RF power transmitters with high power efficiency and linearity: architectures and linearization by digital predistortion

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- Power efficient radio-architectures and algorithms
  - ESIEE Colleagues: M. Abi hussein, C. Berland, O. Venard, M. Villegas
  - Some recent PHD students and post-doc: T. Gotthans, A. Mbaye, S. Wang, V. Bohara
Context and partnerships on non-linear systems and DPD

Industrial partnerships
- Thales C&S (HF and VHF)
- NXP
- Catena BV
- STMicroelectronics
- Teamcast
- CEA Leti
- AWR / NI software tools

Academic partnerships
- Brno university
- Supelec Rennes IETR

Recent research projects
- Par4CR: Partnership for development of cognitive radio. FP7 people IAPP.
- PANAMA: Power Amplifier and antenna for mobile. Catrene
- AMBRUN: Amplification of Wideband multi-channels signals for broadcast and unicast systems. FUI
- MORF2: Multiplex OFDM Radio over Fiber. FUI
- APOGEE: Amplification reconfigurable multimode. FUI

Outline
- Context of 3G/4G/5G systems
- Transmitter Architectures
  - Common Tx architectures
  - Doherty PA
  - Sampled architecture
  - EER
  - ET
- Linearization by digital predistortion
  - Principle
  - Some challenges
CONTEXT OF 3G/4G/5G SYSTEMS

Context and perspectives

- **Today:** OFDMA-SCFDMA/MIMO technologies for 4G systems
- **Cooper’s law** (ArrayComm):
  - Since Marconi 1895, the capacity of radio communications (nb of possible conversations in a given area using the full usable spectrum): \( \times 2 \) every 30 months.
- **The very close future:** capacity 1 Gbps/Km²
  - **new applications, needs and concepts:**
    - Streaming video, social media, maps, cloud computing, IoT, tactile internet, V2X, self-driving, PMR, MANET multi-emitter/receiver modes …
    - Massive MIMO, carrier aggregation, cognitive radio, mmWave
  - **architectures/ technologies for transceivers** to support them.
**PA influence in transmitters**

- Common Modulations: M-QAM, OFDM,…
  - High spectral efficiency
  - But high PAPR

**Non-linearity and Memory effects**

- Signal distortions in the main channel EVM
- Spectral regrowth out of band ACPR

Compromise efficiency/linearity

**Factors of merit: EVM, ACPR, noise**

- **EVM (Error Vector Magnitude)**
- **ACPR (Adjacent Channel Power Ratio)**
- **Noise**: DAC/ADC, phase noise of oscillators, sampling images, frequency images
**BTS and UE power consumption**

- **BTS of cellular networks:** consume 85% of the network energy
- **Typical power consumption:** 150 W to 10KW
- **PA efficiency** depends on the load of the BTS:
  - 10% (low load) → < 10%
  - 50% (busy hour) → < 30%
  - 100% → < 60%

**Smartphone:**
- **Arm A9 CPU:** 0.5 to 1.9 W
- **Display:** 0.5 W
- **GPS:** 0.2 W
- **Microphone, sensors:** 0.1 W each
- **Bluetooth:** 0.1 W
- **Recording video:** 0.2 to 1 W
- **Active cell radio:** up to 0.8 W

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**Diversity of air interfaces in a mobile device**

- **Cellular:** GSM/GPRS/edge, UMTS/HSPA/HSPA+, LTE/LTE-A
- **Modulations:** GMSK, MPSK, MQAM, OFDM, OFDMA, SC-FDMA, FM
- **Spread spectrum, multiple access:** DS-SS, FH-SS, FDMA, OFDMA, TDMA, CDMA
- **Duplex mode:** FDD, H-FDD, TDD

**Tx Bandwidths:**
- 15 to 200 MHz

**Channel bandwidths:**
- 0.2 to 20 MHz (without CA) and 160 MHz in 802.11ac

**Frequencies:**
- most common 0.6 to 6GHz
- 5G: sub-GHz, C-band, mmWave

**Max output power:**
- Typ < 33dBm

**Ex:** Europe LTE FDD bands

- 20 8 3 1 7
- In GHz: 0.8, 0.9, 1.8, 2.1, 2.6

**Need for Multi-Mode Multi-band PAs**
**Heterogeneous Radio Access Network**

- Small cell
- Macro cell
- Relay
- Optical fiber backhaul
- Wireless backhaul

To improve spectral efficiency per coverage area bps/Hz/km²
- Small, micro, pico, femto cells with coordination between cells (interference cancelling ICIC and cooperation CoMP)

