Digital Predistortion for Wideband 5G Transmitters

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Germain Pham
C²S - COMELEC

dpham@telecom-paristech.fr
Outline

- Introduction
- Power amplifier characterization
- Power amplifier modeling for digital predistortion
- The digital predistortion technique
- DPD challenges & Solutions for 5G
- Conclusion
Wireless civilization

The 5G Infrastructure Public-Private Partnership

Central and Eastern Europe
142%

Western Europe
124%

North America
106%

Latin America
108%

China
96%

APAC
112% (excluding China and India)

Middle East
114%

Africa
81%

India
84%

Global penetration
101%

Subscription penetration (percent of population)
5G disruptive capabilities

- Mobile data volume: 10 Tbit/s/km²
- Peak data rate: 10 Gbit/s
- E2E latency: 5 ms
- Reliability: 99.999%
- Service deployment time: 90 minutes
- Energy efficiency: 10% of current consumption
- Number of devices: 1 Mbit/km²
- Mobility: 500 km/h

Source: 5GPPP - 5G Vision
5G Key enabling technologies

- Wide and contiguous spectrum bandwidth
- New flexible resource management and sharing schemes
- Flexible air interfaces
- New waveforms
- Advanced multi-antenna beam-forming and beam-tracking and MIMO techniques
- Millimeter-waves
- Denser cells leading to ultra-dense networks
5G issue #1: Spectrum scarcity

Spectrum allocation in France

Diagram showing spectrum allocation with various labels such as FIXE, MOBILE, AERONAUTIQUE, SCIENTIFIQUE, SATELLITE, METEOROLOGIE, RADIOAMATEUR, RADIOLOCALISATION, and RADIODIFFUSION.
5G Issue #1: Spectrum scarcity – « Zoom »

Spectrum sharing must be rigorously respected

Bandes 700 MHz, 800 MHz et 900 MHz (LTE Band 28, 20, 8)

Bandes 1800 MHz (LTE band 3)

Bandes 2,1 GHz (LTE Band 33 (TDD), 1 (FDD))

Bandes 2,6 GHz (LTE Band 7 (FDD), 38 (TDD))

Note: les éventuelles bandes de garde de 200 kHz, en haut ou bas de bande, ou entre les attributions de deux opérateurs adjacents ne sont pas mentionnées.
5G issue #2: Energy consumption

- 32% increase in 5 years...
  - 65% in BSs

Sources: Vodafone Sustainability Reports 2015 & 2018
The power amplifier linearity/efficiency trade-off

Percentage contribution of total BS power consumption (mean in brackets)

Sources: [Alberto Conte, Alcatel-Lucent Bell Labs France 2012], [Birafane et al. 2010]
Predistortion and Challenges in 5G

**Predistortion principle**

![Diagram of Predistortion principle]

**Predistortion challenges in 5G BSs**

- High signal bandwidths (>100 MHz) → Memory Effects ↑
- Spectral efficient modulation formats → PAPR ↑
- Energy efficient → Nonlinearity ↑
- Low-cost → Cheaper PA with Nonlinearity ↑
Predistortion with « inverse » functions

Definition

• $g(x)$ is inverse of $f(x)$ when $g(f(x)) = x$
  
  – $g(x)$ is usually denoted $f^{-1}(x)$ by mathematicians

  ![Diagram](image)

  – $g(x)$ does not always exist! Particularly true for nonlinear functions.

