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Digital Predistortion for Wideband 5G Transmitters

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Une école de l'IMT

Digital Predistortion for Wideband 5G Transmitters

21st March 2019

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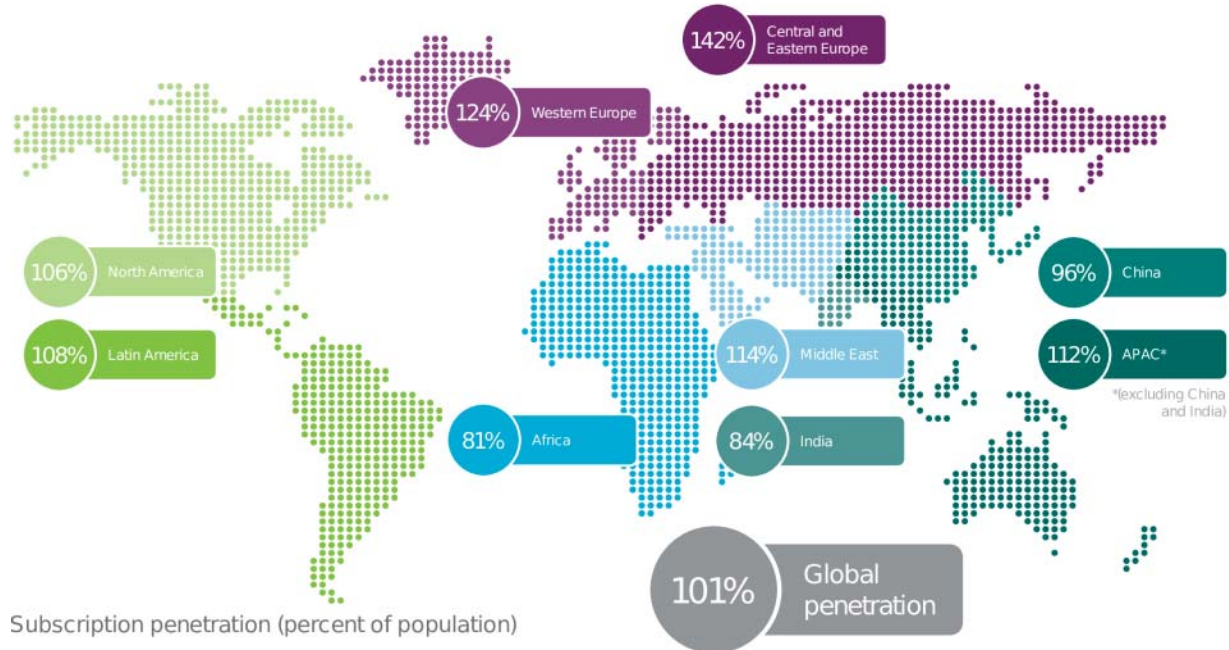




Outline

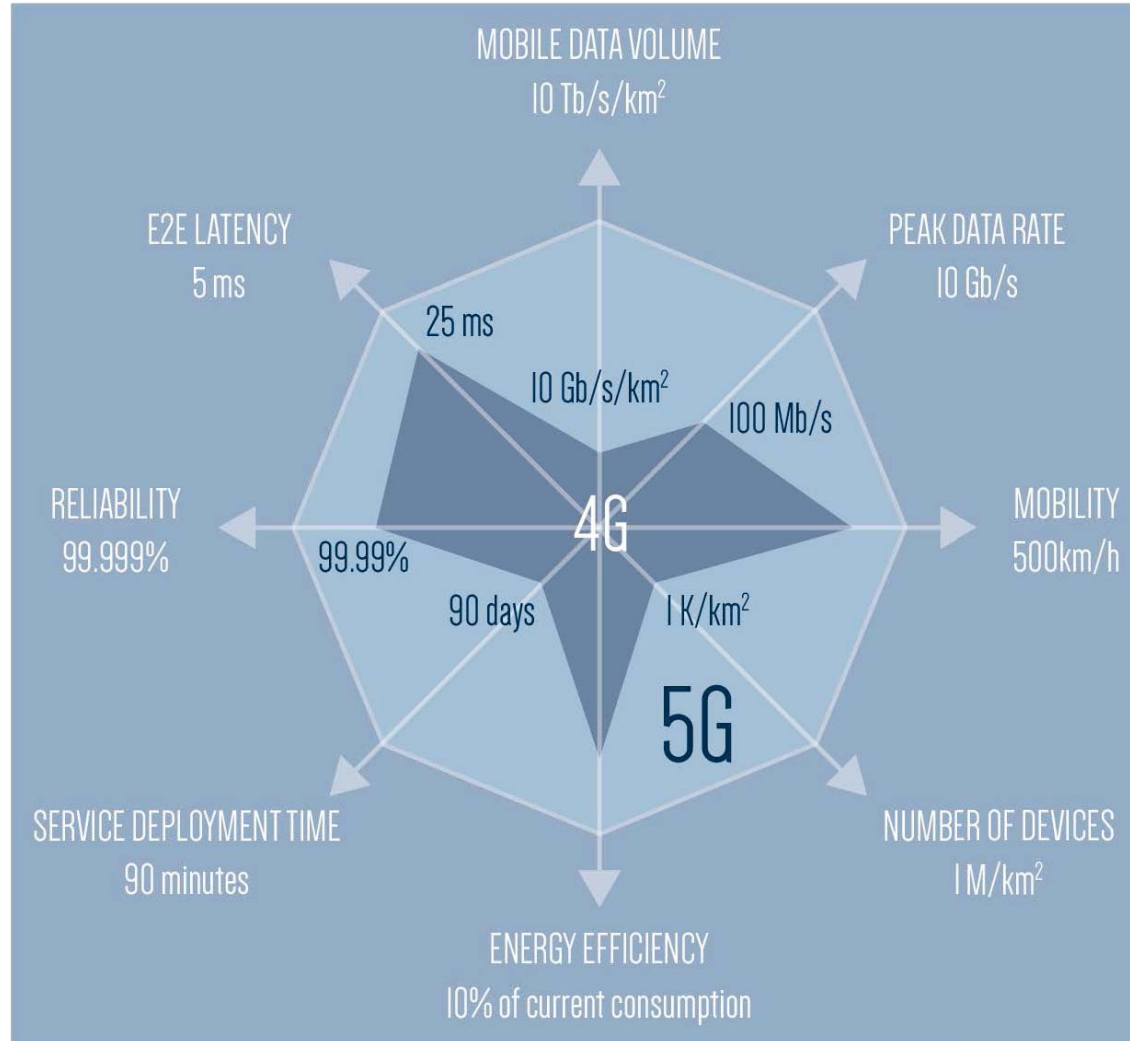
- **Introduction**
- **Power amplifier characterization**
- **Power amplifier modeling for digital predistortion**
- **The digital predistortion technique**
- **DPD challenges & Solutions for 5G**
- **Conclusion**

Wireless civilization



Sources: 5GPPP, Ericsson Mobility Report – Interim Update February 2017

5G disruptive capabilities



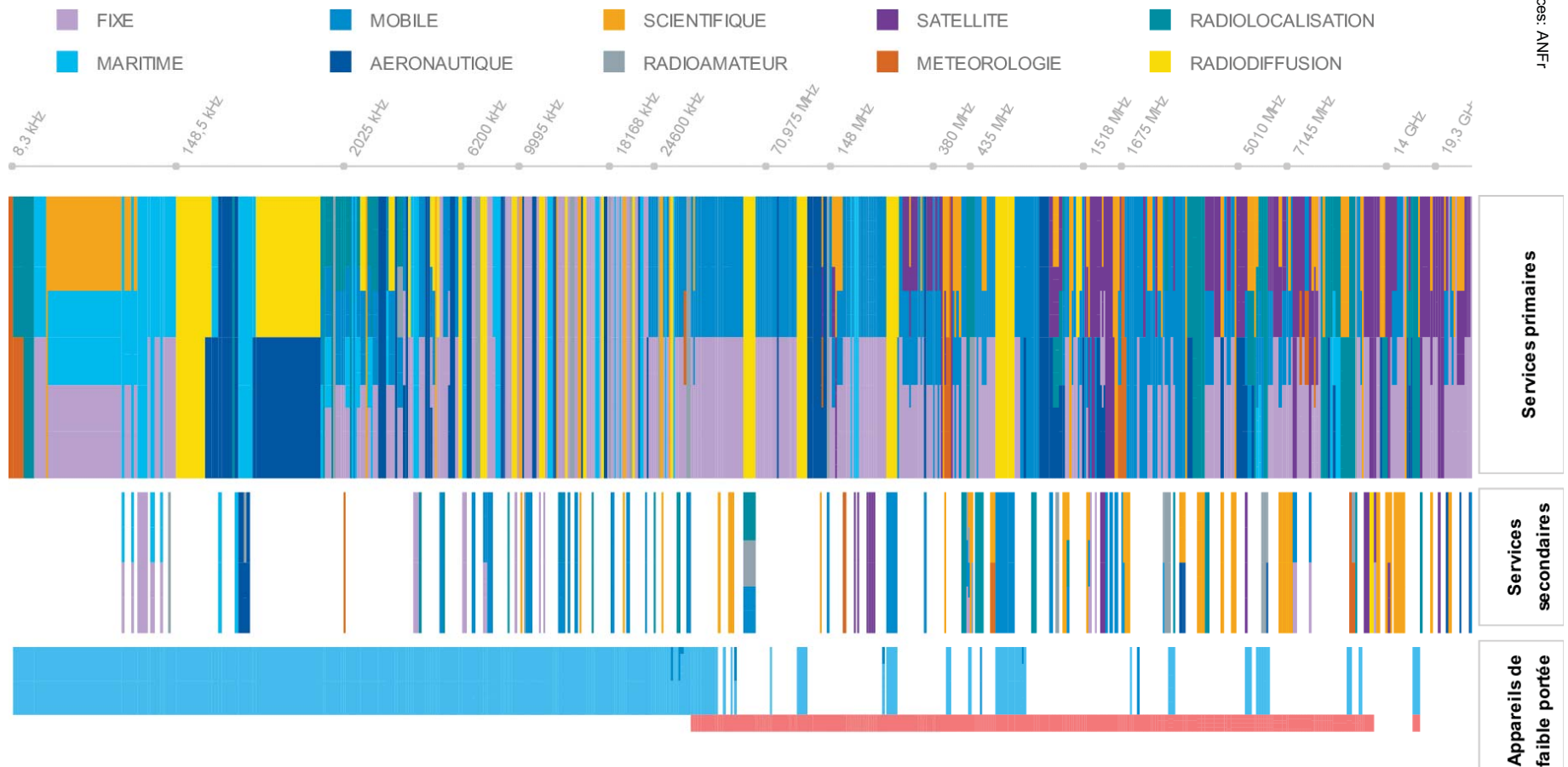
Sources: 5GPPP - 5G Vision

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

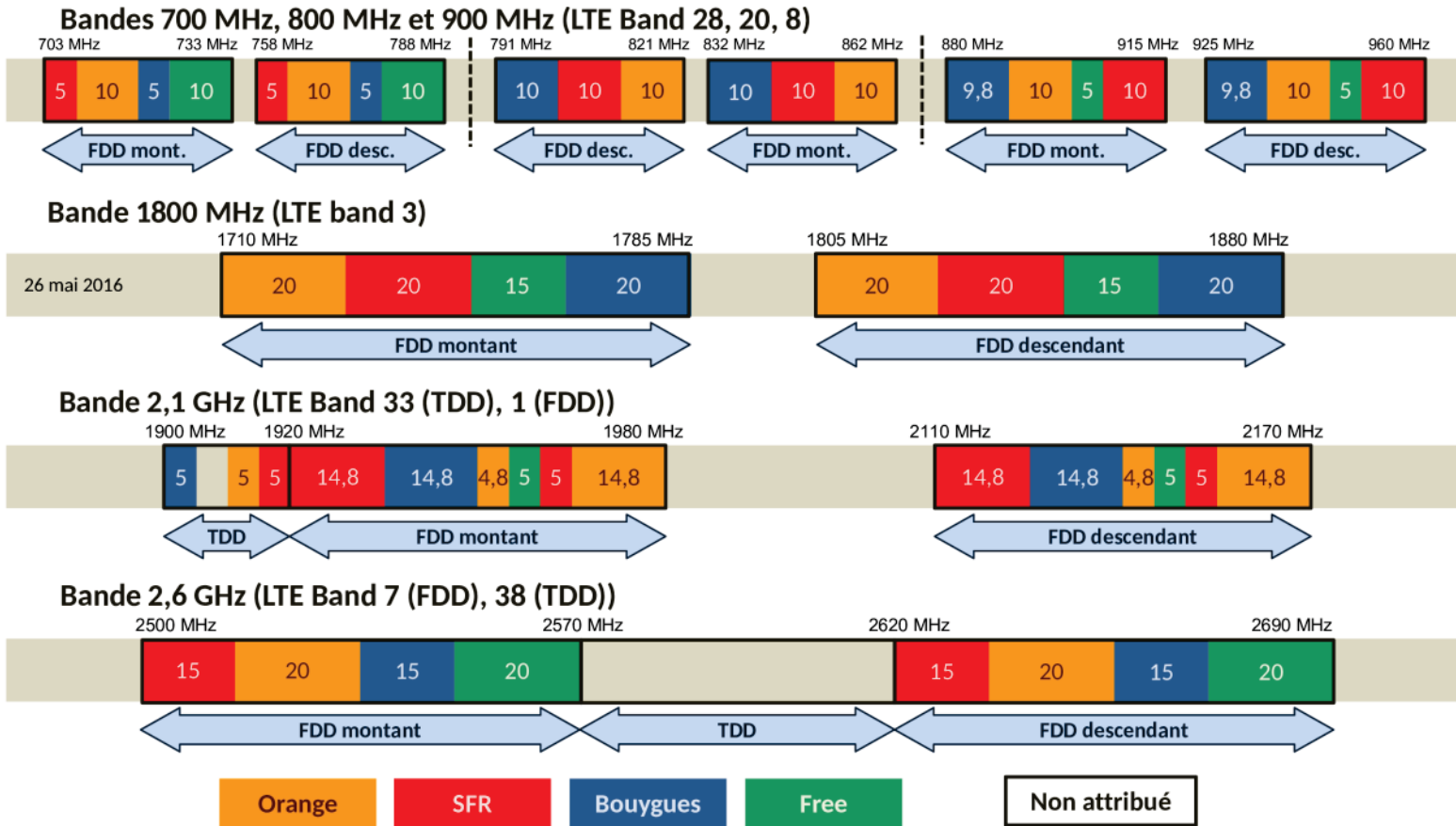


Sources: ANFR

5G Issue #1 : Spectrum scarcity – « Zoom »