Dense network of small cells
- High data rate
- Limited Tx power (1W to 60 W)
- Several technologies and bands
  - Massive MIMO and mmW

**Flexible/ dynamic spectrum access for 4G-5G**

- Increased DL and UL data rate and capacity
- Spectrum scarcity and Fragmented spectrum
- Carrier aggregation CA (LTE-A-3GPP release 10)
  - Combines multiple LTE Component Carriers CC (each up to 20 MHz) to obtain wider BW (efficient use of fragmented spectra)
  - From 5 CC in rel 10 → 32 CC in rel 13 with objective 1Gbps DL
  - Deployment started with DL CA, soon UL CA (China)
  - CA intraband contiguous or not and interband (CC spread across different bands; possibly more than 1 GHz apart)
- Multi-carrier and post-OFDM waveforms
  - Better spectral occupation and efficiency
  - Simplified asynchronous links (IoT) and decreased latency (PMR)
CA: DL data rates 4G towards 5G

CA deployment

- 150 Mbps 10+10 MHz 2x2 MIMO (2013)
- 300 Mbps 20+20 MHz 2x2 MIMO (2014)
- 450 Mbps 256QAM 2x2 MIMO 3GPP Release 13 (2015)
- 600 Mbps 4 CC 256QAM 2x2 MIMO 3GPP Release 17 (2016)
- 1 Gbps 5 CC 256QAM 8x8 MIMO (2020)

Consequence of CA on UE RFFE

- Baseband processors And RF transceiver
- Tx/PAs
- Rx/LNAs
- Band selection, switches, Multiplexers, duplexer, antenna tuning

Challenge: Cross isolation between aggregated bands while maintaining low insertion loss

Must support Multi-bands, multi-modes, CA, MIMO/diversity
**Consequence on UE RFFE**

- **Several antennas and PAs:** low, mid and high bands
  - e.g.: 2 primary cellular / 2 diversity/MIMO antennas.
  - UE receives (or Transmits) simultaneously on multiple Rx bands.
- **Non-Linearities** create harmonics and intermodulation IM<sub>n</sub>
- **Case of widely separated bands**
  - Harmonic frequencies must be considered (B8-B7, B4-B17, ...)
    - Tx/Rx in B8 + Rx in B7: B8 (880-915) 3rd harm falls in Rx B7 (2620-2692)
- **Case of close bands**
  - B2 + B4 (or B8+B20): Tx of one band can desensitize Rx of the other band
  - Intra-band aggregation is easier but generate wide bandwidth signals with high PAPR to be transmitted by a single PA
- **UL CA:** Interband or intraband non-contiguous can create IM that fall into Rx bands or other critical bands (GPS)

**Challenges for UE RFFE**

- **MMMB (Multi-band, Multi-mode) PA**
  - High linearity: still more important than in conventional Tx to avoid harmonics (harmonic isolation 90dB between PA output and Rx input) and IM<sub>n</sub>
  - High efficiency (to compensate high insertion losses after PA)
  - With large bandwidth and high PAPR signals
- **Filters:** very high rejection of harmonics with small insertion loss
- **ET and APT** with wider BW
- **Tunable components:** with linearity and low losses
- **Integration of several antennas**

Objective: good isolation between and within bands, with high linearity and low insertion loss for low power consumption
Towards 5G: objective for PA and linearization techniques

**UE PA**
- MMBB PA
- Very wide band
- Very linear to facilitate CA
- Very low power consumption (battery life)
- Very low cost
- Small size
- Output power < 2W
- Low complexity linearization technique

**BTS small cells PA**
- MMBB PA
- Very wide band
- Very linear to facilitate CA
- Low power consumption to reduce OPEX
- Low cost
- Medium size
- Output power 1 to 60 W
- Possible complex linearization techniques
  - Managing harmonics, cross-talk

