DEMYSTIFYING NON-LINEAR PA BEHAVIOR SEMINAR

In cooperation with Hi-Tech, Maury Microwave and Amcad

ROHDE&SCHWARZ

Make ideas real

AGENDA

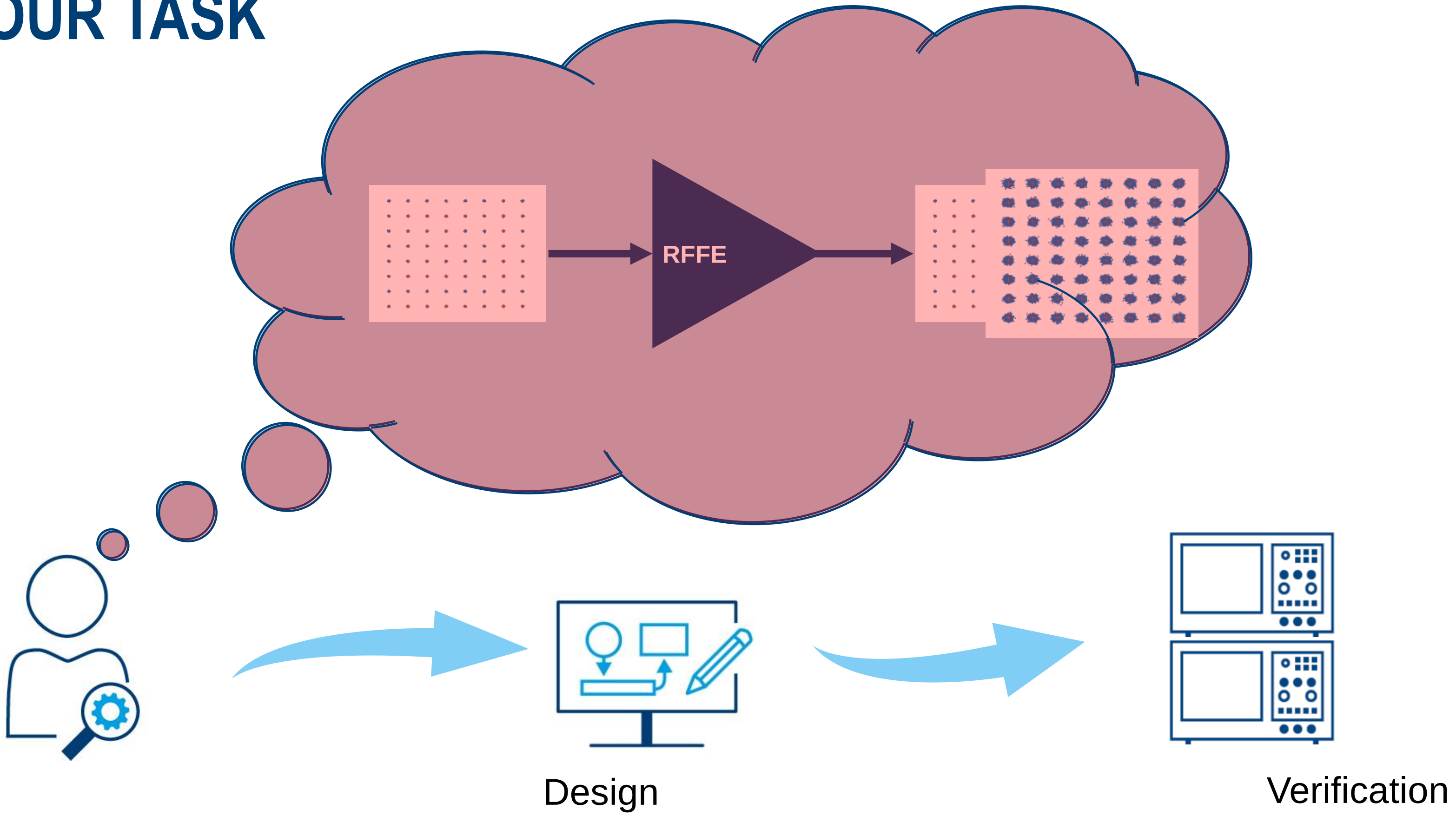
Time	Session
8:30 – 9:00	Welcome reception
9:00 – 10:30	Load-Pull measurements to improve efficiency of power amplifiers
10:45 – 11:00	Coffee / Tea break
11:00 – 12:00	Transistor / Amplifier Characterization by doing load pull measurements to find best efficiency behavior
13:00 – 14:00	Lunch
14:00 – 15:00	From Modelling to Simulation
15:15 – 16:15	**Understand linearity improvement possibilities on a physical amplifier**
16:15 – 17:00	Behavioural Modelling based on Amcad 3 tone Method plus verification on measurements