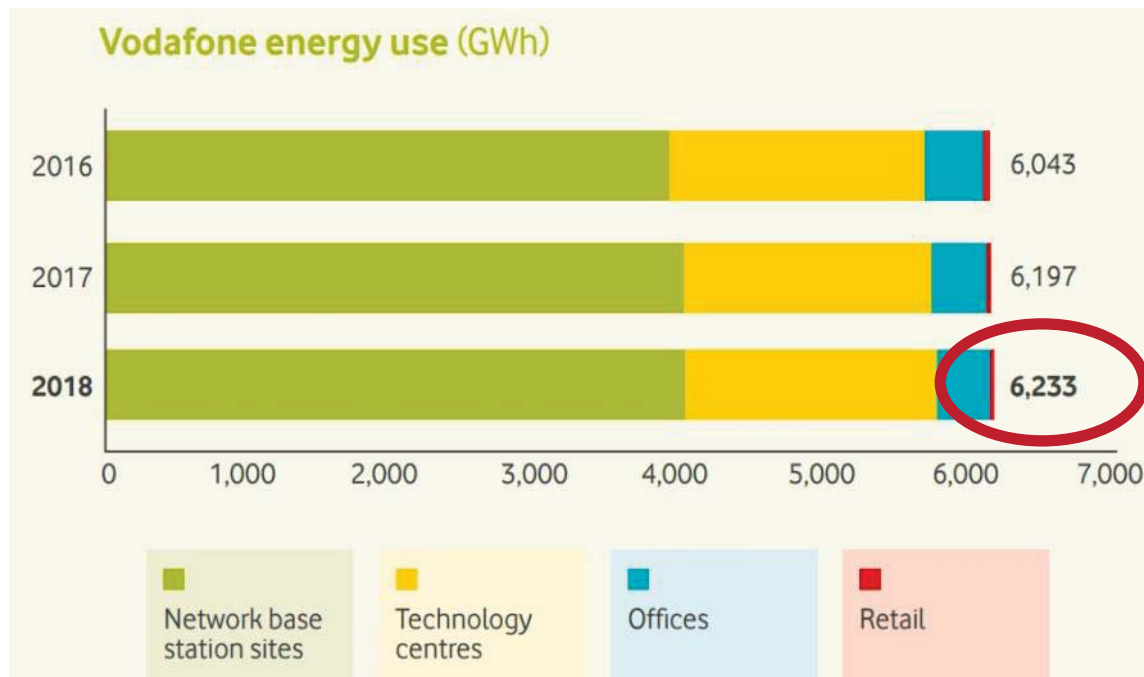
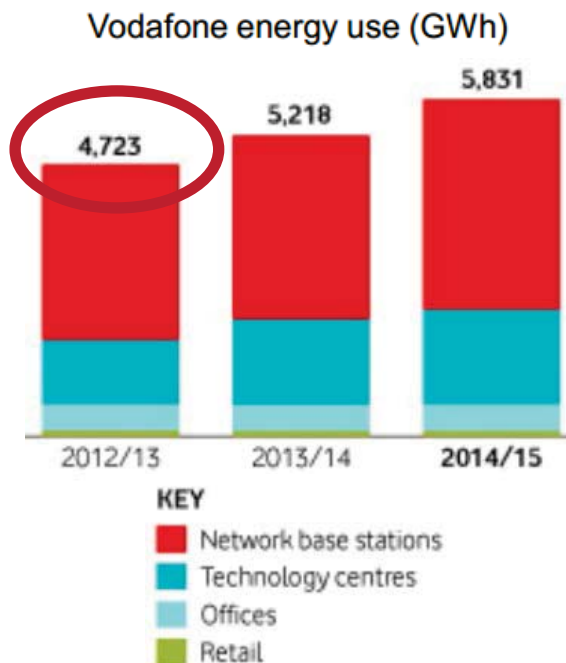
■ Spectrum sharing must be rigorously respected

Sources: ARCEP

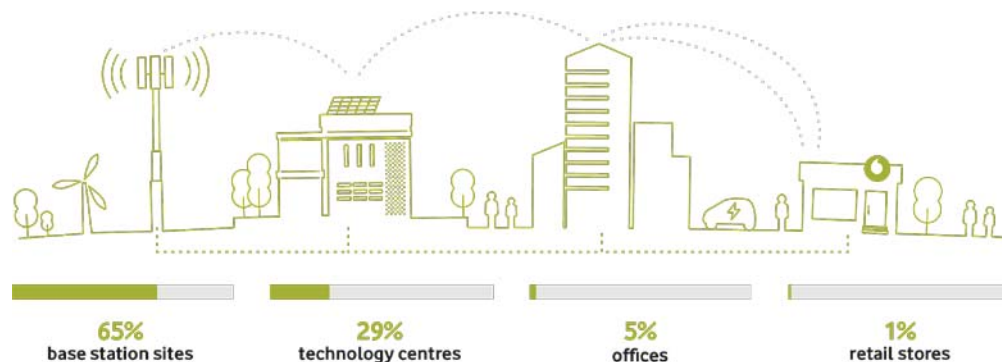


Note: les éventuelles bandes de garde de 200 kHz, en haut ou bas de bande, ou entre les attributions de deux opérateurs adjacents ne sont pas mentionnées

5G issue #2 : Energy consumption

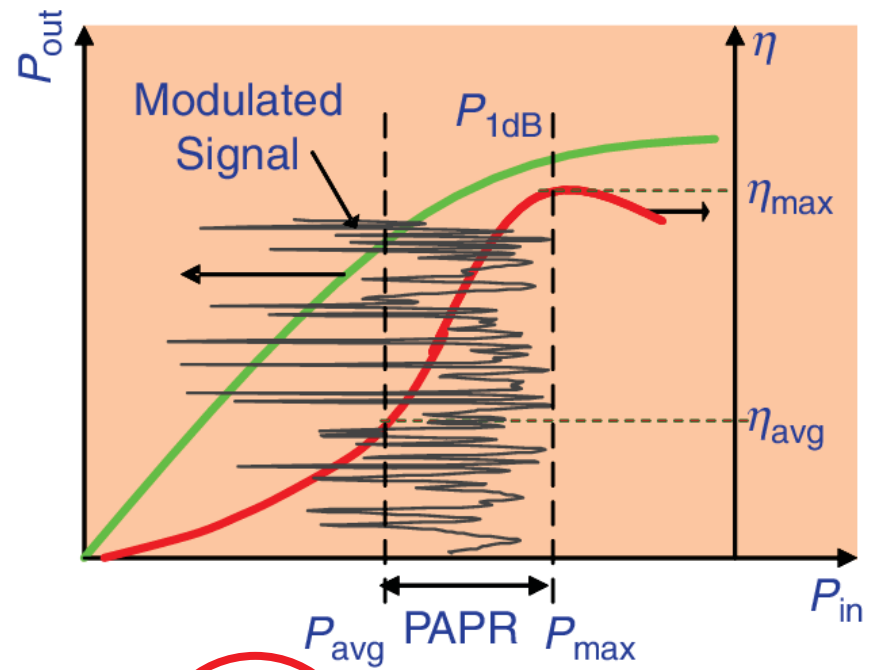
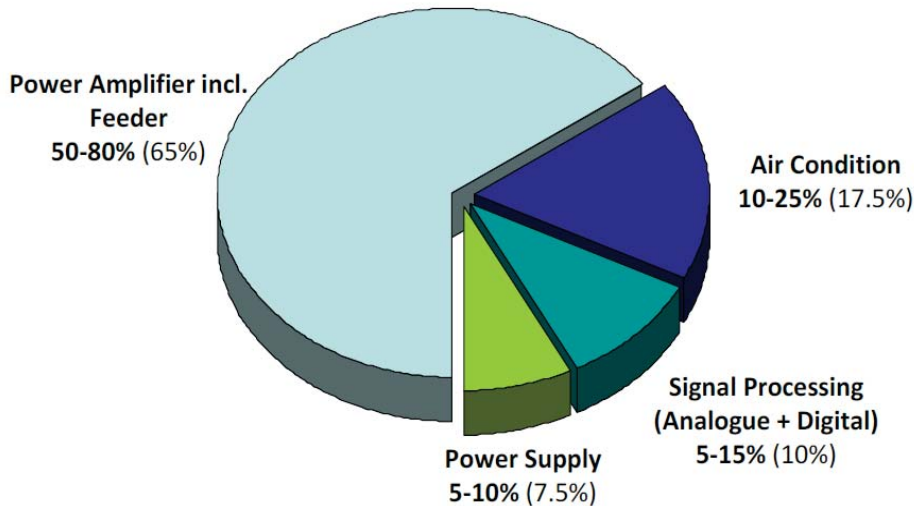


- **32% increase in 5 years...**
 - 65% in BSs

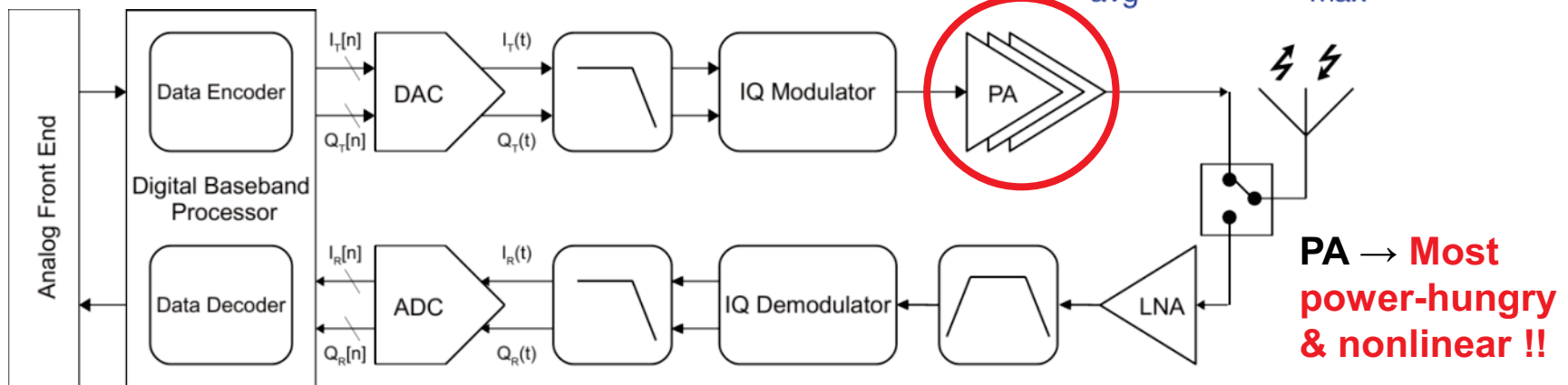


Sources: Vodafone Sustainability Reports 2015 & 2018

The power amplifier linearity/efficiency trade-off



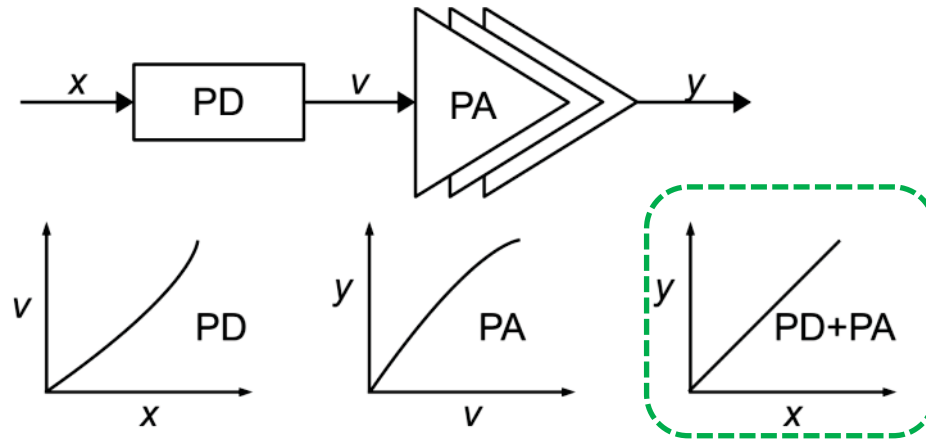
Percentage contribution of total BS power consumption (mean in brackets)



Sources: [Alberto Conte, Alcatel-Lucent Bell Labs France 2012], [Biratane et al. 2010]

Predistortion and Challenges in 5G

Predistortion principle



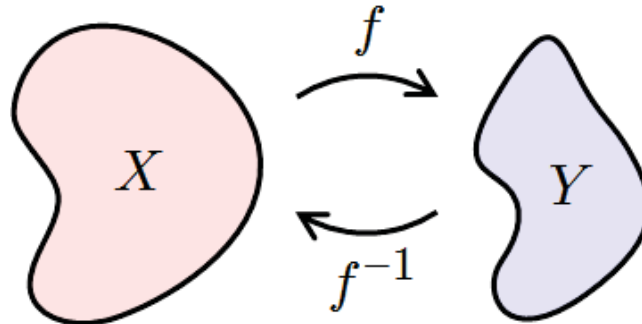
■ Predistortion challenges in 5G BSs

- High signal bandwidths (>100 MHz) \rightarrow Memory Effects \uparrow
- Spectral efficient modulation formats \rightarrow PAPR \uparrow
- Energy efficient \rightarrow Nonlinearity \uparrow
- Low-cost \rightarrow Cheaper PA with Nonlinearity \uparrow

Predistortion with « inverse » functions

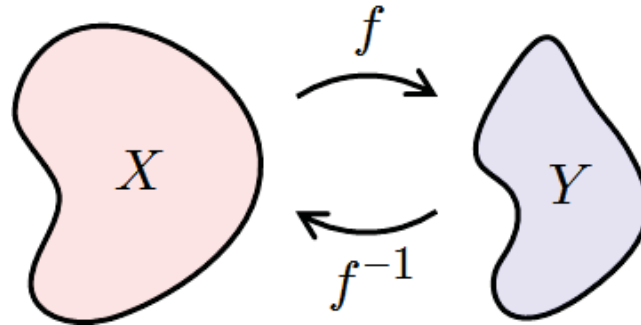
■ Definition

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



- $g(x)$ **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



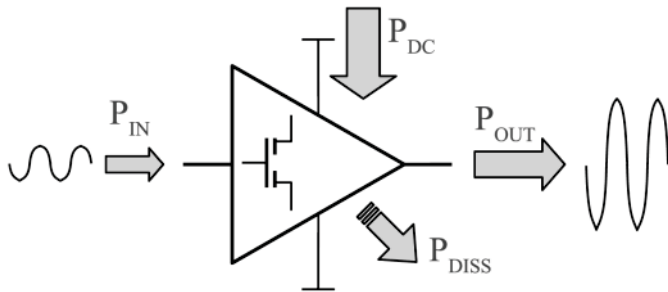
- For DPD systems we only search for approximate inverse
- We need to « know » $f(x)$ to find its inverse $g(x)$
 - First, find an adequate approximation of $f(x)$
 - Second, find an approximate inverse of $f(x)$