**TX ARCHITECTURES**
**Tx architectures**

**Cartesian** \( z(t) = z_x(t) + jz_Q(t) \)  
**Polar** \( z(t) = A(t)e^{j\phi(t)} \)

Common architectures
- **Cartesian** common architectures:
  - 2-stage conversion (heterodyne), direct conversion (homodyne). **Mixer based**
- **Polar** common architectures:
  - Modulation loop. **PLL based**

Architectures for PA linearization and/or efficiency enhancement
- Dynamic biasing, envelope tracking ...
  - Improve efficiency of a quasi-linear PA
- Based on signal transformation or decomposition for constant envelope: LINC, EER, sampled architecture with SMPA
  - Improve linearity of an efficient PA

**Towards digitization of Tx architectures**

**RF analog architectures**
- Improved by digital signal processing

**RF sampled architectures with switched mode PA SMPA**
- Polar or cartesian.
- **RF filtering** to recover the signal

**RF digital architectures with quasi-linear PA**
- Digitization of functional blocks.
- **DAC just before PA.**

**Baseband DAC**
- with increased sampling frequency or **RF DAC**

**Coding of signals**
- **PWM, \( \Sigma \Delta \)**

**RF DAC**
Technological aspects

**Si LDMOS**
- Mature technology robust, DPD friendly, low cost
- But large Cds capacitance

**GaAs HEMT/HBT**
- Microwave applications: defence ...

**Si CMOS**
- Not optimised RF processing.
- Diminution of supply voltage: difficult to generate high power levels
- Increase of switching frequency and density → new digital processing methods

**GaN on SiC**
- High output power thanks to
  - High power density
  - High breakdown voltages
  - Good thermal conductivity
- Wide bandwidth operation
  - High impedance
  - High electron mobility
  - High Ft
- Low capacitance
  - Cds ~ 6pF vs 30 pF for LDMOS
- Reliability ?
- DPD ?
- Cost ? GaN on Si ?
- Evolution towards GaN on Si ?

Methods for improving linearity and efficiency

![Diagram showing different methods for improving linearity and efficiency](slide22)
Basic principles

- With quasi-linear biased class PA (A, AB, B, C)
  - Adaptation to the average or instantaneous power
  - Modification of bias point
    - Dynamic biasing, ET, EER: modifies bias current and voltage
  - Modification of load impedance
  - Doherty PA

- With high-efficiency switched mode PA
  - Modifies the input signal: sigma delta or PWM coding

Principle of Doherty PA

- Dynamically adapt the load in function of the input power from $2\, R_L$ to $R_L$.

- Ideal conditions:
  - Both PA are ideal current generators
  - PA gains identical and independant of biasing and drive level.
  - No parasitics elements
Some improved DPA topologies

- Compensation of parasitics for output power combiner
  - Ex: iDPA (Ampleon) with symmetric topology: instead an equivalent broadband transmission line is used → 28 % fractional bandwidth
- Asym 2 ways: max efficiency at 9.5 dB back-off but degrades BW
- N-way DPA: 1 main PA + N-1 peak PA, asymmetric or symmetric
  - To increase efficiency in an extended back-off range
  - Improved fractional BW up to 50%

Current DPA for 10 dB PAPR, 20 MHz input signals
- Fractional bandwidth ~ 50 %
- Drain efficiency ~ 50 %
- DPD is generally needed

Digitally driven dual input DPA

- With baseband processing
  - Generate input signals for carrier and peak PAs
  - Improving linearity, Phase alignment, and efficiency
- Two separate RF inputs

Roland Sperlich, Gregory Clark Copeland, Russell Hoppenstein, Hybrid Doherty Amplifier System and Method, US patent 20080111622 A1
**Sampled architectures with SMPA**

- RF or baseband coding with PWM or sigma-delta
- Constant envelope → saturated or switched mode PA
- Band-pass RF filter to reconstruct the signal and filter the coding noise. Critical element!
- Oversampling of signals before coding

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**Sampled architectures with SMPA**

- **Good candidates for multiradio Tx** able to support wireless communications standards below 6 GHz
  - high efficiency power amplifiers such as switched-mode PAs.
  - highly flexible and easy to integrate because of their sampled/digital nature.
- **Transmitter efficiency** depends on:
  - Signal coding efficiency, PA efficiency, RF filter
- **Reconstructed signal quality** function of:
  - Type of coding, sampling frequency, BW limitation, reconstruction filter
- **Output filter bandwidth:**
  - in a multi-channel system, the bandwidth should be the total bandwidth and not that of a single channel (ex: a full LTE band: 60 MHz for LTE band 1)
  - To alleviate the number of filters
  - But OSR is reduced