  • $g(f(x)) = x$ is usually possible only for a limited range of $x$
    
    – Example: $f(x) = x^2$; $g(x) = \sqrt{x}$ only for $x \geq 0$
      
      (Note the different « nature » of $f(\cdot)$ and $g(\cdot)$)
Consequence on predistortion process

- For DPD systems we only search for approximate inverse
- We need to « know » $f(x)$ to find its inverse $g(x)$
  - First, find an adequate approximation of $f(x)$
  - Second, find an approximate inverse of $f(x)$
Power amplifier characterization
Considered power amplifier

- Abstract view
- General circuit model

Device example
PA characteristics – more details

Actual PA example

**TYPICAL CHARACTERISTICS — 2110–2200 MHz**

- $V_{DD} = 28$ Vdc, $I_{DQI} = 600$ mA, $V_{GSB} = 0.6$ Vdc
- Single-Carrier W-CDMA, 3.84 MHz Channel Bandwidth

**Figure 6. Single-Carrier W-CDMA Power Gain, Drain Efficiency and ACPR versus Output Power**

Source: NXP Semiconductors -- RF Power LDMOS Transistor - A3T21H360W23S
Dynamic characterization with Modulated Signals

- Amplitude and Phase transfer function

**Measurement results with**

LTE signal BW= 20 MHz, PAPR=12.1 dB
Dynamic characterization with Modulated Signals

- Adjacent Channel Leakage (or Power) Ratio (ACLR/ACPR)

Example:
5G specifications ACLR > 45 dBc

\[ ACPR_{dB} = 10 \log_{10} \left( \frac{\int_{BW_{main}} P(f) \, df}{\int_{BW_{adj}} P(f) \, df} \right) \]
Dynamic characterization with Modulated Signals

**Error Vector Magnitude (EVM)**

\[
EVM(\%) = \sqrt{\frac{1}{N} \sum_{i=1}^{N} |S_{actual,i} - S_{ideal,i}|^2} \div \sqrt{\frac{1}{N} \sum_{i=1}^{N} |S_{ideal,i}|^2}
\]

Example:
EVM<12.5% pour LTE-A pour 16-QAM
Linearity requirements for 3G/4G/5G base stations

<table>
<thead>
<tr>
<th>Standard Multiplexing Type</th>
<th>UMTS [37] WCDMA</th>
<th>WiMAX [38] OFDMA</th>
<th>LTE [39] OFDMA</th>
<th>LTE-A [40] OFDMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-channel bandwidth (MHz)</td>
<td>5</td>
<td>1.25, 5, 10, 20</td>
<td>1.4, 3, 5, 10, 15, 20</td>
<td>20</td>
</tr>
<tr>
<td>Maximum aggregated bandwidth (MHz)</td>
<td>60 (12-band)</td>
<td>20</td>
<td>20</td>
<td>100 (5-band)</td>
</tr>
<tr>
<td>In-band requirement EVM(^a) (%)</td>
<td>&lt; 12.5</td>
<td>&lt; 6</td>
<td>&lt; 12.5</td>
<td>&lt; 12.5</td>
</tr>
<tr>
<td>Out-of-band requirement</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACLR1(^b) (dBc)</td>
<td>&lt; −45</td>
<td>&lt; −45</td>
<td>&lt; −45</td>
<td>&lt; −45</td>
</tr>
<tr>
<td>ACLR2(^c) (dBc)</td>
<td>&lt; −50</td>
<td>&lt; −50</td>
<td>&lt; −45</td>
<td>&lt; −45</td>
</tr>
</tbody>
</table>

\(^a\) Based on the 16-QAM modulation scheme.
\(^b\) Refers to the first adjacent channel leakage power ratio.
\(^c\) Refers to the second adjacent channel leakage power ratio.

PA modeling for Digital Predistortion
Characterization and modeling method

Select stimulus type and parameters

Aquire DUT input and output signals

De-embedded data from measurement planes

Identify model

Evaluate model performances

Select model structure

Select model dimension

Source: 2015 - Ghannouchi, Hammi, Helaoui - Behavioral Modeling and Predistortion of Wideband Wireless Transmitters
Modeling accuracy assessment

- **Time domain metric**
  - Normalized Mean Square Error

\[
NMSE = 10 \log_{10} \left( \frac{\sum_{\ell=1}^{L} |y_{\text{model}}(\ell) - y_{\text{meas}}(\ell)|^2}{\sum_{\ell=1}^{L} |y_{\text{meas}}(\ell)|^2} \right)
\]
Nonlinear models – the most popular