UNDERSTAND LINEARITY IMPROVEMENT POSSIBILITIES ON A PHYSICAL AMPLIFIER

ROHDE & SCHWARZ

Make ideas real

YOUR TASK



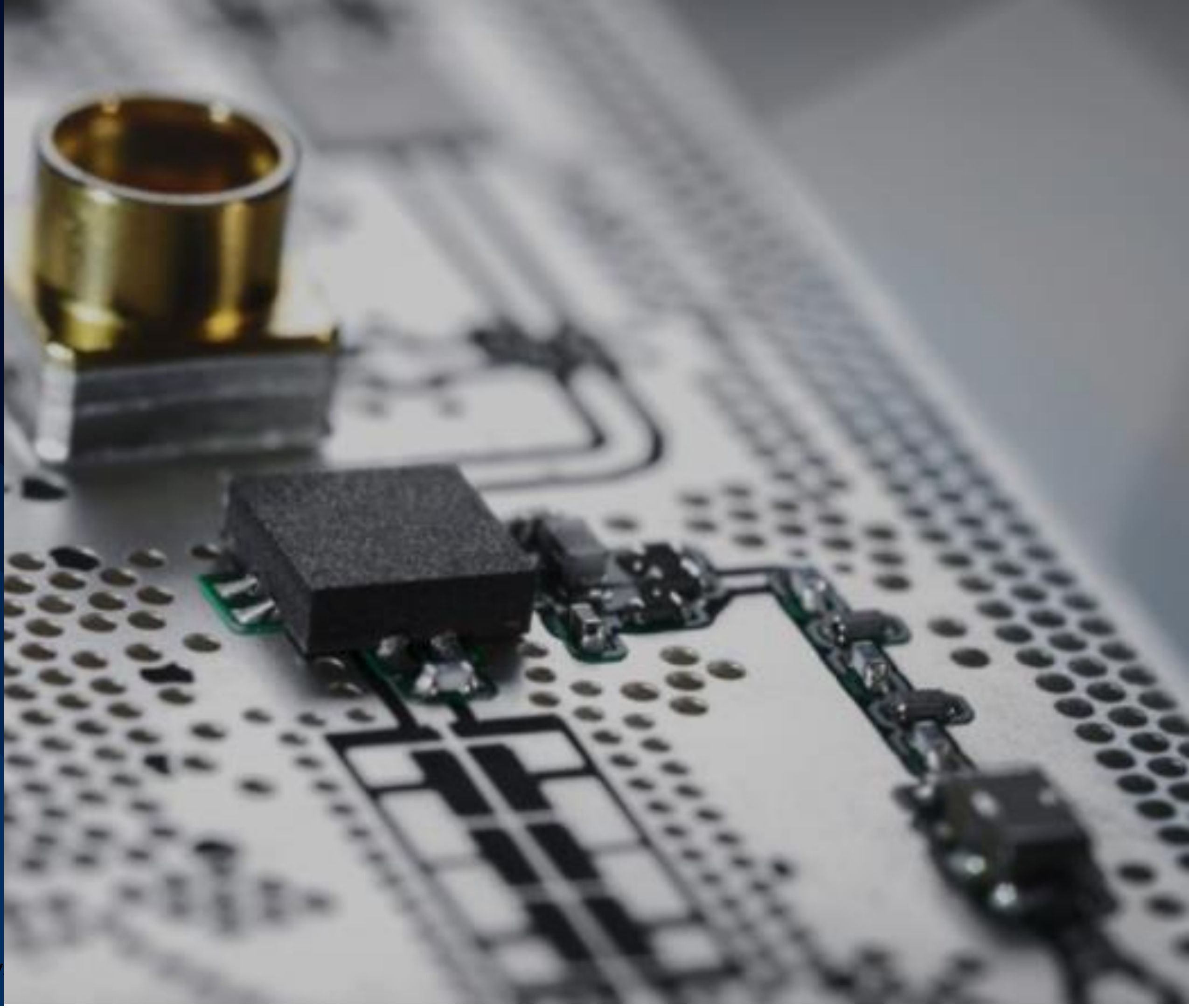
OUTLINE

- Intro and motivation
- Effect of linearization
- Why modulated signals

- Getting to the best possible PA performance
- Deriving models for linearization

- Conclusion

Understand linearity improvement possibilities on a phy



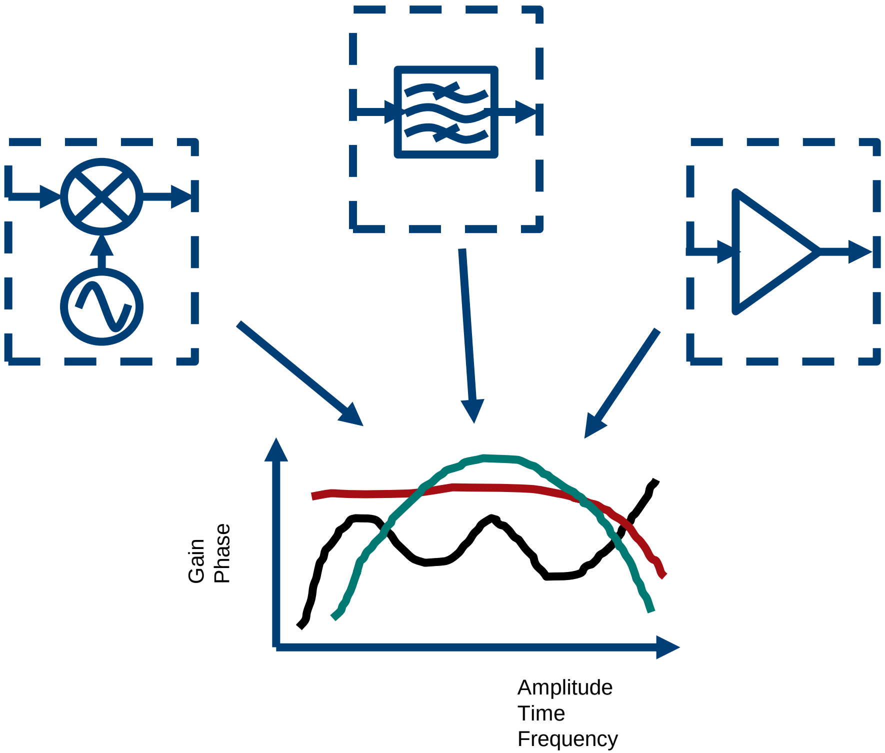
UNDERSTANDING DISTORTIONS

- Distortion limits RFFE performance

- Distortions might generally be defined as variations in complex gain (amplitude and phase) in three domains:
  - Amplitude (e.g. non-linear distortion)
  - Frequency (e.g. linear distortions)
  - Time (e.g. memory effects)