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Séminaire COMELEC 02/03/2017
Sampled architectures with SMPA

- **RF sigma-delta coding**: sampling frequency 4 times (or twice) the carrier frequency. Jararaman (1998)
- **Baseband coding** with polar or cartesian architectures:
  - polar sigma/delta, cartesian sigma/delta, polar PWM and Cartesian PWM architectures.
  - PWM or sigma delta: periodic reference signal at \( f_{pwm} \), smaller than sigma/delta sampling frequency.

Ex of architectures with base-band \( \Sigma \Delta \) coding

To minimize noise folding:
\[ f_{\Sigma \Delta} < 2 f_c \]
\[ f_{\Sigma \Delta} = 2 f_c / m \]
**PADR vs PAPR**

**Ex: ideal PWM baseband coding polar architecture**

\[ x(t) = x_1(t)x_2(t) \]

- \( x_1(t) \) is PWM coded on 2 levels (1 or 0). Duration of pulses proportional to \( A(t) \).
- \( x_2(t) \) multiplied by the PWM train of pulses. Also known as carrier PWM or burst mode amplification.
- \( x(t) \) is reconstructed by a pass-band RF filter after PA.
- Coding efficiency defined as:
  \[ \eta_{c} = \frac{P_{\text{band}}}{P_{\text{total pulse train}}} \]
- For \( A(t) = A \), pulse duty cycle \( \delta \) proportional to \( A/A_{\text{max}} \):
  \[ \eta_{c} = \frac{\delta^2}{\delta} = \delta. \]
- Average coding efficiency:
  \[ \bar{\eta}_{c} = \frac{1}{P_{\text{ADR}}} \]
- Global efficiency = product of coding and PA efficiencies:
  \[ \eta = \bar{\eta}_{c}\eta_{PA} = \frac{\eta_{PA}}{P_{\text{ADR}}} = \frac{\eta_{PA}}{\sqrt{P_{\text{PAPR}}}}. \]

Could be optimised by recuperating and recycling out of band energy at PA output with efficiency.

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**EER Envelope Elimination and Restoration**

\[ x(t) = A(t)\cos(\omega t + \phi(t)) \]

- Proposed by Kahn
- Very good efficiency = RF PA efficiency 
  \* x BB PA efficiency
- Saturated RF PA or SMPA

- Necessitates a very precise synchronization of both paths
- Calibration loop or adaptive filtering to compensate for the time misalignment
- Difficulties with low level envelope amplitude
- Bandwidths of components are higher than the original signal bandwidth

Barely used
**ET Envelope Tracking**

\[ x(t) = A(t) \cos(\omega t + \phi(t)) \]

\[ x_1(t) = A(t), \quad x_2(t) = A(t) \cos(\omega t + \Phi(t)) = x(t). \]

- **Instantaneous envelope** signal modifies the supply voltage of the RF PA.
- Envelope mapping optimized for a given criterion: maximum efficiency, constant gain.
- **Does not track very low level envelope amplitude** unlike EER.
- **Challenge**: designing an ET power supply wideband, highly efficient and low noise for very wide band and high PAPR signals.

**Envelope mapping for ET**

- RFPA efficiency and gain depend on RF input voltage and on supply voltage \( V_{PS} \).
- Different efficiency curves for different supply voltages.
- Mapping of the magnitude: optimal relation between \( A(t) \) and \( V_{PS} \) for a given criterion.
- Criterion maximum efficiency (DPD to correct gain and phase distortion).
- Criterion constant gain (alleviates DPD, phase distortion mainly).
- A minimum value is fixed for \( V_{PS} \).
**APT Average Power Tracking**

- **Average power** modifies the RF PA voltage supply per block
- **Slow variations**
- **Efficient low noise switch mode power supply:** ∼95% efficiency
- **Improves global efficiency at low and medium average output power**
- **But does not improve efficiency at high output power (PAPR problem).**
- **Tx efficiency up to 30% with LTE UL signals (6dB PAPR) and UE PA**
- **Can be associated with ET**