- Baseband equivalent signal

\[ x(t) = A(t) \ e^{j\theta(t)} \quad (A(t), \theta(t) \in \mathbb{R}) \]

- Memoryless systems

\[ y(t) = x(t) \cdot G\{A(t)\} = A(t) \ G_A\{A(t)\} \ e^{j(\Phi_G\{A(t)\}+\theta(t))} \]

  - Polar Saleh Model

\[ G_A\{A(t)\} = \frac{\alpha_a}{1 + \beta_a A^2} \]

\[ \Phi_G\{A(t)\} = \frac{\alpha_\Phi}{1 + \beta_\Phi A^2} \]

  - Polynomial

\[ y(t) = \sum_{k=1}^{N} a_k \ |x(t)|^{k-1} x(t) \]

  - Odd order only Polynomial

\[ y(t) = \sum_{k=0}^{N} a_k \ |x(t)|^{2k} x(t) \]
Nonlinear models – the most popular

- Memory polynomial based models
  - Memory polynomial
    \[ y_{MP}(n) = \sum_{m=0}^{M} \sum_{k=1}^{K} a_{mk} x(n - m) |x(n - m)|^{k-1} \]
  - Odd orders only memory polynomial
    \[ y_{MP}(n) = \sum_{m=0}^{M} \sum_{k=0}^{K} a_{mk} x(n - m) |x(n - m)|^{2k} \]
Nonlinear models – the most popular

- Volterra series models

\[ y_{\text{volterra}}(n) = \sum_{k=1}^{K} \sum_{m_1=0}^{M} \cdots \sum_{m_k=0}^{M} h_k(m_1, \cdots, m_k) \prod_{j=1}^{k} x(n - m_j) \]

- Many variations

  - Comparison between memory polynomial based models. (a) Weakly nonlinear memory effects, (b) mildly nonlinear memory effects, and (c) strongly nonlinear memory effects

Source: 2015 - Ghannouchi, Hammi, Helaoui - Behavioral Modeling and Predistortion of Wideband Wireless Transmitters
The digital predistortion technique
Fundamental elements

- **Principle (reminder)**

  Predistortion and PA characteristics, resulting in a matching transfer function.

- **Transmitter architecture**

  - Predistorter's nonlinear characteristics and the PA must match.
  - Nonlinearity of the PA varies with time due to changes in the drive signal, aging, or drifts.
    - Track variations and update predistortion function.

  Diagram showing the transmitter architecture with various components including Predistorter, DAC, ADC, IQ modulator, and power amplifier.
DPD architectures – Closed loop

Closed loop (direct) architecture

Advantages
- No modeling of the PA
- Compensates for time-varying effects

Drawbacks
- Suitable for memoryless systems
- No direct relation between error signal and predistorter’s coefficients

References:
DPD architectures – Open loop

Direct (PA) learning architecture

- « 2 steps » learning
  - PA model is identified first; then the inverse is derived from the PA
  - A theoretical inverse model can be computed as the p-th order inverse
    - Suitable for memoryless systems
DPD architectures – Open loop

- **Indirect learning architecture**

```
\[ x_{in}(n) \xrightarrow{\text{Digital Predistorter}} x_{in \ PA}(n) \xrightarrow{\text{PA}} y_{out}(n) \]
```

- **« 1 step » learning**
  - the PD function is directly derived by calculating the post-inverse of the PA
  - Suitable for memory systems
Computation methodology of the inverse

**Match** $y_{DPD,id}$ and $y_{DPD,est}$

**Example of model oriented metrics**
- Normalized Mean Square Error
  
  $NMSE = 10 \log_{10} \left( \frac{\sum_{\ell=1}^{L} |y_{est}(\ell)-y_{id}(\ell)|^2}{\sum_{\ell=1}^{L} |y_{id}(\ell)|^2} \right)$
Conventional DPD models