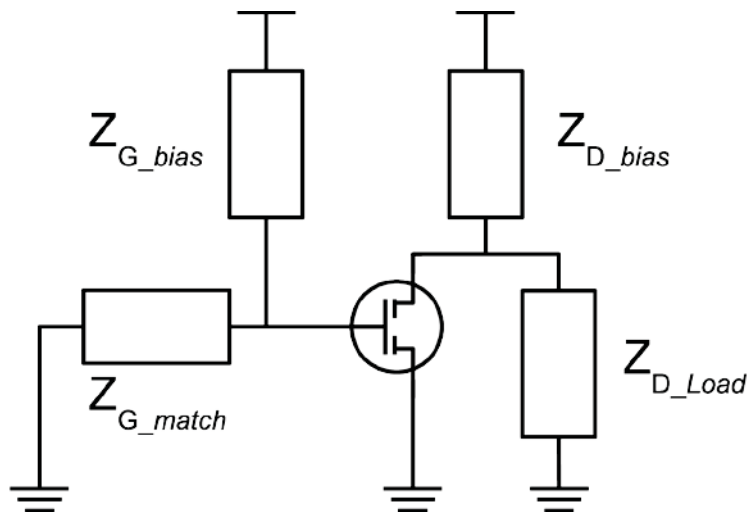
Power amplifier characterization

Considered power amplifier

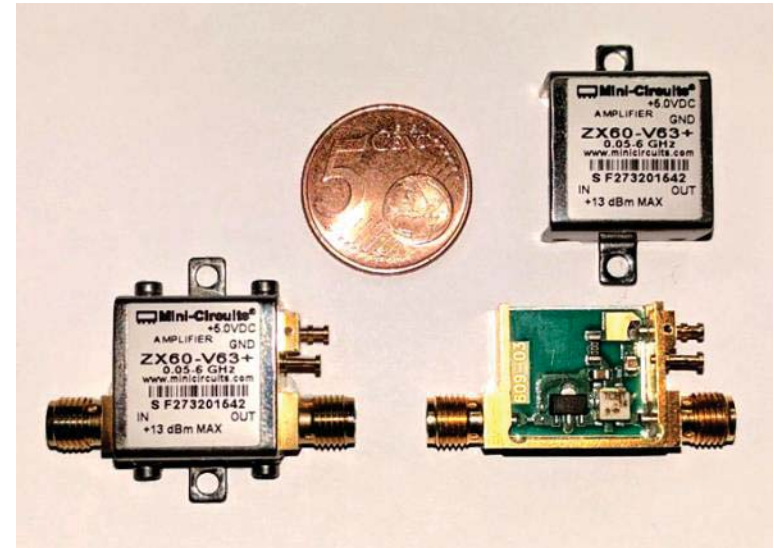
■ Abstract view



■ General circuit model



■ Device example



PA characteristics – more details

Actual PA example

TYPICAL CHARACTERISTICS — 2110–2200 MHz

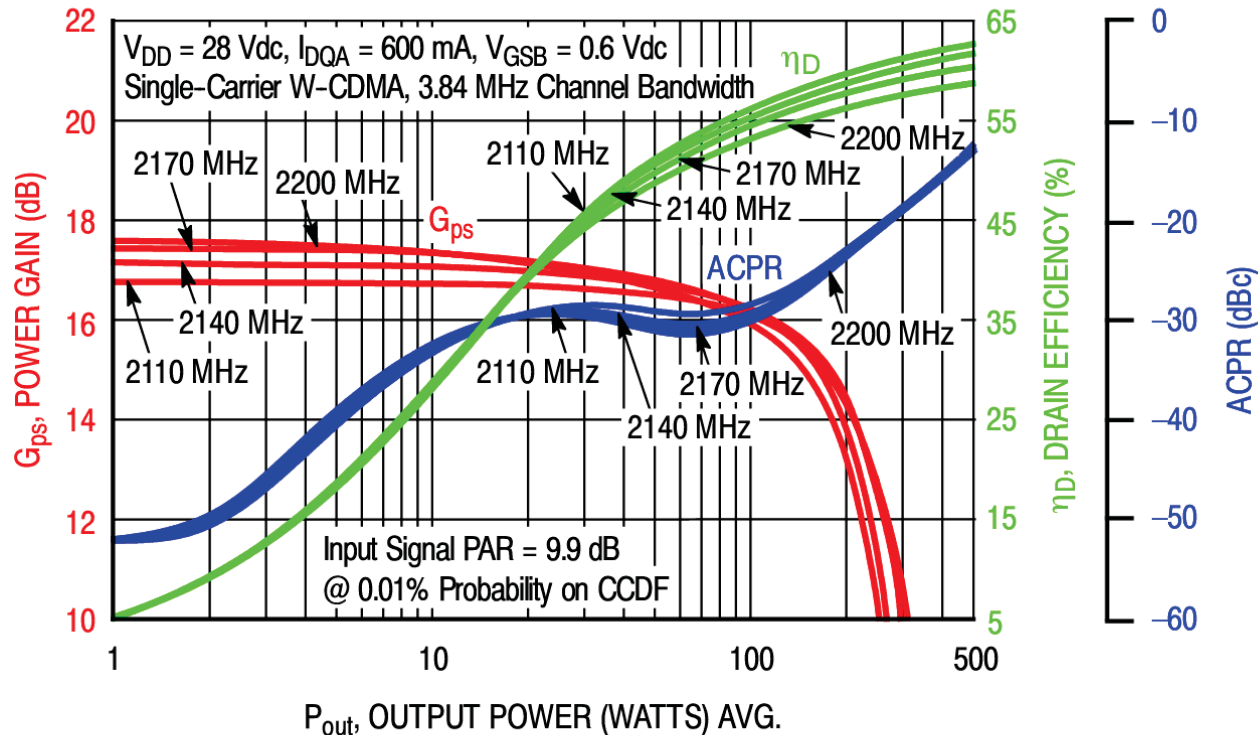


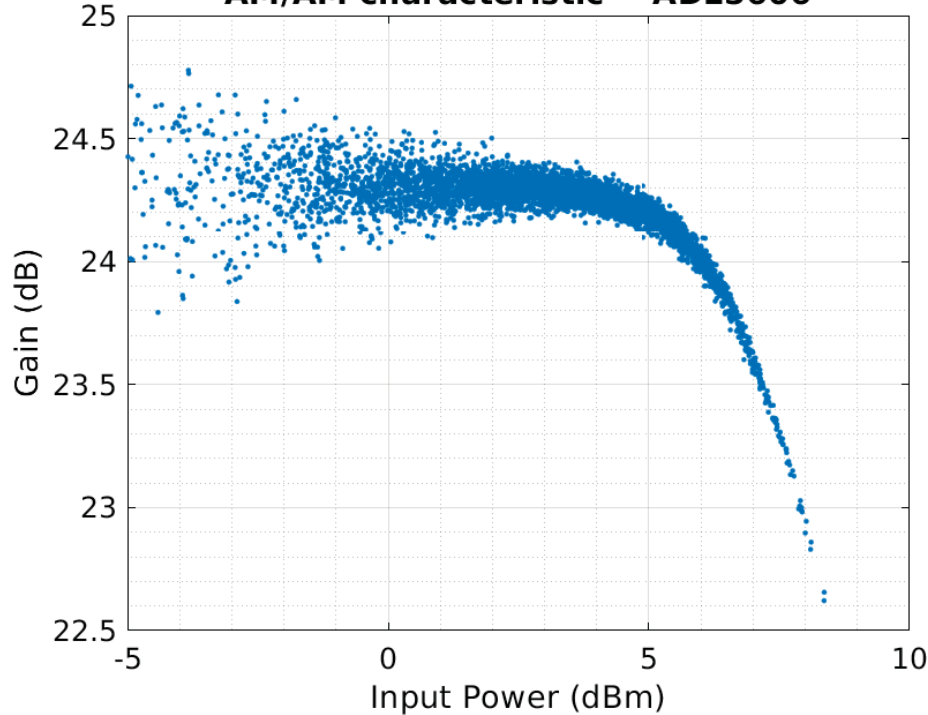
Figure 6. Single-Carrier W-CDMA Power Gain, Drain Efficiency and ACPR versus Output Power

Source: NXP Semiconductors -- RF Power LDMOS Transistor - A3T21H360W23S

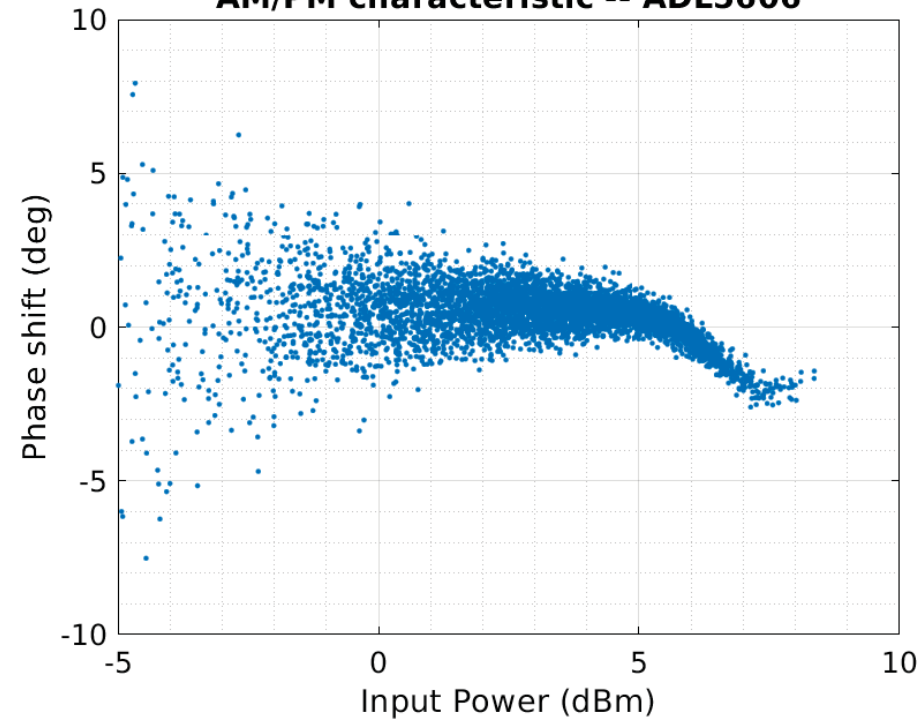
Dynamic characterization with Modulated Signals

■ Amplitude and Phase transfer function

AM/AM characteristic -- ADL5606



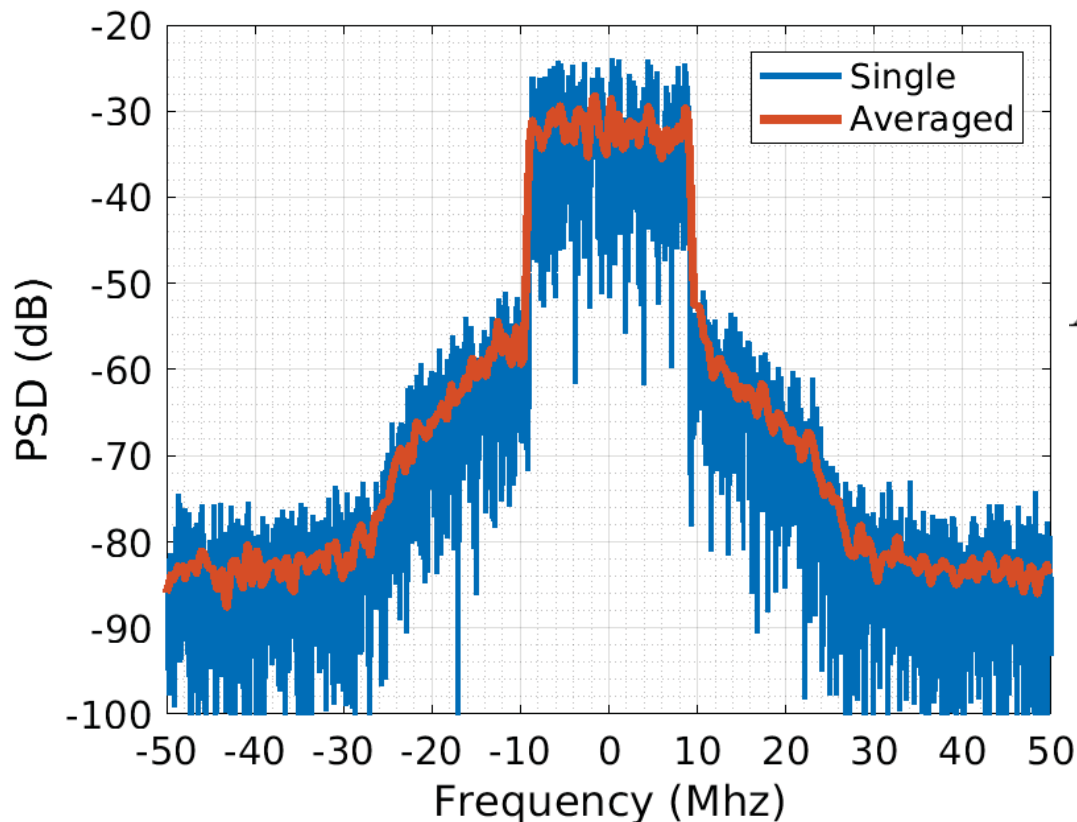
AM/PM characteristic -- ADL5606



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)