- All RFFE components demonstrate all the distortions, in varying proportions:
  - **Mixers** and **Amplifiers** often contribute most to **non-linear** and **memory effect** distortions
  - **Filters** often contribute the most **linear** distortion

- Distortion reduction is called **Linearization**

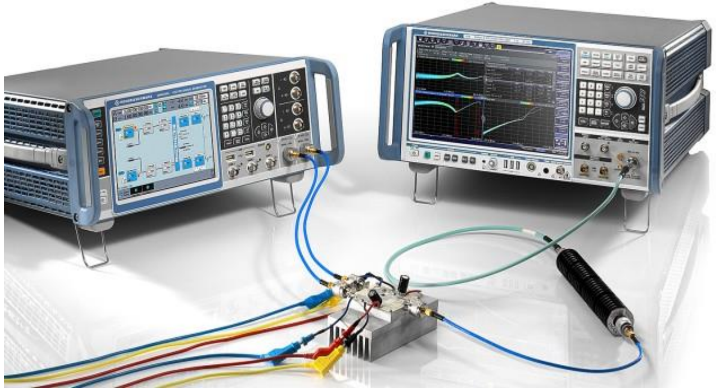


WHY LINEARIZATION?

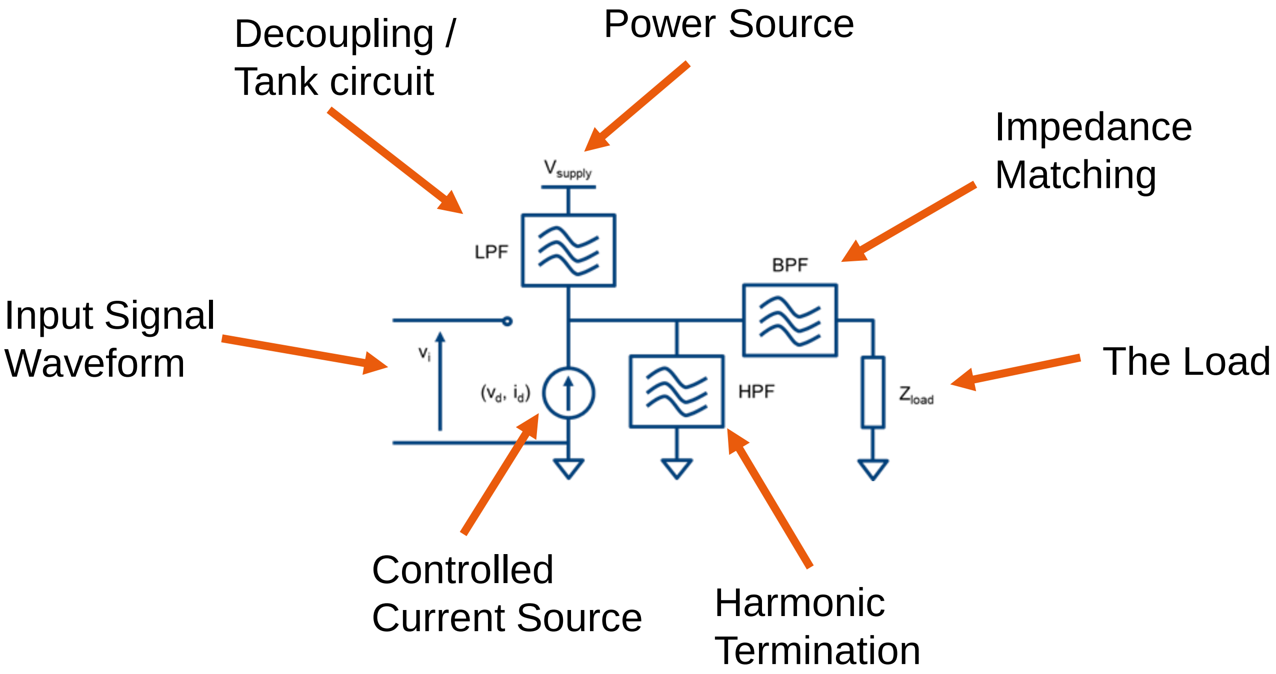
- Challenging RF signals on RF frontends
  - 5G in mmWave and RF, mMIMO, beamforming, increasing bandwidth, higher order modulations, digital payloads, wideband Electronic Warfare (EW)
- Significant power consumption is in the RF Front-End (RFFE)
  - Operating close to saturation offers best energy efficiency
  - Technologies such as GaN absolutely require digital predistortion for linear operation
- Various PA topologies studied
  - Doherty, Load Modulated Balanced Amplifier (LMBA), Outphasing, …