[Diagram showing various DPD models and their complexity-performance relationship with references to literature, including [Ghannouchi 2009]]
Objective functions and computational aspects

**Least-squares (LS):** \( \min_{\hat{A}} \| \hat{y}(n) - \Gamma_x(n) \cdot \hat{A} \|^2 \)

- Common approaches: Moore–Penrose pseudo-inverse \( A^+ = (A^H A)^{-1} A^H \), QR decomposition, SVD
- Significant computational complexity \( \mathcal{O}((M \times K)^3) \)

**Least-mean-squares (LMS):** \( \min_{\hat{A}} E[\| \hat{y}(n) - A^H(n) \cdot \gamma_x(n) \|^2] \)

- Iterative approach: \( e(n) = \hat{y}(n) - A^H(n) \cdot \gamma_x(n) \)
  \[ \hat{A}(n+1) = \hat{A}(n) + \mu e^*(n) \gamma_x(n) \]
  - Reduced computational complexity \( \mathcal{O}(M \times K) \)
  - Convergence issues \( (\mu) \)
Objective functions and computational aspects

- **Recursive (weighted) least-squares (RLS):**
  \[
  \min \sum_{i=0}^{k} \lambda^{k-i} |y(i) - A^H(i) \cdot \gamma_x(k)|^2
  \]

  - Iterative approach:
    \[
    e(k) = y(k) - A^H(k-1) \cdot \gamma_x(n)
    \]
    \[
    s(k) = S(k-1) \cdot \gamma_x(n)
    \]
    \[
    \kappa(k) = \frac{s(k)}{1 + \gamma_x^H(n) \cdot s(k)}
    \]
    \[
    S(k) = \frac{1}{\lambda} [S(k-1) - \kappa(k) \cdot \kappa^H(k) \cdot s(k)]
    \]
    \[
    A(k) = A(k-1) + e^*(k) \cdot \kappa(k)
    \]

- Increased computational complexity \(O((M \times K)^2)\)
- Robust convergence
Conclusion

- **Main learning architectures**
  - DLA
  - ILA

- **Choosing an appropriate minimization method requires a reasonable amount of knowledge of the specific identification problem**
  - Stability, speed of convergence and implementation complexity can largely vary between the different methods.
DPD challenges & Solutions for 5G
TX feedback path: the bottleneck

- ADC bandwidth feedback limitation
  - Learning phase
TX feedback path: Band limited and/or low rate DPD techniques

- Band-limited feedback
  [Ma, 2014], [Zhang, 2015]

  Bulky RF filter

  Lower ADC sampling rate

  Compute PA model first

  Sampling frequency of PA model
  = Fullband of distorted signal

- Low rate identification
  [Hammler, 2014]

  xK parallel circuits
TX feedback path: New low rate DPD architecture

- **Subband approach**

  - **Digital Data**
  - **Digital Front-end**
  - **Predistortion**
  - **Multi-band Adaptation**
  - **Frequency Band Decomposition ADC**
  - **Relax speed & computational constraints of DSP**
  - **Reduce sampling rates With subband signals Parallel ADC**

BW ~ 100MHz
TX feedback path : Solution to the signal reconstruction

- Frequency domain

Subband 1
Subband 2
Subband 3

Fullband representation

Time-domain
Low sampling frequency

Frequency domain
TX feedback path: New subband DPD architecture

- FFT-based subband digital predistortion

\[
\begin{align*}
\tilde{X} &= \text{fft}(\tilde{x}) \\
\tilde{Z}_{\text{Lin}} &= \text{fft}(\tilde{z}_{\text{Lin}}) \\
\tilde{Z}_{\text{Lin}} &= \Gamma_V \tilde{h}^{pd} = \tilde{X} \\
\Gamma_V &\sim (\text{fft}(\tilde{z}) \text{ fft}(\tilde{z}|\tilde{z}|^2) \text{ fft}(\tilde{z}|\tilde{z}|^4) \ldots)
\end{align*}
\]
TX feedback path: FFT-based subband DPD – Mitigating subband edge effects