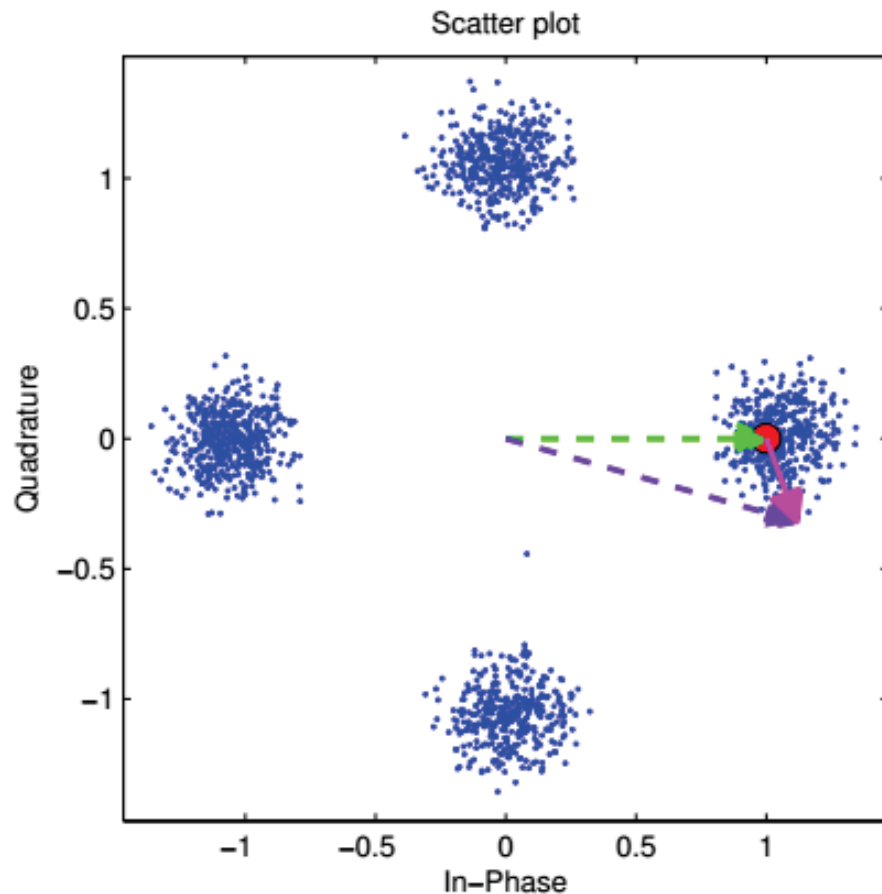


$$ACPR_{dB} = 10 \log_{10} \left(\frac{\int_{BW_{main}} P(f) df}{\int_{BW_{adj}} P(f) df} \right)$$

Example :
5G specifications ACLR > 45 dBc

Dynamic characterization with Modulated Signals

■ Error Vector Magnitude (EVM)



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

Example :
EVM < 12.5% pour LTE-A pour 16-QAM

Linearity requirements for 3G/4G/5G base stations

TABLE 1. Linearity requirements in typical 3G/4G base stations.

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

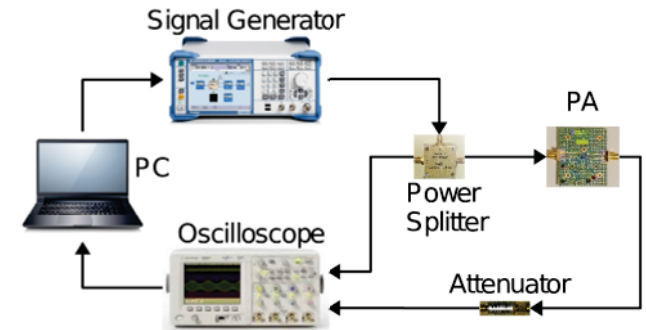
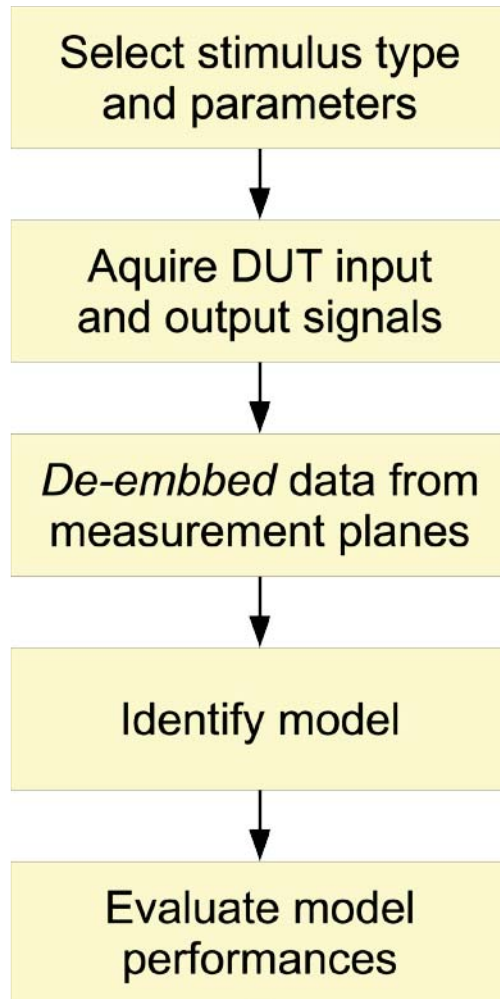
^a Based on the 16-QAM modulation scheme.
^b Refers to the first adjacent channel leakage power ratio.
^c Refers to the second adjacent channel leakage power ratio.

Source: 2014 - Guan, Zhu - Green Communications: Digital Predistortion for Wideband RF Power Amplifiers



PA modeling for Digital Predistortion

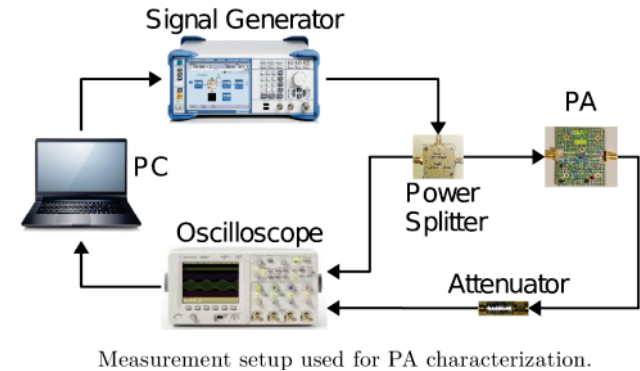
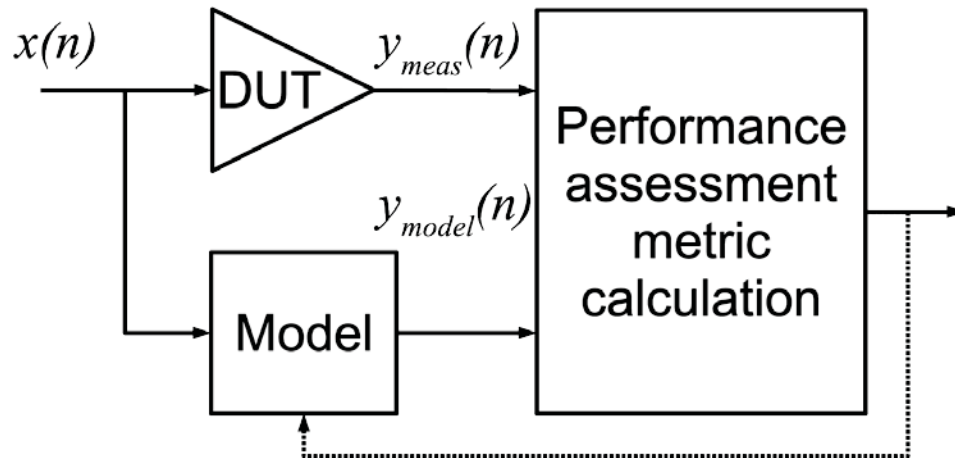
Characterization and modeling method



Measurement setup used for PA characterization.

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

Modeling accuracy assessment



■ Time domain metric

- Normalized Mean Square Error

$$-NMSE = 10 \log_{10} \left(\frac{\sum_{\ell=1}^L |y_{model}(\ell) - y_{meas}(\ell)|^2}{\sum_{\ell=1}^L |y_{meas}(\ell)|^2} \right)$$

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

$$y_{MP}(n) = \sum_{m=0}^M \sum_{k=0}^K a_{mk} x(n-m) |x(n-m)|^{2k}$$

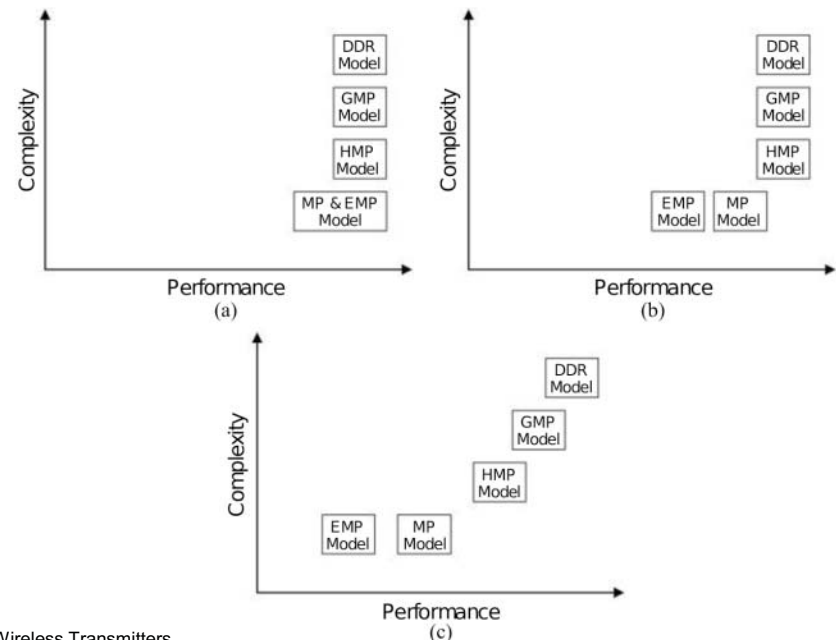
Nonlinear models – the most popular

■ Volterra series models

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

■ Many variations

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



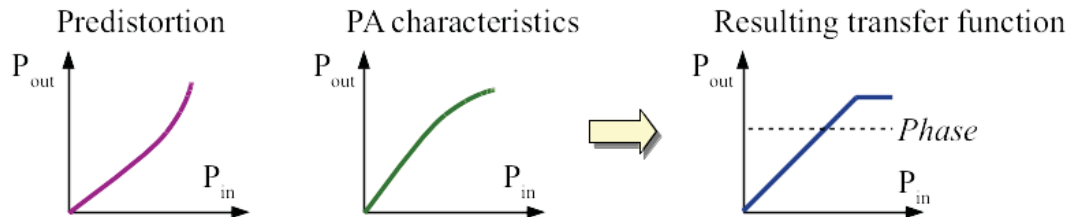
Source: 2015 - Ghannouchi, Hammi, Helaoui - Behavioral Modeling and Predistortion of Wideband Wireless Transmitters



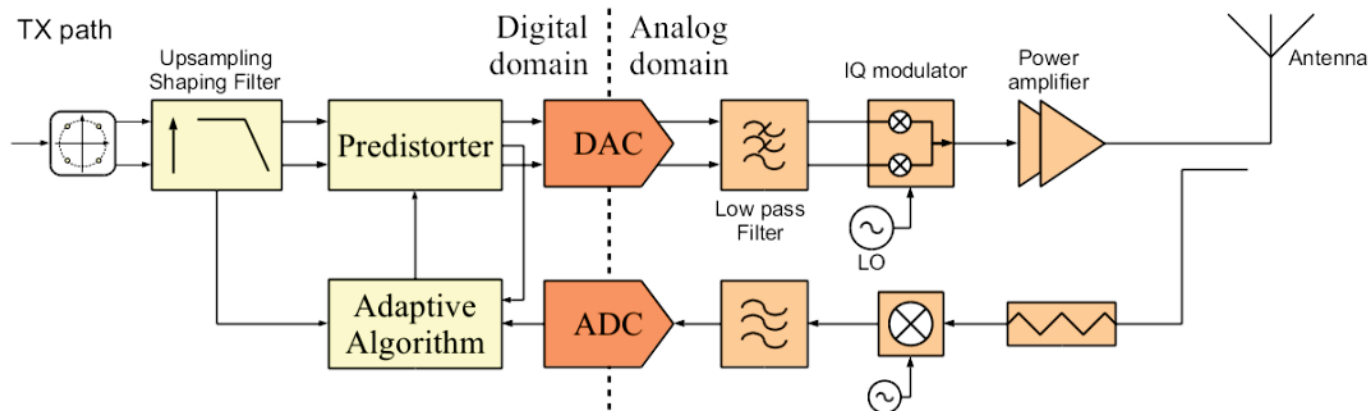
The digital predistortion technique

Fundamental elements

■ Principle (reminder)



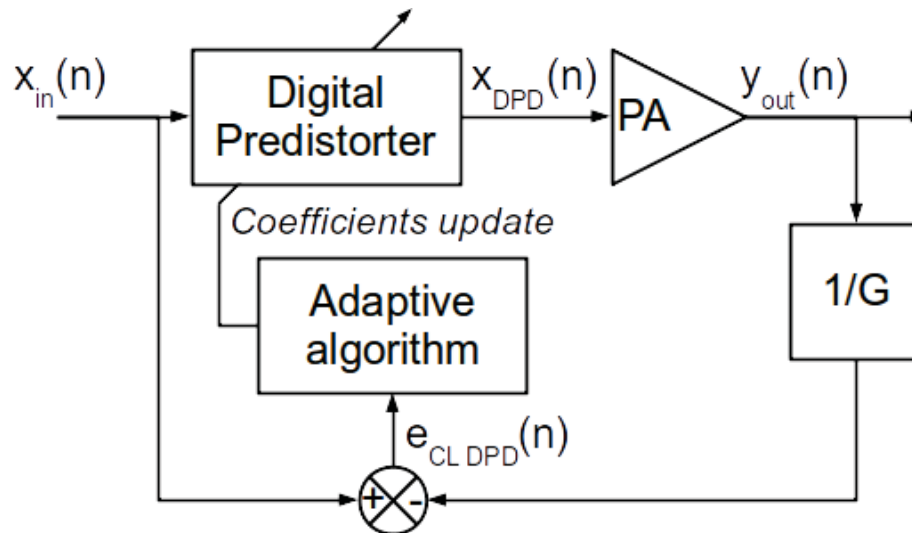
■ Transmitter architecture



- 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

DPD architectures – Closed loop

■ Closed loop (direct) architecture



■ Advantages

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

■ Drawbacks

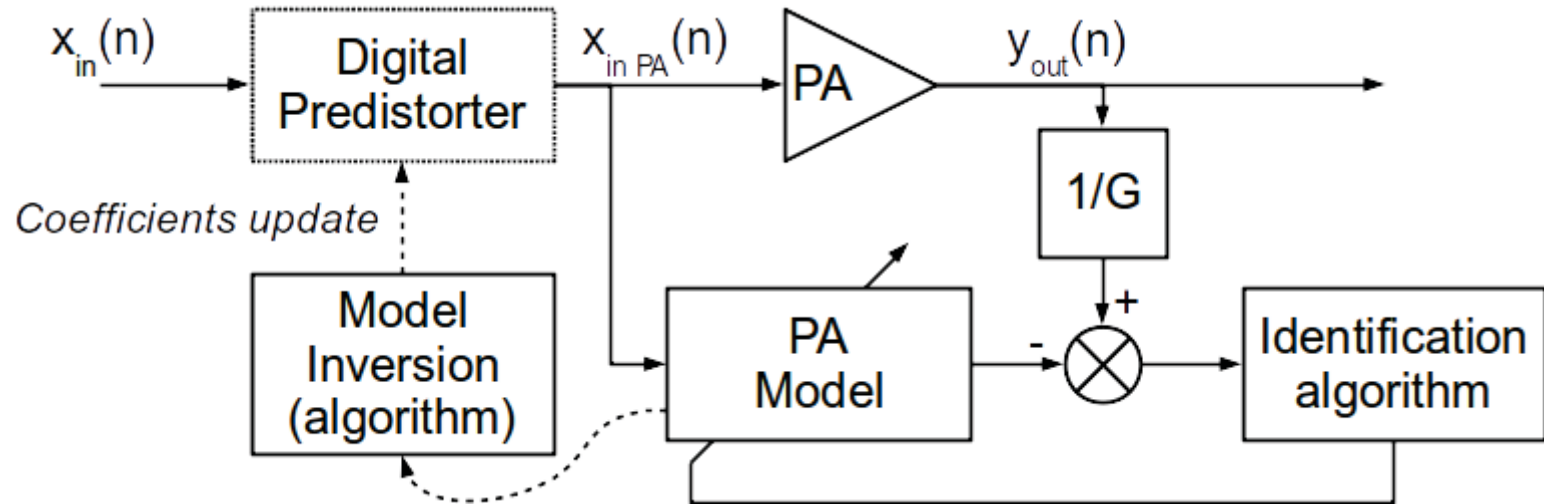
- Suitable for memoryless systems
- No direct relation between error signal and predistorter's coefficients