- PA gains in efficiency but is highly non-linear

  → Linearization is a _*MUST*_

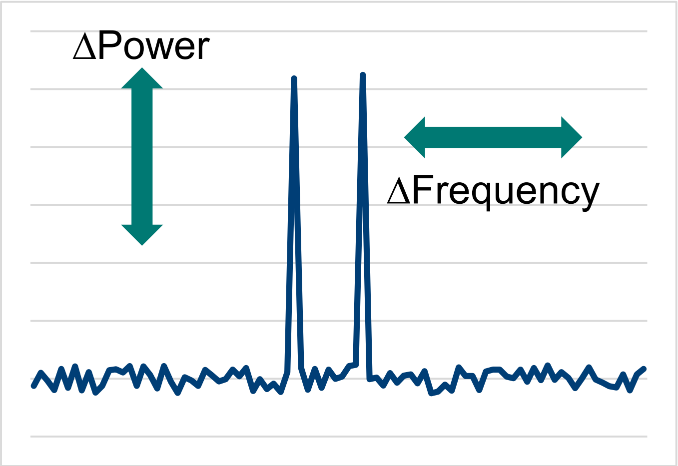


THE RF AMPLIFIER BUILDING BLOCK

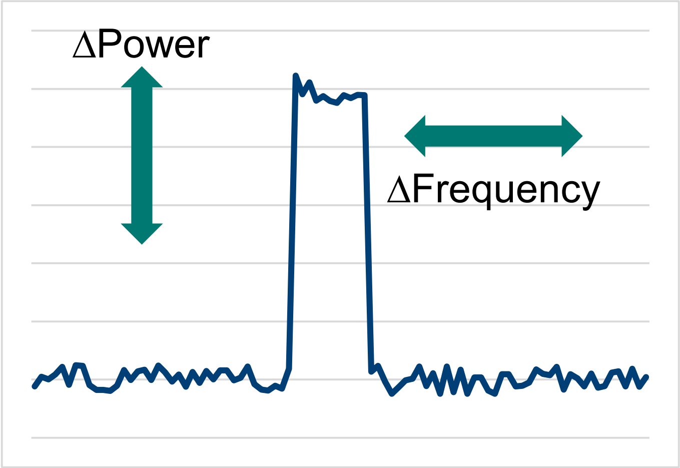


WHY MODULATED MEASUREMENTS

- Traditional approach – VNA with CW measurements
- CW signals do not accurately represent modern signals



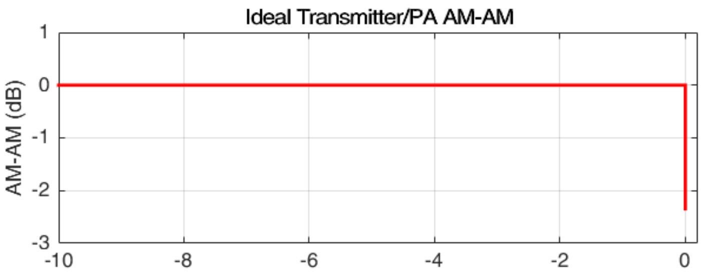
- Alternative approach – use the same signal that will be amplified
- Modern signals are wider BW’s, higher crest factors
  - Consider integrated power in channel, overshoot in symbol transitions, etc.

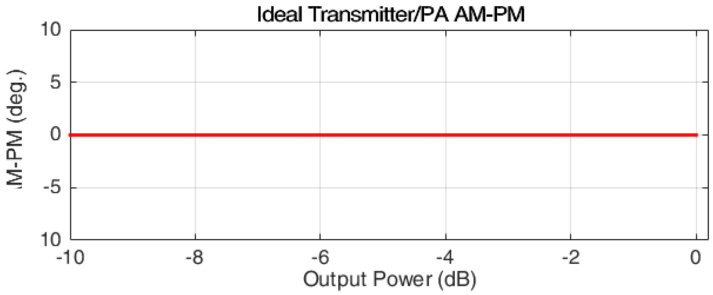


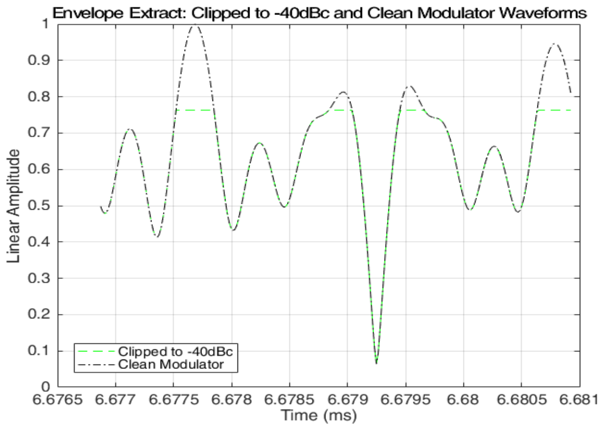
WHY LINEARIZATION

- ► Dreamland: Ideal amplifier with “hard limiter” response
  - AM/AM: Brick-wall behavior
  - AM/PM: eliminated – No distortion