- Limited subband signal reconstruction

\[ Z_{\text{Lin}} \equiv \hat{\Gamma}_V \hat{h}^{pd} = \hat{X} \]
\[ \hat{\Gamma}_V \sim \left( \text{ftf} (\hat{Z}) \text{ftf}(\hat{Z} | \hat{Z}|^2) \text{ftf}(\hat{Z} | \hat{Z}|^4) \ldots \right) \]
TX feedback path: FFT-based subband DPD
– Linearization performance

Correction performance of FFT-based Limited Subband DPD

Error between ideal PD and FFT-based Limited Subband PD

ACLR (dB)

35 40 45 50 55 60

Number of bins per subband (%)

60 70 80 90 100

MSE of PD principal coefficients (dB)

-70 -60 -50 -40 -30 -20 -10 0 10 20

Number of bins per subband (%)

60 70 80 90 100
TX feedback path: FFT-based subband DPD – Linearization performance

Output spectra comparison

AM/AM comparison
RX forward path: the bottleneck

- DAC bandwidth limitation
  - Correction phase

Predistorted LTE-A ~500MHz
MxBW ~ 500MHz
Basic Principle of Analog RF Predistortion

- ARFPD performed mostly in RF, with baseband analog correction signal

- Analog multipliers are used to generate correction signal

For a two-tone signal with memoryless PA

Choose $k_3$ based on PA nonlinearity
Memory-Aware ARFPD

- Roger ISSCC 2013
- CMOS IC implementation in 180nm
  - Power consumption = 200 mW
  - Max. sig. BW = 20 MHz
- EMP based predistorter

\[
Z_{PD,EMP}(t) = x(t) \sum_{k=0}^{K-1} \sum_{q=0}^{Q} a_{kq} \left| x(t - t_p) \right|^k
\]

- Huang et al. TMTT 2015
- Measurement-instruments-based ARFPD platform
  - Max. sig. BW = 80 MHz
- FIR filter in digital BB added to EMP
  - Improves linear memory distortion correction performance

\[
Z_{PD,FIR-EMP}[n] = \sum_{l=0}^{L} h_l x[n - l] \times \\
\sum_{k=0}^{K-1} \sum_{q=0}^{Q} a_{kq} \left| \sum_{l=0}^{L} h_l x[n - l - q] \right|^k
\]
Advantages and Disadvantages of ARFPD

**Advantages:**
- Digital baseband clocked at normal clock rates
- Relaxed specifications of the entire Tx

**Disadvantages:**
- In practice only EMP can be used → limited performance
  - MP needs Q number of RF delays and RF vector multipliers
- Analog implementation → noise, mismatch, offsets, PVT variations
- Inherent nonlinearity is caused by
  - Signal amplitude expansions and compressions, ex: \((0.1)^2 = 0.01\) and \(10^2 = 100\), require high dynamic range
  - Internal bandwidth expansion, ex: correction up to IMD5 requires 1X, 3X, 5X internal bandwidths

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**Overall Low Power!!**
TX forward path: improving DPD architecture – The hybrid Mixed-Signal Predistorter (MSPD)

- **Advantages:**
  - FIR-MP MSPD provides good linearization performance
  - Digital baseband needs to support just the BW
  - Relaxed specifications for DACs and reconstruction filters

- **Disadvantages:**
  - Modulator and Bandpass filter still need 5X BW
  - Analog implementation challenges because of non-idealities
Conclusion
Conclusion

- Digital predistortion is a hot research topic
- Fundamental design considerations of DPD systems have been introduced
- It requires trans-disciplinary skills
  - Analog/RF
  - Data converters
  - Digital
- Many design elements are interacting
  - Multi-level approach is required
- New approaches are required for integration with disruptive technologies for 5G
  - Massive MIMO
  - mmWave