References:

- C. D. Presti, D. F. Kimball and P. M. Asbeck, "Closed-Loop Digital Predistortion System With Fast Real-Time Adaptation Applied to a Handset WCDMA PA Module," in IEEE TMTT ; March 2012.
- Fadhel M. Ghannouchi , Oualid Hammi , Mohamed Helaoui, "Behavioral Modeling and Predistortion of Wideband Wireless Transmitters", John Wiley & Sons ; Jul 2015

DPD architectures – Open loop

■ Direct (PA) learning architecture

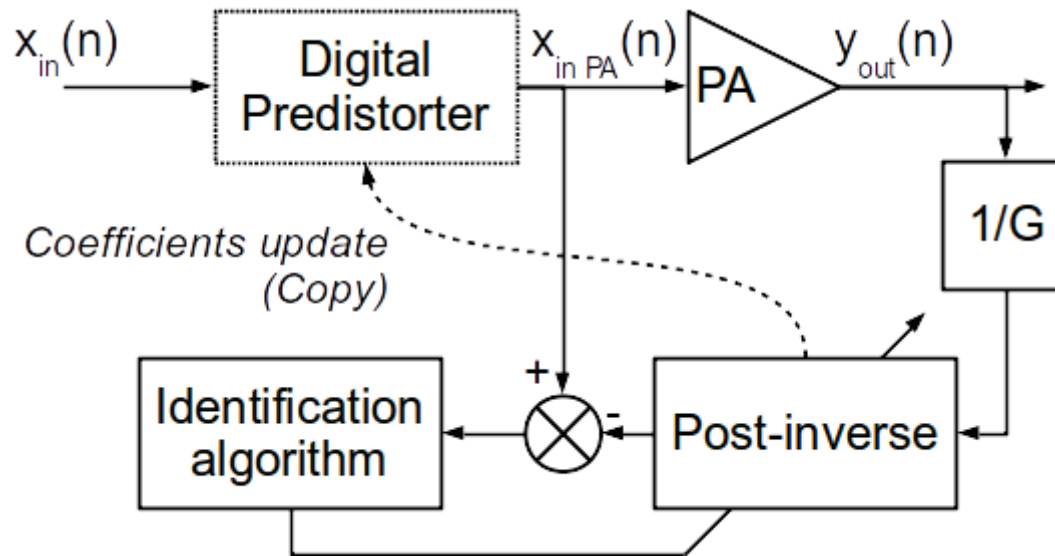


■ « 2 steps » learning

- 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

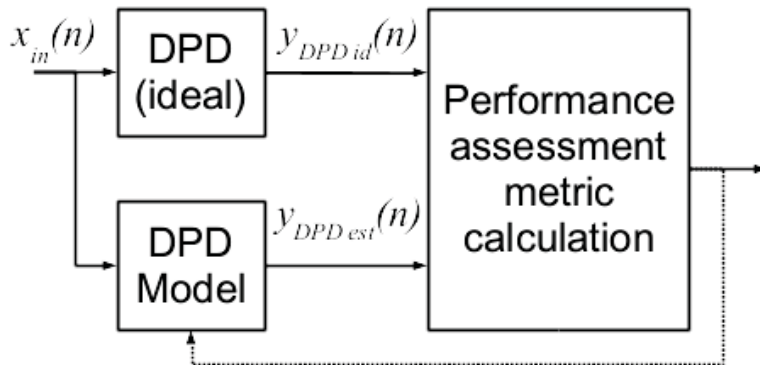
■ Indirect learning architecture



■ « 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

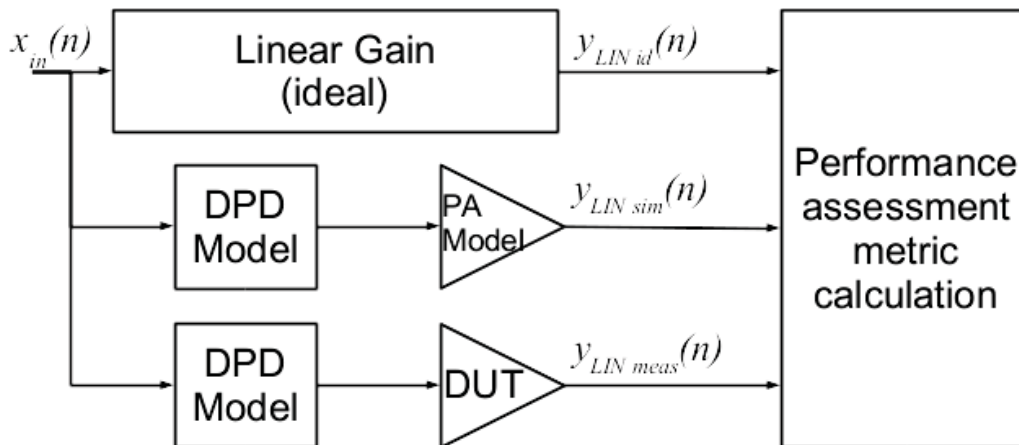


- Match $y_{DPD,id}$ and $y_{DPD,est}$
- Example of model oriented metrics

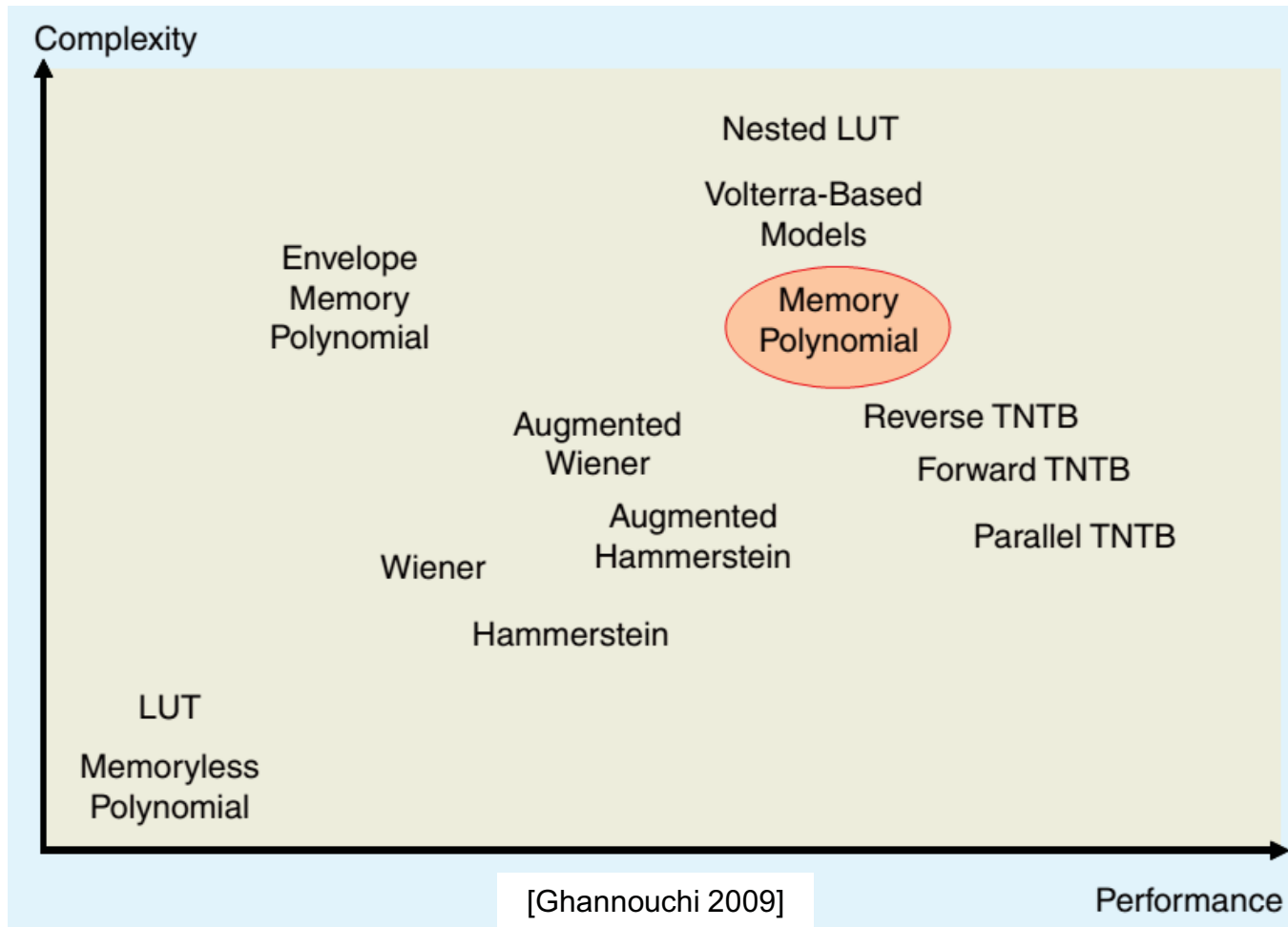
- Normalized Mean Square Error

– $NMSE =$

$$10 \log_{10} \left(\frac{\sum_{\ell=1}^L |y_{est}(\ell) - y_{id}(\ell)|^2}{\sum_{\ell=1}^L |y_{id}(\ell)|^2} \right)$$



Conventional DPD models



Objective functions and computational aspects

- **Least-squares (LS):** $\min_{\vec{A}} \|\vec{y}(n) - \Gamma_x(n) \cdot \vec{A}\|^2$
 - 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):** $\min_{\vec{A}} E[|y(n) - \vec{A}^H \cdot \vec{\gamma}_x(n)|^2]$
 - Iterative approach:
$$\begin{aligned} e(n) &= y(n) - \vec{A}^H(n) \cdot \vec{\gamma}_x(n) \\ \vec{A}(n+1) &= \vec{A}(n) + \mu e^*(n) \vec{\gamma}_x(n) \end{aligned}$$
 - Reduced computational complexity ($\mathcal{O}(M \times K)$)
 - Convergence issues (μ)

Objective functions and computational aspects

■ Recursive (weighted) least-squares (RLS):

$$\min_{\vec{A}} \sum_{i=0}^k \lambda^{k-i} |y(i) - \vec{A}^H(i) \cdot \vec{\gamma}_x(k)|^2$$

- Iterative approach:

$$e(k) = y(k) - \vec{A}^H(k-1) \cdot \vec{\gamma}_x(k)$$

$$\vec{s}(k) = \mathbf{S}(k-1) \cdot \vec{\gamma}_x(k)$$

$$\vec{\kappa}(k) = \frac{\vec{s}(k)}{1 + \vec{\gamma}_x^H(k) \cdot \vec{s}(k)}$$

$$\mathbf{S}(k) = \frac{1}{\lambda} \left[\mathbf{S}(k-1) - \frac{\vec{\kappa}(k) \cdot \vec{\kappa}^H(k)}{\lambda + \vec{\gamma}_x^H(k) \cdot \vec{s}(k)} \right]$$

$$\vec{A}(k) = \vec{A}(k-1) + e^*(k) \cdot \vec{\kappa}(k)$$

- Increased computational complexity ($\mathcal{O}((M \times K)^2)$)
- 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.