→ linear system, just cutting of peaks through hard limiter

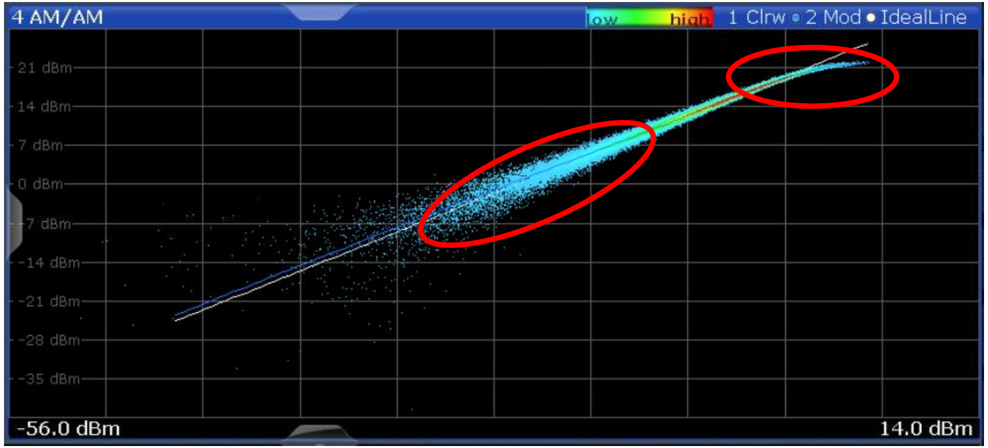






WHY LINEARIZATION

- Two areas of interest:
  - compression
  - memory effect



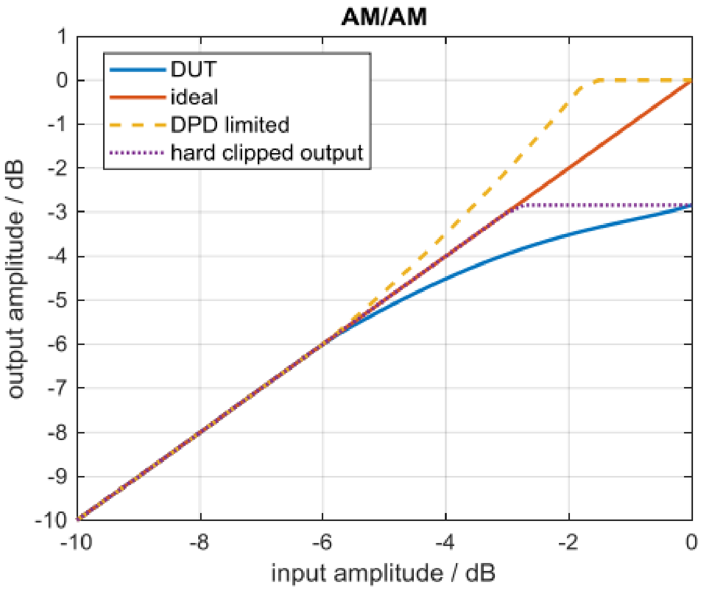
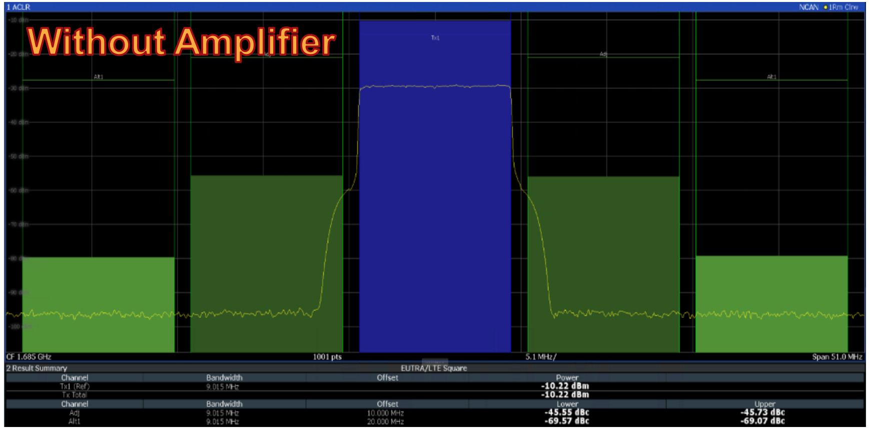
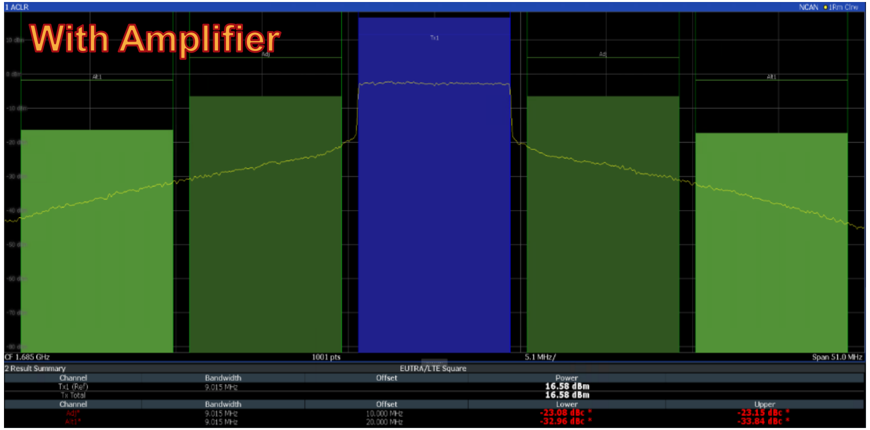


Figure 4 Overview plot: measured AM/AM, ideal output, pre-distorted input signal, and target output signal (hard clipped)