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**ET power supply**

- **Objective:** high efficiency, accurate, wide band, low noise, able to manage high PAPR signals
- **Common approach:**
  - APT + linear error amplifier coupled with a diplexing circuit
  - 85% efficiency for 20 MHz LTE signals → efficiency ∼45% for LTE Tx at high power
ET characteristics

- Efficiency for LTE UL 6dB PAPR ~ 50 % at high power
- Good synchronisation of both paths necessary (1% of 1/BW)
- Constant gain mapping interesting: efficiency only slightly decreased and better linearity. Small decrease of the RF PA gain (1 to 2 dB typical)
- Careful design of the PA supply line is necessary (minimize bias bypass capacitance)
- Supply noise must be minimized (conversion to RF noise)
- Load impedance variation (antenna, duplex filters, ...) must be compensated
- For the future: greater bandwidths and PAPR
  - Necessary to consider the memory effects (bias network response ...)
  - High bandwidth error PA
  - Higher integration to minimize PA supply line problems


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In between EER and ET

**EER**
- RF input:
  - Constant envelope
  - Very wide BW
- Envelope signal
  - High PAPR
  - Wide BW

**ET**
- RF input:
  - High PAPR
  - Moderate BW
- Envelope signal
  - High PAPR
  - Wide BW

- Between ER and ET
  - Different decomposition of the signal
  - RF input between constant envelope and complete signal
  - Restoration realized by RF stage and dynamic power supply.

Reduce constraints on PAs design

Reduce PAPR or BW

EF-PER envelope factorization with partial elimination and restoration

Slide 37

Slide 38
EF-PER

\[ x(t) = A(t) \cos(\omega t + \phi(t)) \]
\[ x_1(t) = A(t)^\alpha \quad x_2(t) = A(t)^\beta \cos(\omega t + \phi(t)) \]

New degree of freedom to share constraints (PAPR, BW) between RF and baseband paths.

Mapping function: \( g() \), linear for \( \alpha + \beta = 1 \).

OFDM 1024 carriers, 64 QAM, 256 Symbols

LINEARIZATION BY DIGITAL PREDISTORTION

Principle of digital predistortion
**Equivalent filtered baseband model**

**RF domain**

![RF domain diagram]

\[ x(t) = \Re\{\tilde{x}(t)e^{j\omega t}\} \]

\[ y(t) = \Re\{\tilde{y}(t)e^{j\omega t}\} \]

**Baseband model**

![Baseband model diagram]

**Common baseband parametric models stemming from Volterra series**

- **Interests and drawbacks**
  - **Generality**: arbitrary precision, linearity vs coefficients
  - **Complexity**: non-orthogonal kernels, number of kernels, convergence

\[ y(n) = \sum_{k=0}^{K-1} \sum_{m_{1}=0}^{M_{1}-1} \cdots \sum_{m_{K-1}=0}^{M_{K-1}-1} h_{2k+1}(m_{1}, \ldots, m_{2k+1}) \prod_{i=1}^{2k+1} x(n-m_{i}) \prod_{i=4}^{2k+1} x(n-m_{i}) \]

- **Techniques to decrease complexity**
  - MP: Memory polynomial models (Kim, Constantinou)
  - GMP: generalized MP
  - Separation NL and memory: wiener, Hammerstein
  - Multi-stage models
Common parametric models

MP: Memory Polynomial
J. Kim, K. Constantinou

\[ y(n) = \sum_{k=0}^{K-1} \sum_{m=0}^{M-1} a_{k,m} x(n - m) [x(n - m)]^k \]

GMP: Generalized Memory Polynomial
D.R. Morgan, Z. Ma, G. Zierdt, J. Pastalan

\[ y(n) = \sum_{k=0}^{K-1} \sum_{m=0}^{M-1} a_{k,m} x(n - m) [x(n - m)]^k + \sum_{k=1}^{K-1} \sum_{l=0}^{L-1} \sum_{m=1}^{M-1} b_{k,l,m} x(n - l) [x(n - l - m)]^k + \sum_{k=1}^{K-1} \sum_{l=0}^{L-1} \sum_{m=1}^{M-1} c_{k,l,m} x(n - l) [x(n - l + m)]^k \]