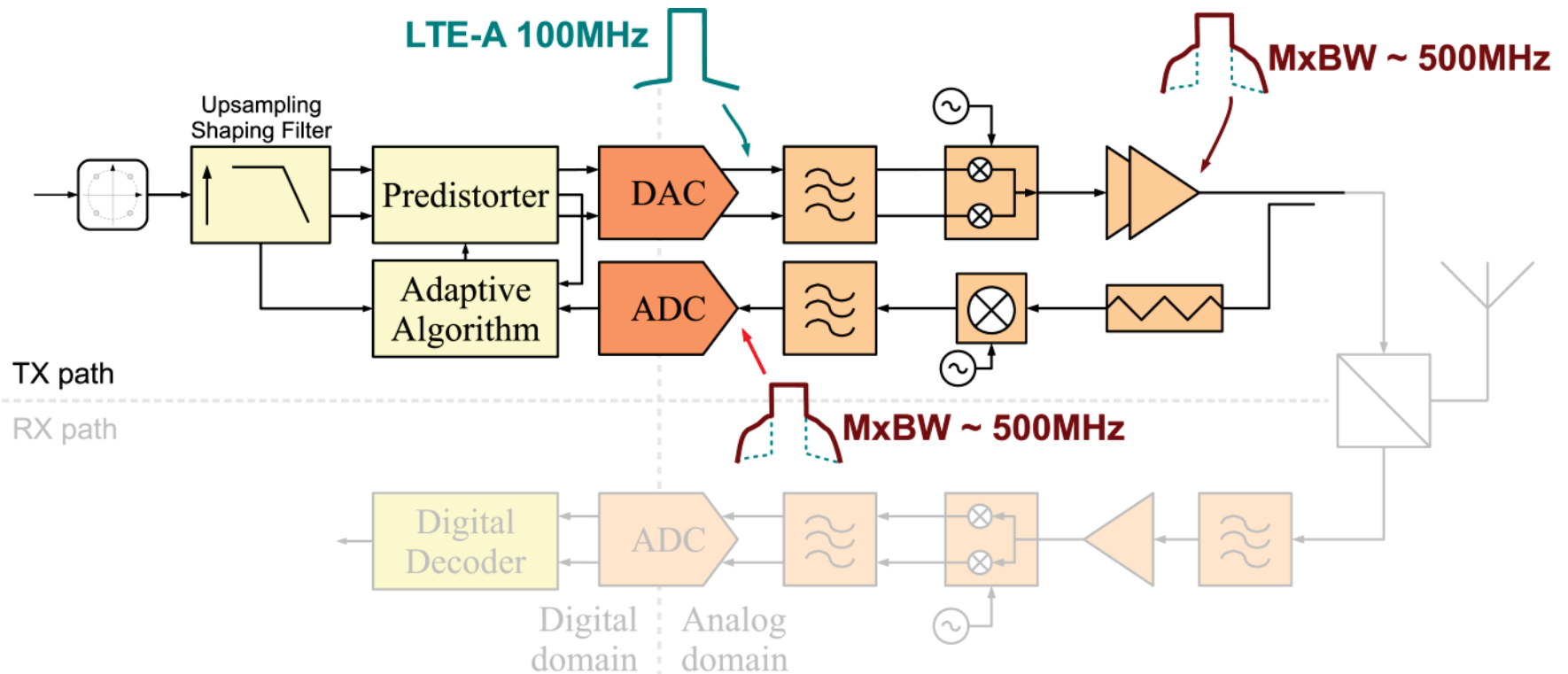


DPD challenges & Solutions for 5G

TX feedback path : the bottleneck

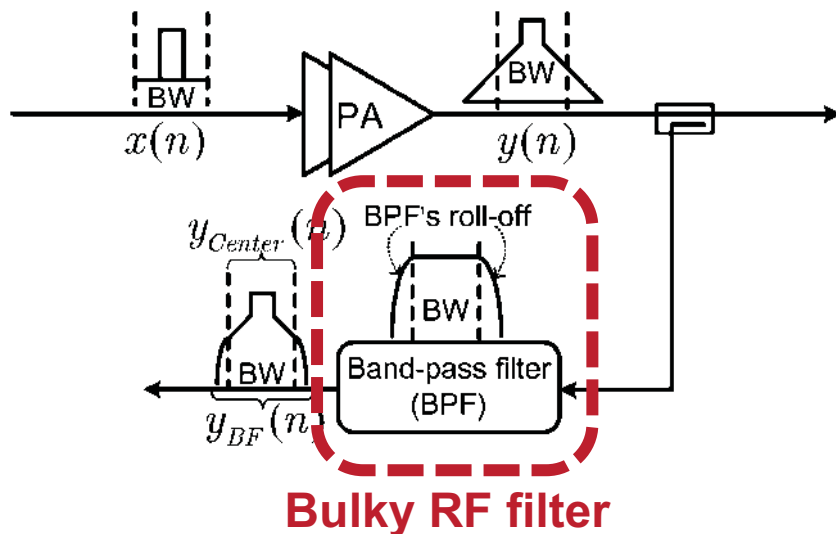
■ ADC bandwidth feedback limitation

- Learning phase

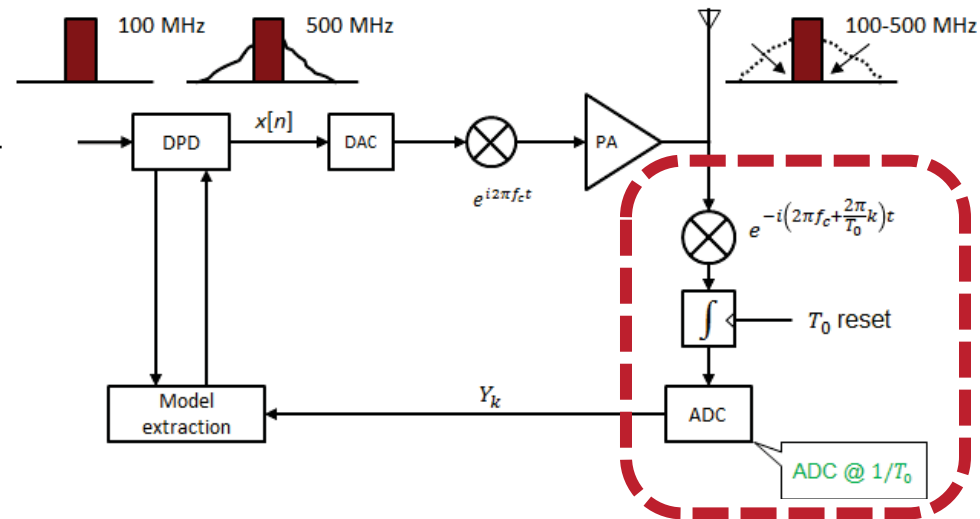


TX feedback path : Band limited and/or low rate DPD techniques

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



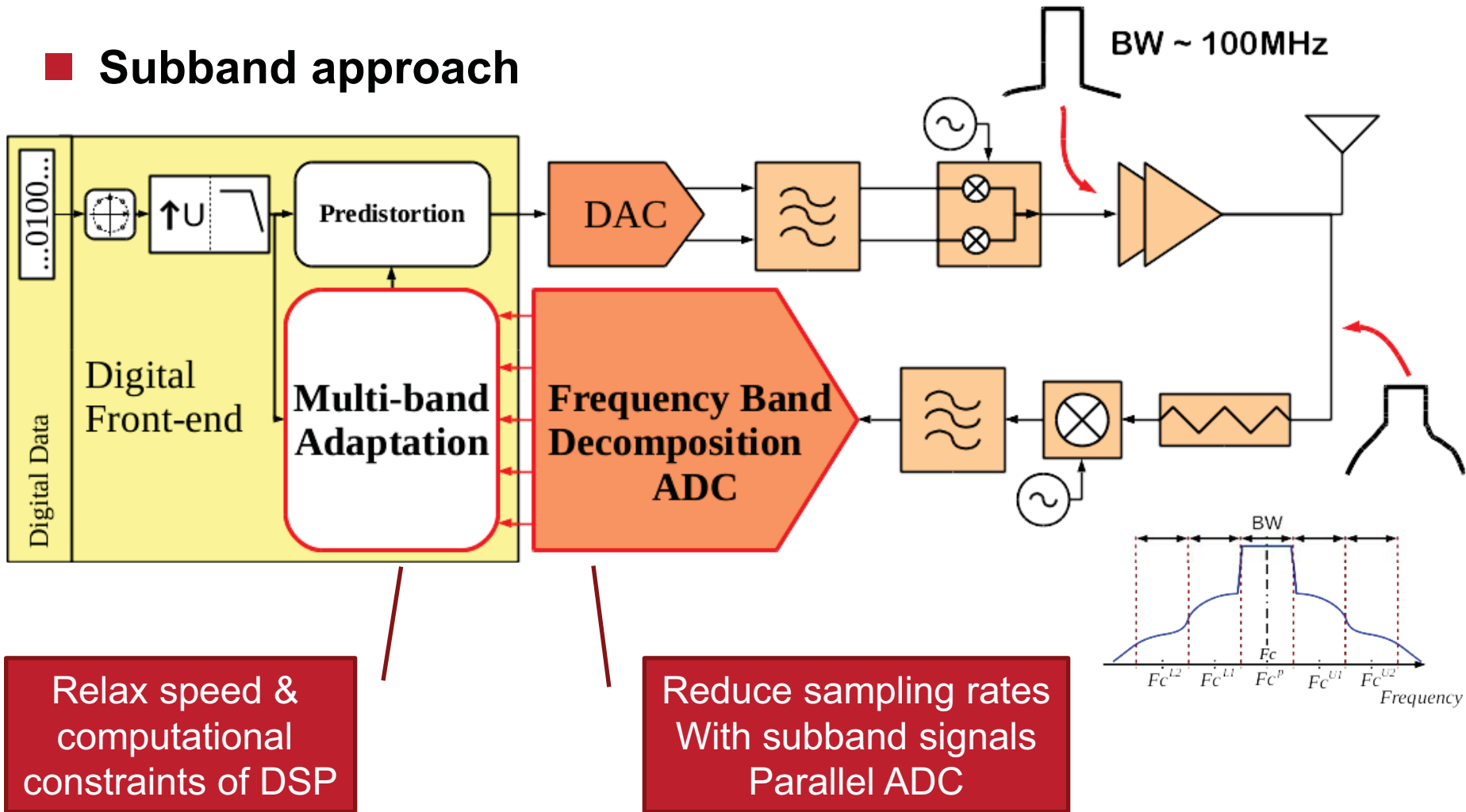
- Low rate identification [Hammler, 2014]



- Lower ADC sampling rate 😊
- Compute PA model first 😞
- Sampling frequency of PA model = Fullband of distorted signal 😞

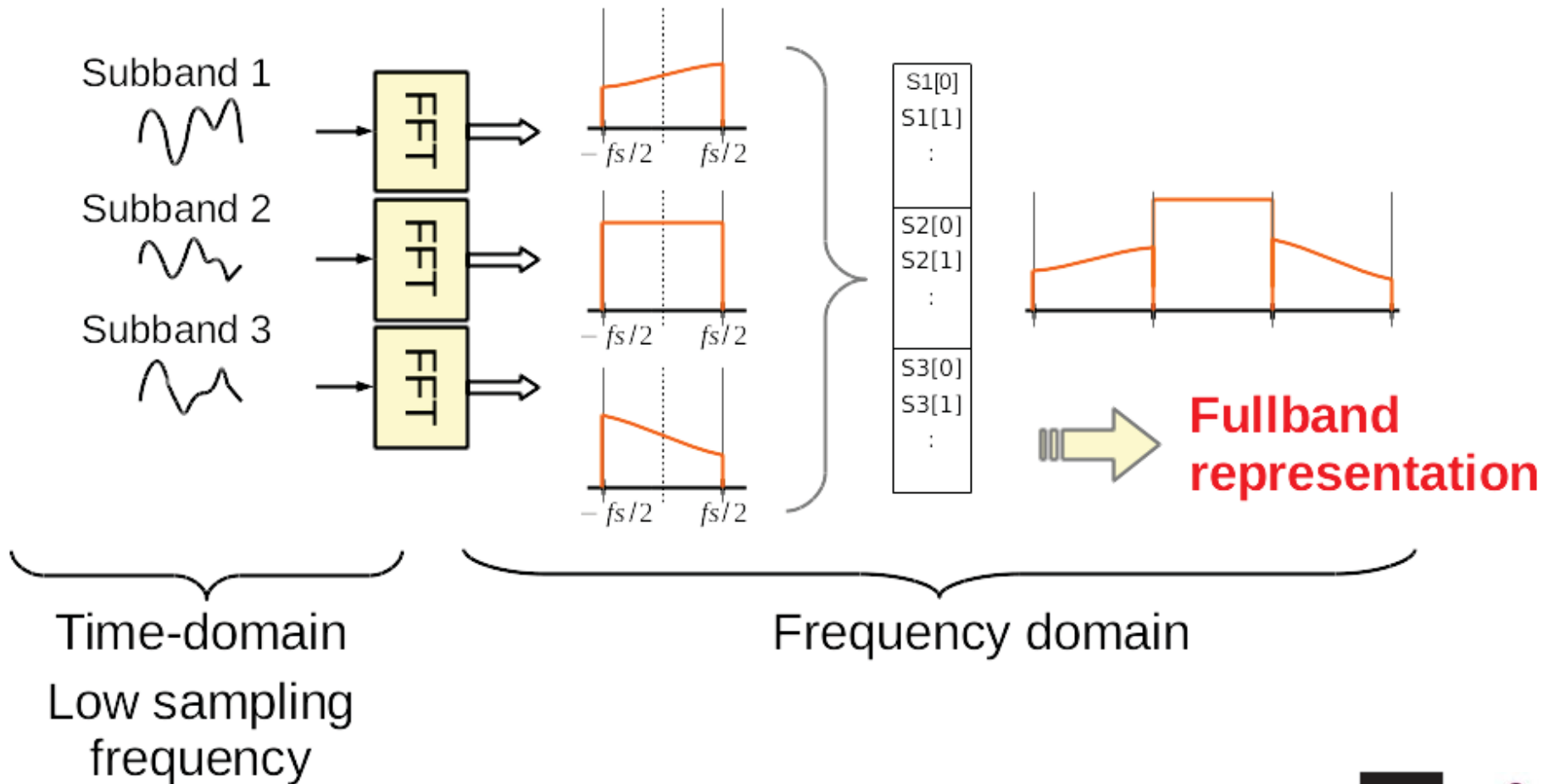
TX feedback path : New low rate DPD architecture

■ Subband approach



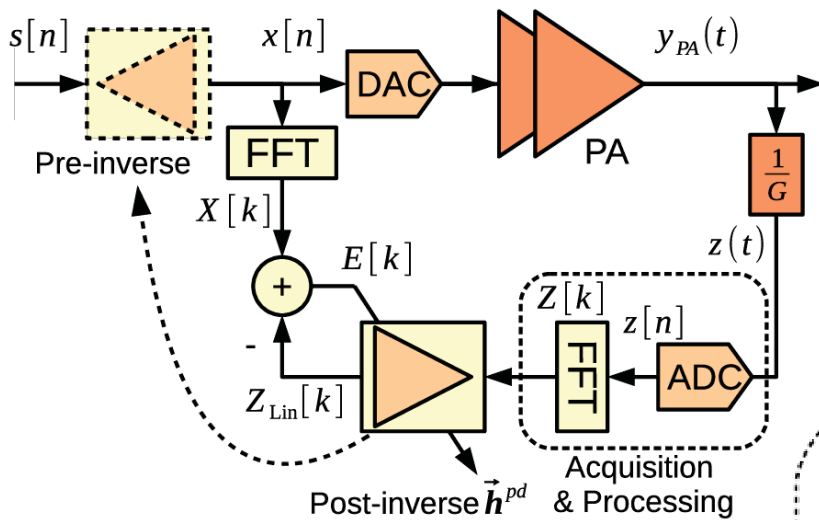
TX feedback path : Solution to the signal reconstruction