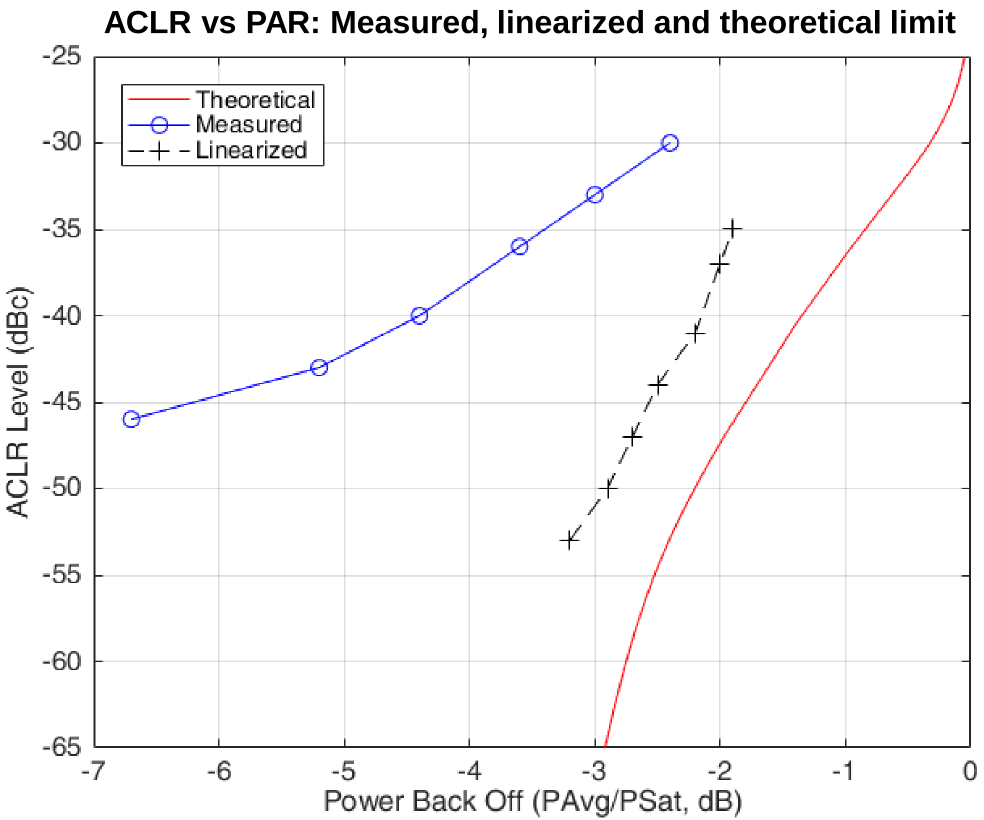
WHY LINEARIZATION

- ACLR measurements determine the channel power and adjacent channel power
- Amplifiers can cause spectral regrowth to occur in adjacent channels resulting in more power





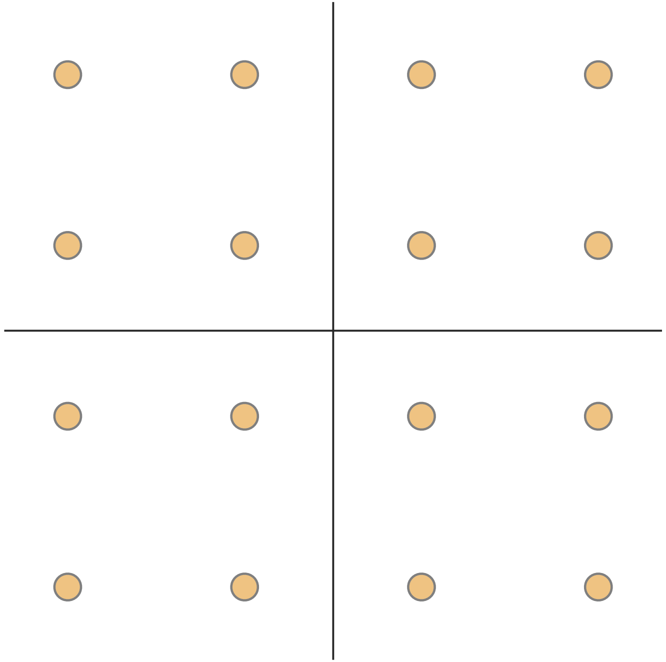
LINEARIZATION: MEASUREMENT EXAMPLE



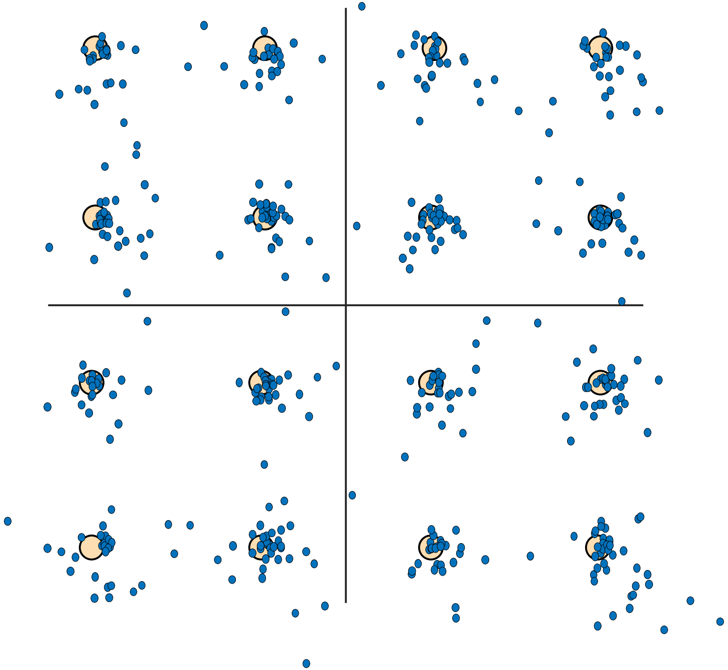
- In this specific example, digital predistortion (DPD, memoryless, polynomial) is applied to a device used a mobile front-end, with a standard test signal.

ERROR VECTOR MAGNITUDE

- Ideal constellation diagram



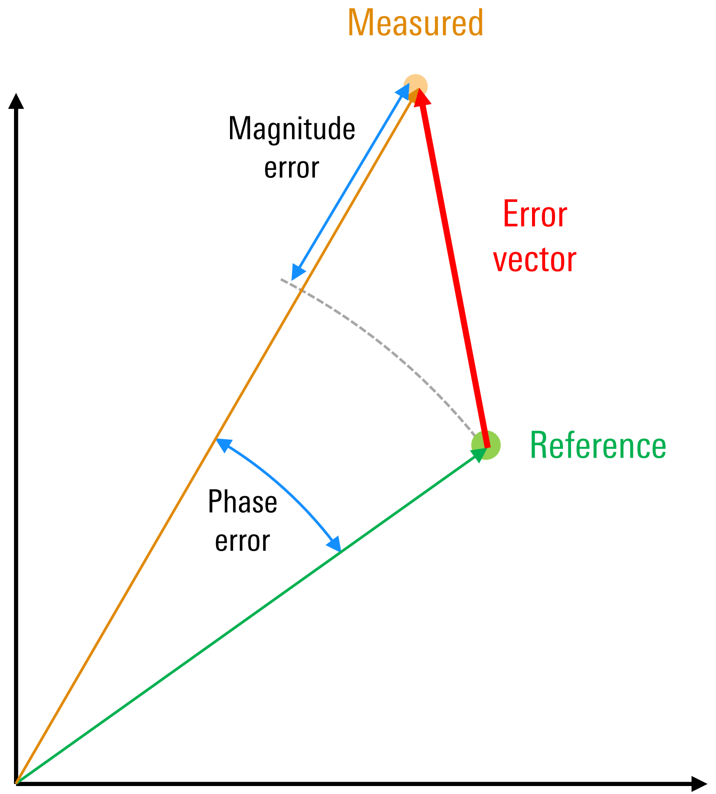
- It might look different after going through the PA



