technologies (Example: UMS)

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<th>Technology Type</th>
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**Fig. from Ref. 15**

- 0.25 & 0.15µm pHEMT
- 2µm HBT technology
- 0.7µm MESFET
- Schottky technology

Our processes include:
- Air bridges
- MIM capacitors
- TaN and TiWSi resistors
- 100µm & 70µm thinning
- Via-holes
Figure References