■ Frequency domain



TX feedback path : New subband DPD architecture

■ FFT-based subband digital predistortion

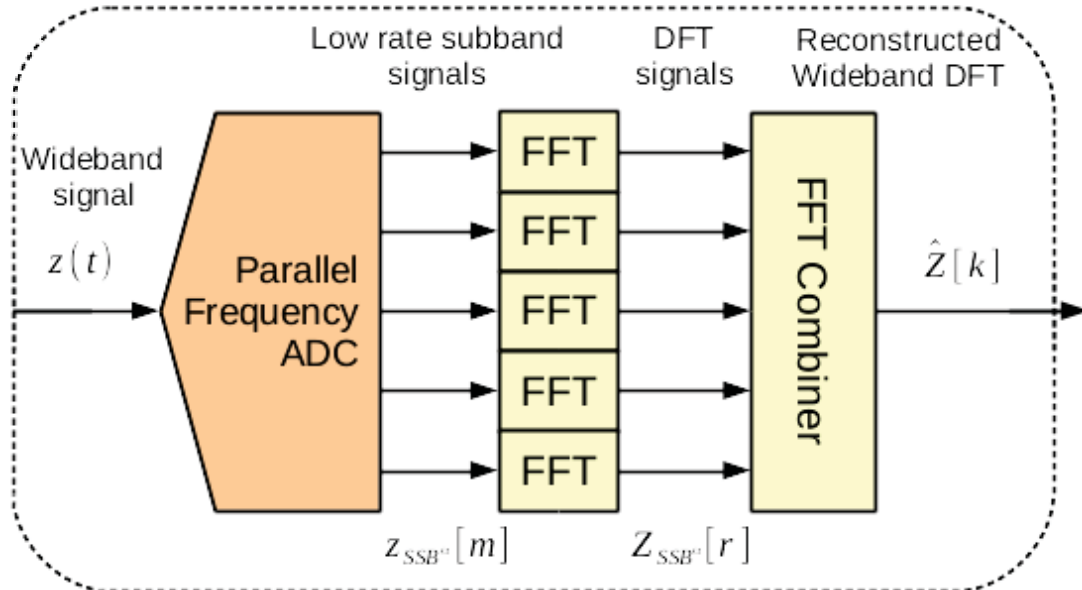


$$\vec{X} = \text{fft}(\vec{x})$$

$$\vec{Z}_{\text{Lin}} = \text{fft}(\vec{z}_{\text{Lin}})$$

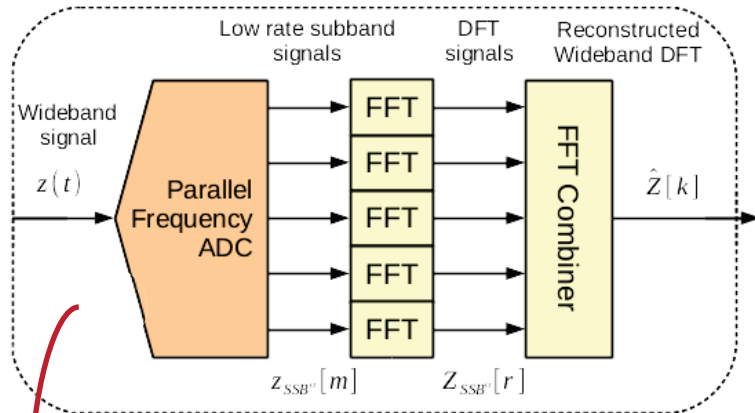
$$\vec{Z}_{\text{Lin}} \equiv \Gamma_V \vec{h}^{pd} = \vec{X}$$

$$\Gamma_V \sim (\text{fft}(\vec{z}) \text{fft}(\vec{z}|\vec{z}^2) \text{fft}(\vec{z}|\vec{z}^4) \dots)$$

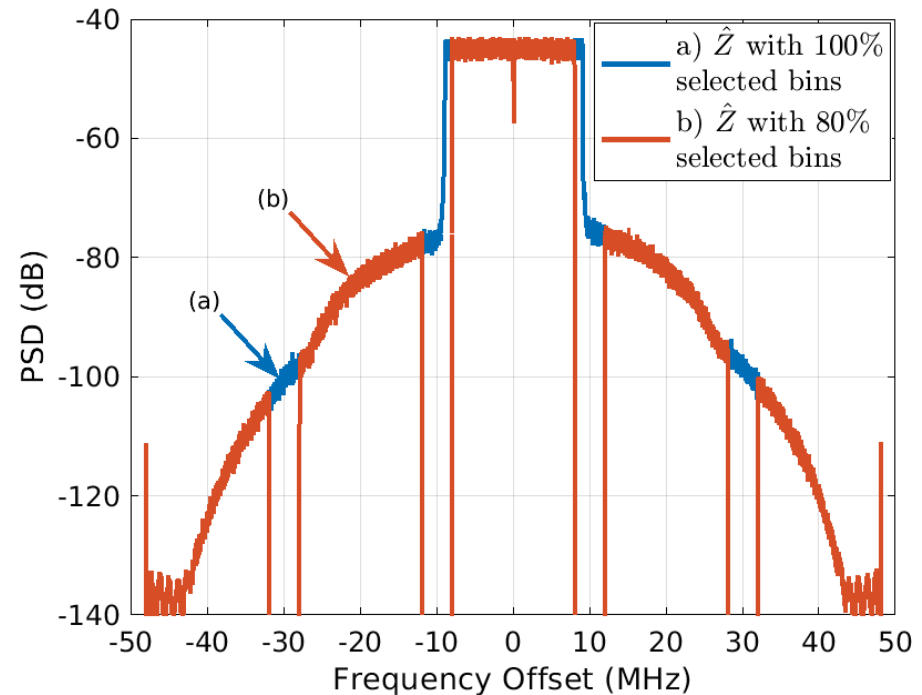
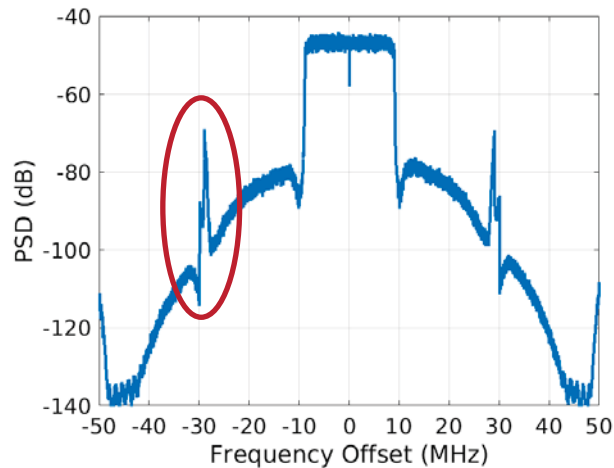


TX feedback path : FFT-based subband DPD – Mitigating subband edge effects

■ Limited subband signal reconstruction



Non ideal



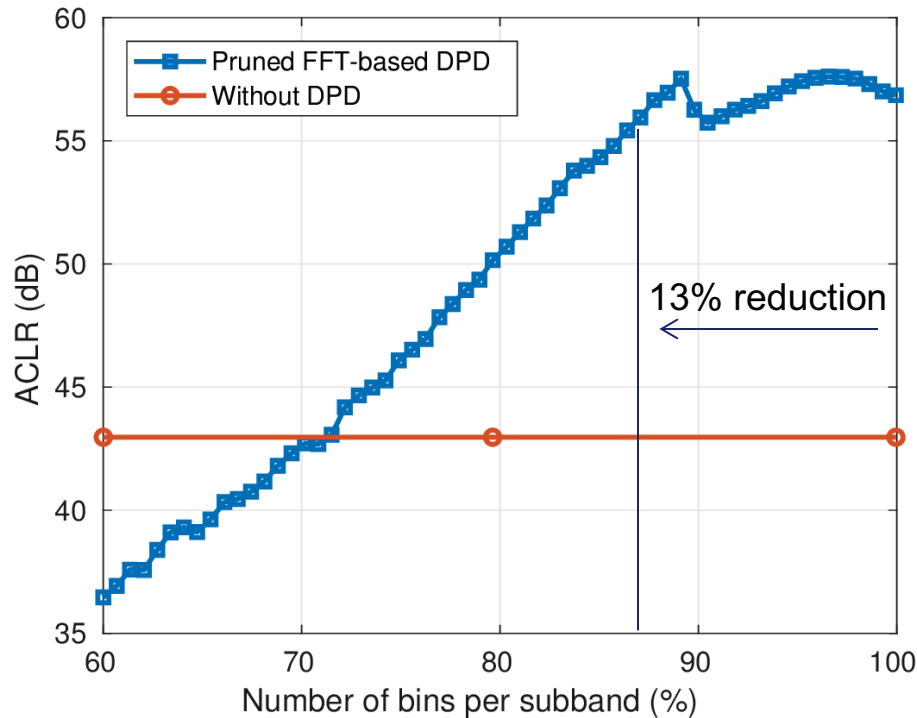
Exclusion of subband edges

$$\vec{Z}_{\text{Lin}} \equiv \widetilde{\Gamma}_V \vec{h}^{pd} = \vec{X}$$

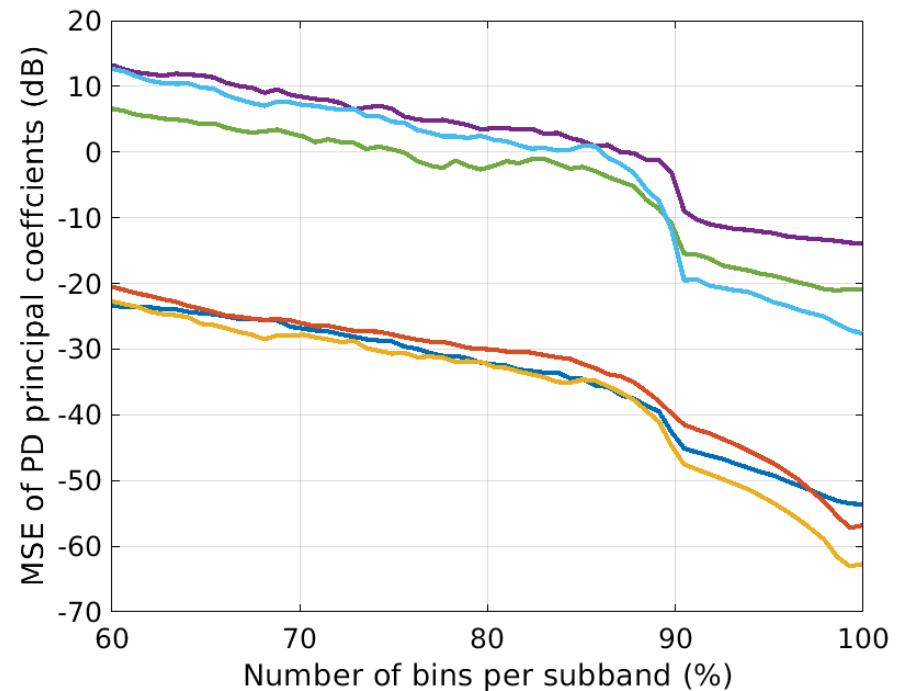
$$\widetilde{\Gamma}_V \sim \left(\widetilde{\text{fft}}(\vec{z}) \quad \widetilde{\text{fft}}(\vec{z}|\vec{z}|^2) \quad \widetilde{\text{fft}}(\vec{z}|\vec{z}|^4) \quad \dots \right)$$

TX feedback path : FFT-based subband DPD

– Linearization performance



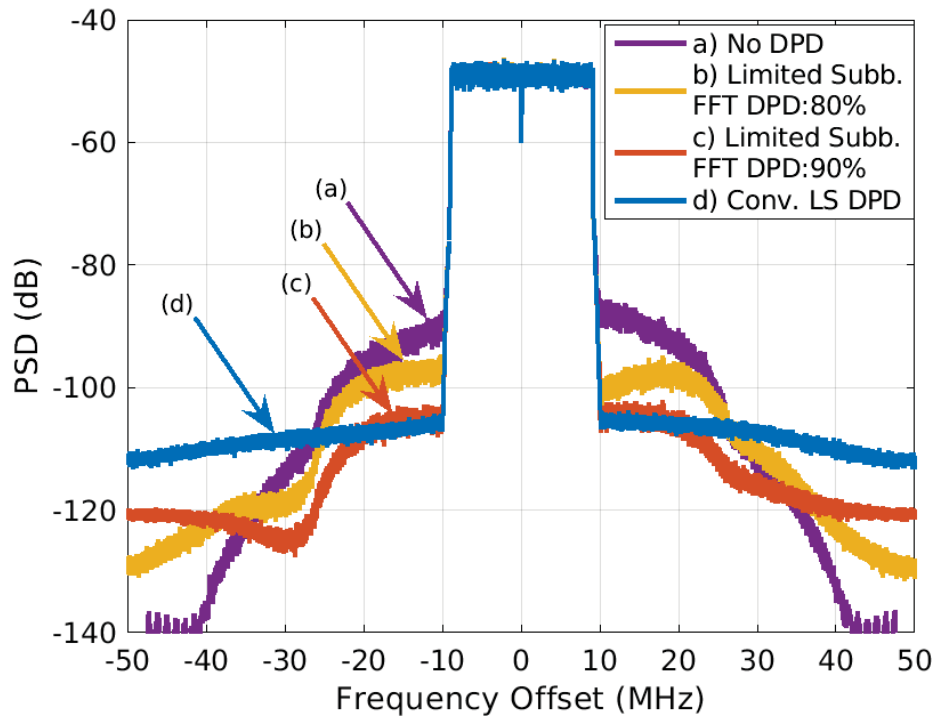
Correction performance of
FFT-based Limited Subband DPD



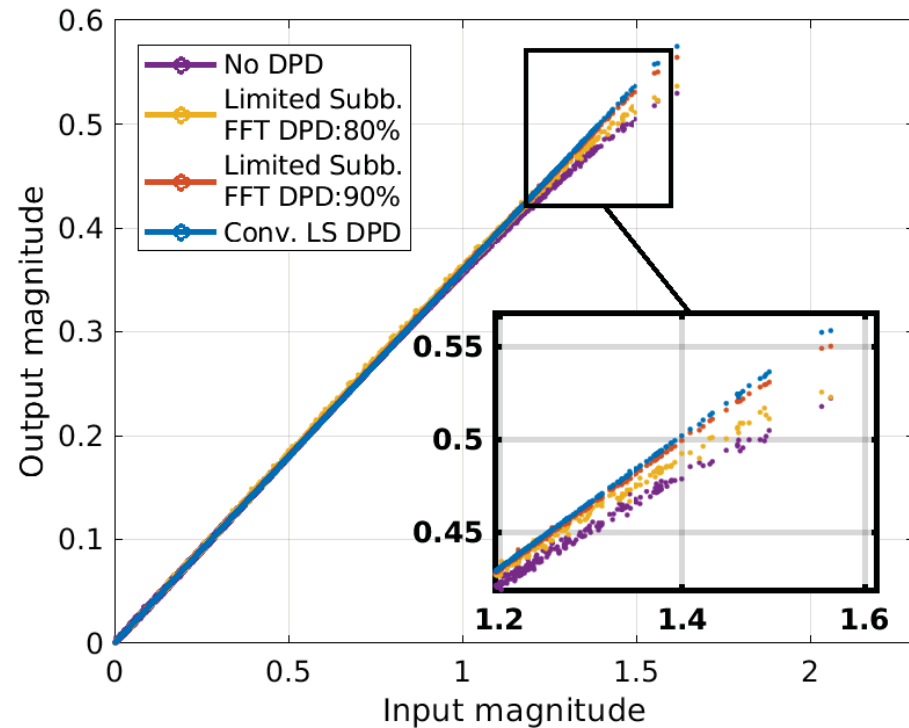
Error between ideal PD and
FFT-based Limited Subband PD