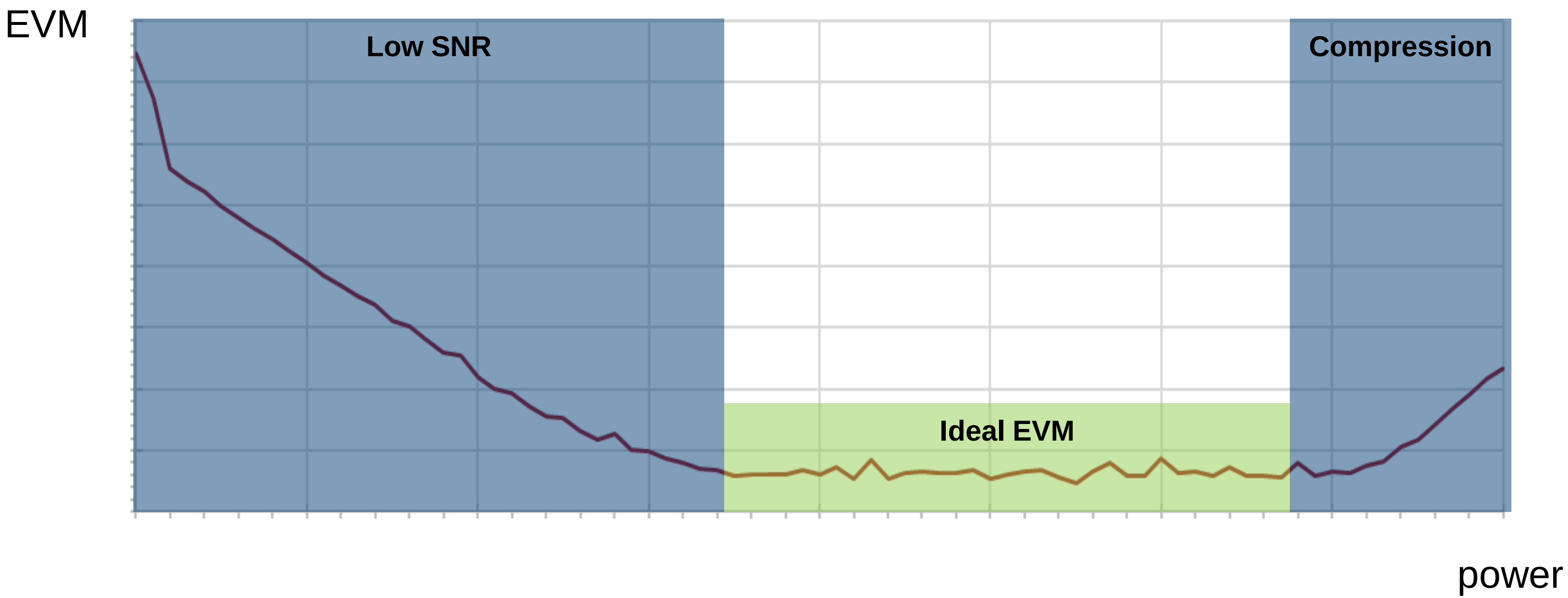
ERROR VECTOR MAGNITUDE

- Error vector: difference between ideal constellation point and actual sample
- EVM to high → BER is increasing
  - Higher modulation scheme → lower EVM required

- EVM: FOM for inband signal performance
  - Compression, non-linearity
  - Noise (low SNR)
  - Frequency response
  - Inter-symbol interference