DDRI:
Dynamic Deviation Reduction
A. Zhu, C. Pedro, T.J. Brazil

\[ y(n) = \sum_{k=0}^{K-1} \sum_{i=0}^{I-1} g_{2k+1,i}(z) x(n - i) \]
\[ + \sum_{k=1}^{K-1} \sum_{i=1}^{I-1} g_{2k+1,i}(z) x(n) \sum_{j=1}^{M} x^j(n) x^j(n - i) \]

Neural networks

- Network topology, non linear activation function
- Learning: Lenvenberg-Marquardt
- Multi-layer perceptrons, universal approximation theorem (Cybenko)
- PA model: complex signals and dynamic behavior

NNETS
- Bounded nonlinear functions
- Complexity of training algorithms

Volterra series (pruned)
- Linear to their coefficients
- Low complexity
- Based on unbounded functions

DPD identification, vocabulary

**ILA: Indirect Learning approach**

- Desired complex gain of the cascade DPD + PA
- Nonlinear x-filtered LMS (NFXLMS), NFXRLS, Nonlinear Adjoint LMS and RLS.
- Direct Analytical inversion
- Pth order inverse

**DLA: Direct Learning approach**

- Nonlinear x-filtered LMS (NFXLMS), NFXRLS, Nonlinear Adjoint LMS and RLS.
- Direct Analytical inversion
- Pth order inverse

Some results on a broadcast Doherty PA

**PM K=13, M=1.**

**DDR2 K=13, M=1.**

**GMP 16 coefficients**

\[ z_p = \Phi b, \ LS \ on \ N \ samples \]

\[ e(n) = x(n) - z_p(n) \]

\[ \Phi^{dL} = \Phi^{dL} \]
Some challenges for DPD

- **DPD Architectures** and identification algorithms
  - Multi-stages
  - Partitioning of the input signal space: SCPWL (piecewise linear), decomposed vector rotation, vector switched model
- **Wide bandwidths**: multi-band, subbands, harmonics
- **Low complexity DPD** for low power PA (UE)
- **DPD and new waveforms for 5G**: FBMC, UFMC, GFDM ...
- **DPD in MIMO systems**: cross-talk
- **Joint optimisation DPD / CFR** (Crest Factor Reduction)
- **Dimensioning**: determination of DPD model structure
- **Output load mismatch**: PA gain variation, impairments
- **Agile DPD**: non stationary signals, dynamic reconfiguration for different transmission scenarios, operating points and CFR/DPD
Architectures for baseband DPD

- **Choice criteria**
  - Representation of non-linearities and memory effects
  - Processing of complex signals
  - Linearity with respect to the coefficients
  - Good conditioning of computation for model identification
  - Computational complexity of the DPD and its identification
  - Efficiency for complex PA structures: Doherty, ET

- **Some interesting approaches**
  - Multi-stages structures
  - Partitioning of the input signal: AM/AM
    - Simplicial canonical piecewise linear function (SCPWL)
    - Decomposed Vector Rotation-Based model: Zhu 2015
    - Decomposition of the input signal space by VQ: Vector Switched Model: S. Afsardoost, T. Eriksson, C. Fager, 2012

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Multi-stages DPD

Abi Hussein M., V. A. Bohara, and O. Venard. Multi-Stage Digital Predistortion Based on Indirect Learning Architecture. ICASSP2013
Models SCPWL and decomposed vector rotation

Model SCPWL Chua et Kang 1970 extended to the case with memory. No polynomials with high degrees but absolute values.

\[
y(n) = \sum_{i=0}^{M} a_i x(n-i) + b + \sum_{k=1}^{K} c_k \left[ \sum_{i=0}^{M} a_{ki} x(n-i) - \beta_k \right] \]  
\(K\) partitions

But: But non-linear with respect to coefficients and does not take into account complex signals.

Decomposed Vector Rotation-Based model A. Zhu, 2015.

\[
\tilde{x}(n) = \left[ \tilde{x}(n) \right] e^{j\varphi(n)} \text{ vector decomposition and phase restoration.}
\]

\[
\tilde{y}(n) = \sum_{i=0}^{M} a_i \tilde{x}(n-i) + \sum_{k=1}^{K} \sum_{i=0}^{M} c_{ki} \left[ \tilde{x}(n-i) - \beta_k \right] e^{j\varphi(n-i)}
\]

Possibility to add cross-terms to improve accuracy of the model.