TX feedback path : FFT-based subband DPD

– Linearization performance



Output spectra comparison

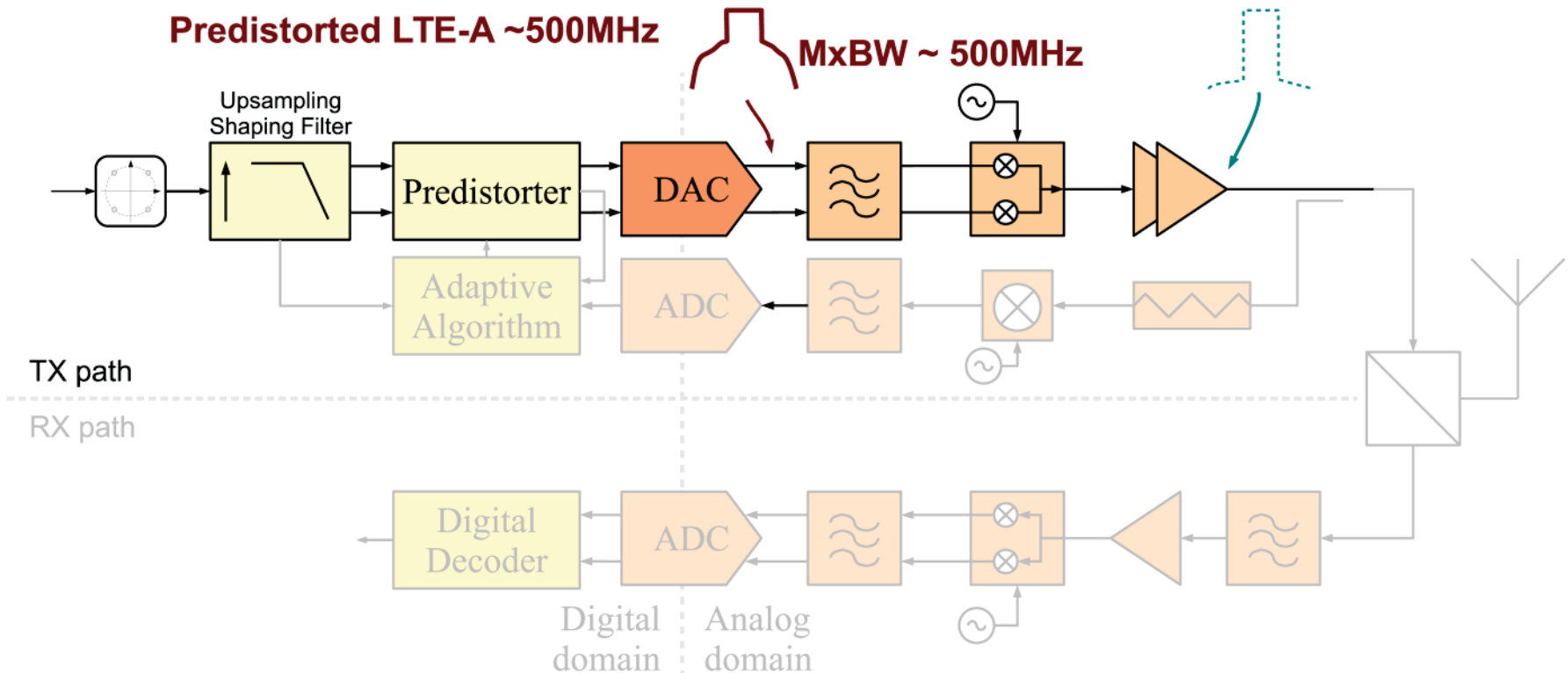


AM/AM comparison

RX forward path : the bottleneck

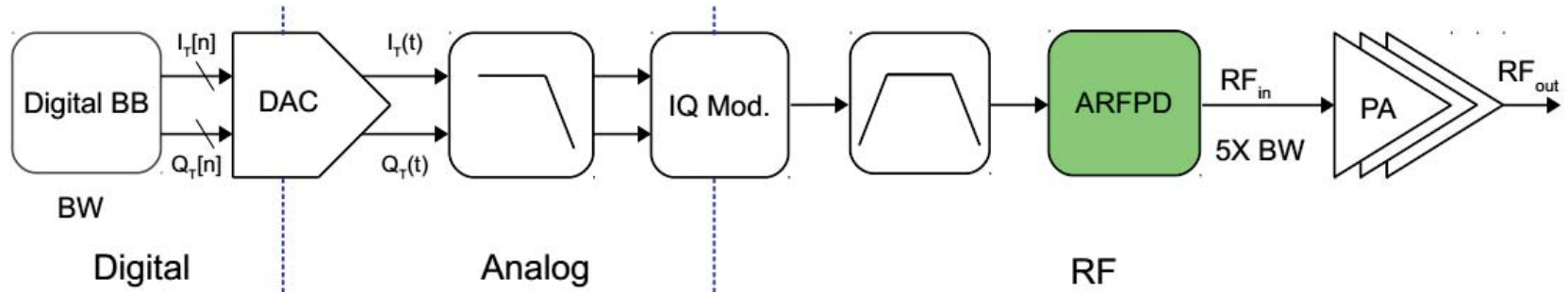
■ DAC bandwidth limitation

- Correction phase



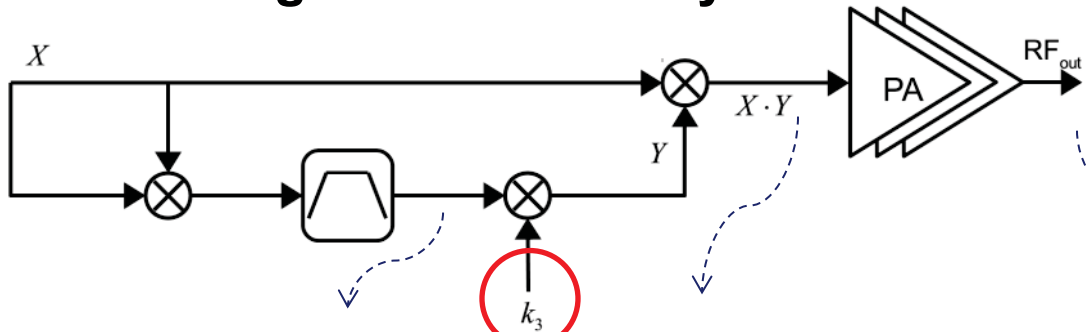
Basic Principle of Analog RF Predistortion

ARFPD performed mostly in RF, with baseband analog correction signal

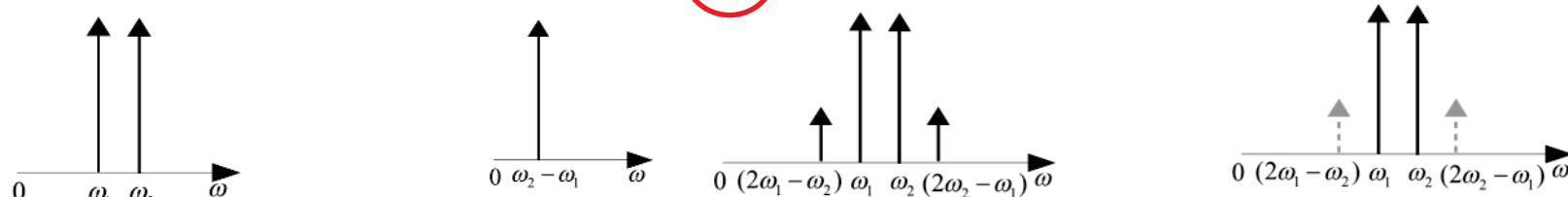


- Analog multipliers are used to generate correction signal

For a two-tone signal with memoryless PA



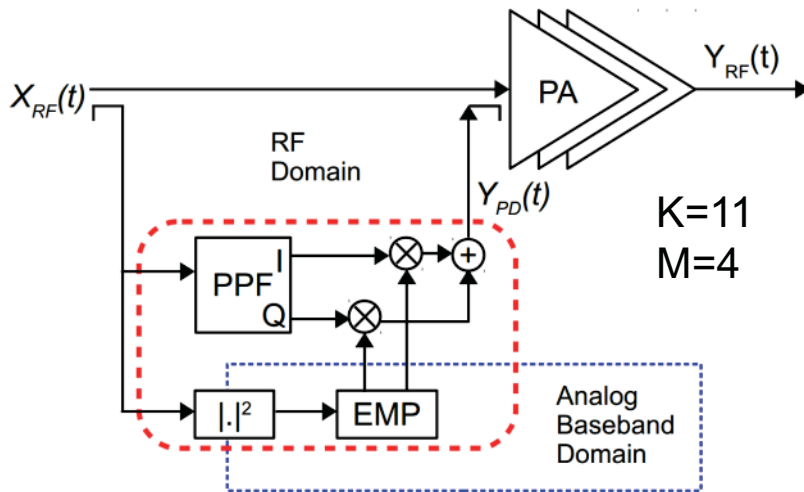
Choose k_3 based on PA nonlinearity



Memory-Aware ARFPD

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

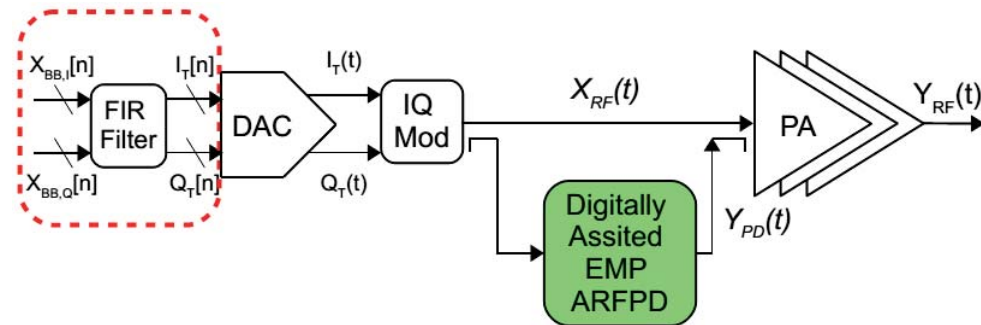
$$Z_{PD,EMP}(t) = x(t) \sum_{k=0}^{K-1} \sum_{q=0}^Q a_{kq} |x(t - t_p)|^k$$



- 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:

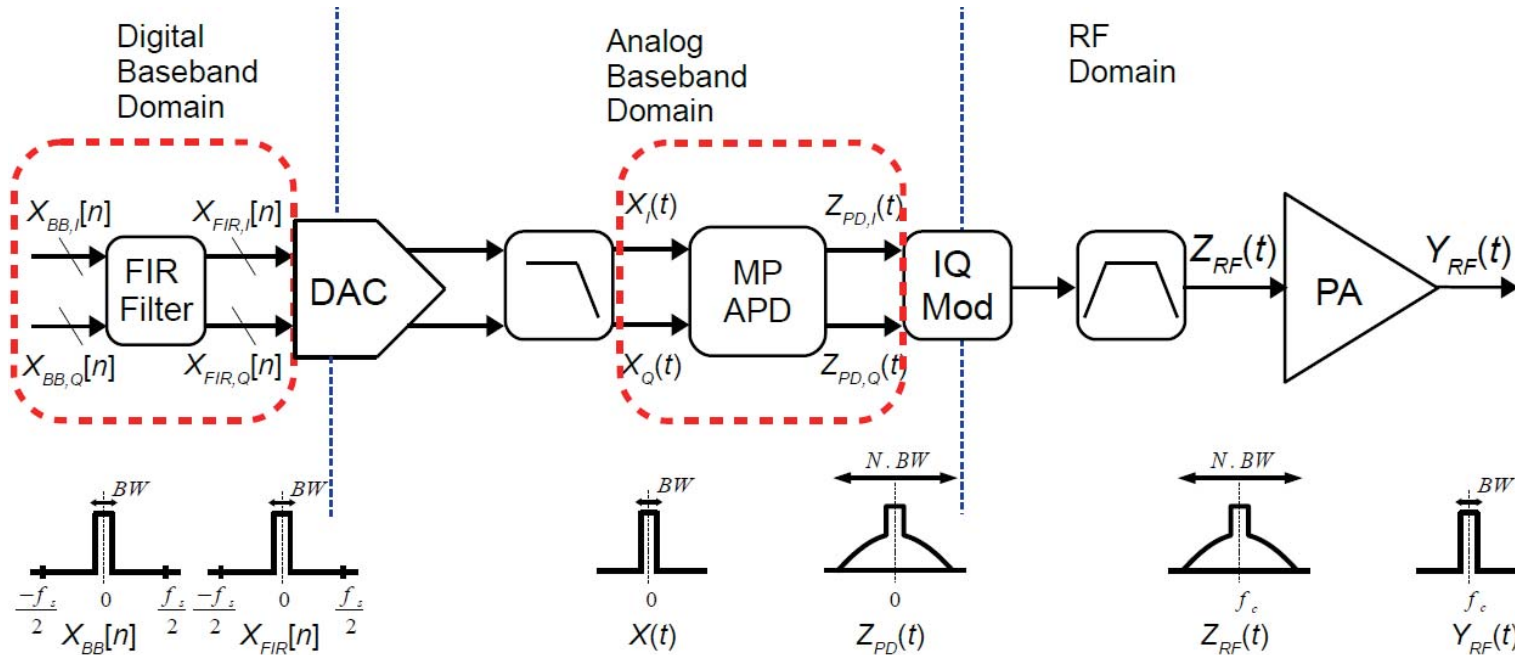
- Digital baseband clocked at normal clock rates
- Relaxed specifications of the entire Tx

} → Overall Low Power!!

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

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