Multi-band (mux) DPD

Ex: tactical multiplex 1 OFDM or QAM + 1 GMSK with frequency hopping.

Global DPD: full band
- Global digitizing of the multiplex signal
- Application of the DPD similar to uniband DPD
- Possible for limited bandwidth
- BW < 40MHz here

Multi-band DPD
- Separate digitizing of bands
- Separate processing of bands
- Necessary to take into account the contribution of other subbands
**Dual-band input: psd at PA output**

Interactive analysis. Consideration of modulated signals.
Origin and propagation of spurious: contributions of the different circuits.

Two signals 40 MHz apart,
7th order PA NL model
PA output:
40 signals near Tx bands

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**Dual-band DPD**

F. Ghanouchi,
P. Roblin ...

With a Single Feedback Loop
Y. Liu, J. Yan, P. Asbeck,
2015
Subband DPD

Successive simplification steps

\[ z_p = F(z) \]

DPD and harmonic filtering

- Objective: reduce the bulky harmonic filters at the PA output
- DPD: linearisation of the fundamental band and reduction of harmonics
- Equivalent filtered baseband model no more valid: \( \rightarrow \) harmonic injection

Arbitrary waveform generator MXG8190A, 12GS/s
baseband Bandwidth = 6 GHz
Digital frequency conversion
Digital oscilloscope 81004B, 40 GSps

Low complexity DPD model: FLUT filtered lookup table

- For mobile handsets or wide BW signals
- DLA for the LUT
- ILA for the filters

Test:
Class AB PA, 1.455 GHz, AsGa MESFET
Signal: sum of 16 CDMA, 16 QAM, RRC=0.22
LUT N=64
FLUT N=64, L=8 (FIR lengths)
MEM-POLY, K=6, M=1

FLUT: 10 times less complex than memory polynomial and gain of 6 dB on ACPR vs LUT.

Dimensioning of the DPD

MP and DDR models: 2 parameters

MP: Limit NMSE -36 dB.
- $M = 1$ et $K = 9 \text{ or } 10$
- Nb coefficients: $K(M+1) \sim 20$ coefs

DDR2: NMSE -40,8 dB.
- $M=1$ et $K=13$,
- 32 coefs

GMP model: 8 parameters $K_x, L_x$

Exhaustive search, e.g. integers bounded to $10^8$ tests.

Exhaustive Search: Nb of coefficients < 80

4 790 361 structures
Search duration ~ 2 days

Search algorithms:
to find solutions with good tradeoff between accuracy and complexity

Dimensioning of the DPD

Search algorithms:
- Genetic integer algorithms
- Hill-climbing type algorithms with different neighborhoods

Combined criterion
- Additive
- Multiplicative

Ex: hill climbing
Less than 5000 tests executed in a few minutes

Other approaches
- Parametric: Sparsity hypothesis of Volterra kernels
- Non-parametric: Kernel smoothing estimator

• Important to detect variation of system gain due to VSWR or any kind of system gain modification (power supply ...).
• Application of an adaptative corrective gain.
• Interest of an adaptive output matching network

Joint optimization of DPD and CFR

Common CFR usually degrades signal quality. Limitation of possible avalanche at the DPD output.

What should be the min crest factor reduction for $\text{PAPR}_{\text{DPD}} < \text{PAPR}_{\text{Limit}}$?

- $\Delta_{\text{pap}} = \frac{2 \cdot \text{pap}_\text{PA}}{\text{pap}_\text{PA}}$ is the highest nonlinearity order in GMP model

- Combining Crest Factor Reduction and Digital Predistortion with automatic determination of the necessary Crest Factor Reduction gain, EUMW 2014

Conclusion

- ET, DPA and sampled mode architectures (SMPA) are good candidates for 5G BTS and UE.
  - Some on going research on DPA for handsets
- GaN should improve performance thanks to higher speed and smaller $C_{\text{ds}}$
- CMOS progress will facilitate high speed sigma delta and sophisticated signal processing to compensate dirty RF.
- Integration of PA + ET to simplify supply line design
- RF filters critical elements for switched mode architectures and cross isolation (CA). Tunability?
- DPD should consider harmonics of signals (analog PD?)
- CFR may be useful even for sampled mode architectures (PADR-PAPR)