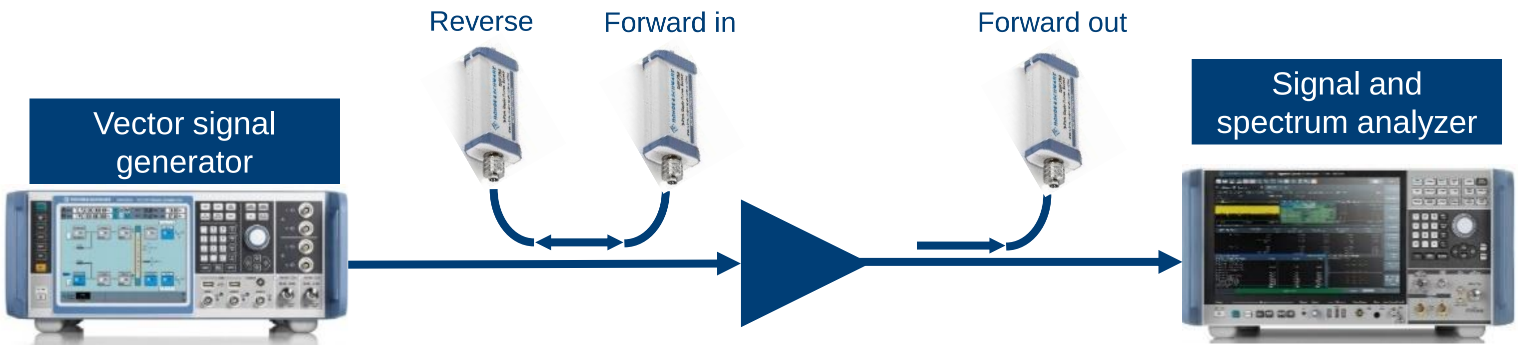


ERROR VECTOR MAGNITUDE



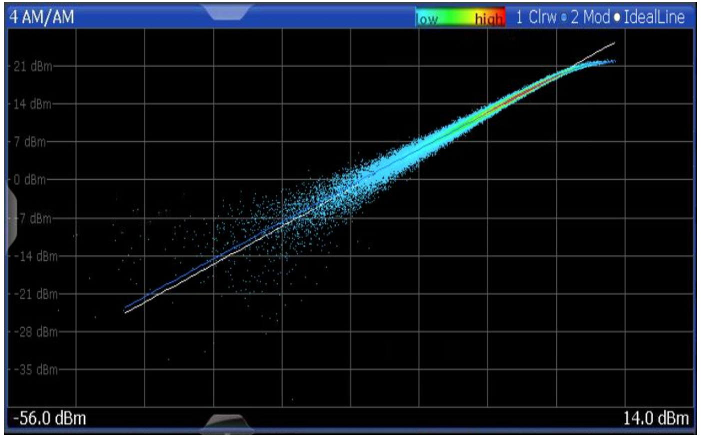
HARDWARE VERIFICATION
MODULATION TESTS

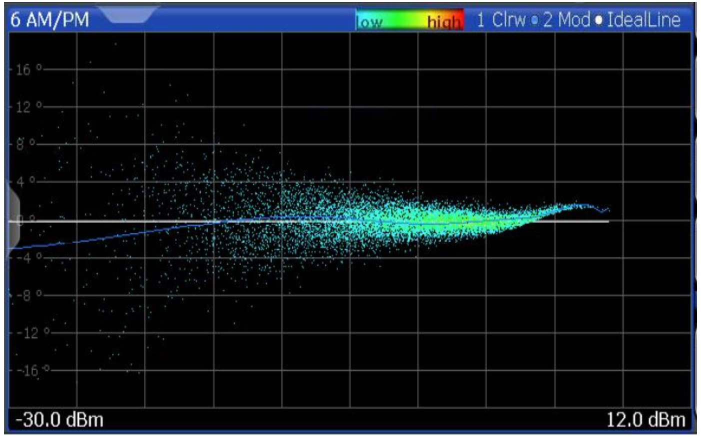
- ► Channel power
- ► Adjacent Channel leakage ratio, ACLR / ACP
- ► Modulation performance: EVM
- ► Distortion: AM/AM and AM/PM



HARDWARE VERIFICATION
DISTORTION

- Linearity of amplitude and phase through the amplifier
- Using signal fidelity from modulation
- Variance gives indication on memory effect based distortion





GOAL: HOW GOOD CAN A PA BE?

- DPD is used in real systems to optimize the PA performance
- DPD is a specialty of each system manufacturer and the “secret sauce” in between vendors

- PA manufacturer has no access to these sometimes significant size DPD teams
- Looking for an easy way to understand how good their devices can be

- **Direct DPD** is offering this capability
  - Iterative approach
  - Compares ideal input signal to received distorted signal and calculates a new pre-distored signal on a sample-by-sample base
  - Takes care of non-linearity, memory effect, distortion
  - Provides insight to what can be reached

AMPLIFIER OPTIMIZATION

OPTIMIZATION OPTIONS

- Optimization is very much dependent on application
  - Maximum output power for CW or pulses
  - Linearity for best modulation capabilities
  - Efficiency for lowering power consumption and thermal management
- Different use cases ask for different optimization
- Optimization: mixture between simulation and measurement aided development
- Waveform engineering with different classes of amplifiers: class A, AB, B, C, …
- User-defined CFR
- Different topologies
  - Envelope tracking
  - Doherty amplifier
  - Load Modulated Balanced amplifier
- Linearization
  - Digital predistortion

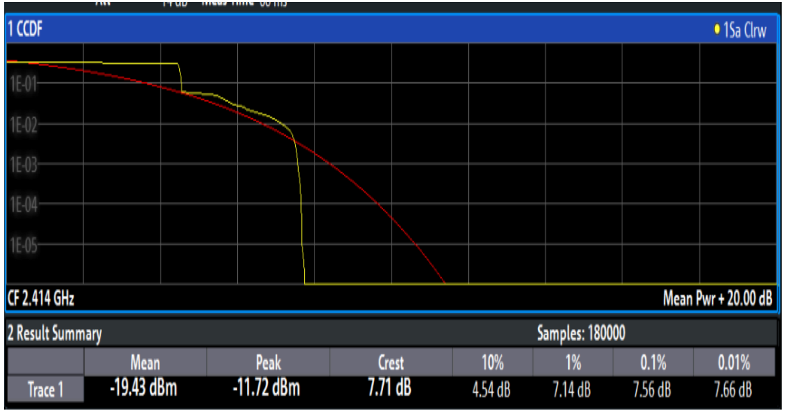
OPTIMIZATION OPTIONS
CFR

- Crest factor: Ratio peak to average
- Rare peaks ask for large back-off

- Issues:
  - Compression creates intermodulation expanding spectrum of signal
  - In DAC: back-off limits resolution of RMS values → quantization noise

  → both increase ACP

- CFR:
  - Defined clipping **and** filtering
  - Manage harmonic distortion



OPTIMIZATION THROUGH DPD

- ► Pre-distort signal to compensate DUT characteristics
- ► Close to compression: Efficiency ↑ but non-linearity ↑
  → Linearization is a _*MUST*_
- ► PA designer: need understanding of system level performance with ideal predistortion on EVM and ACLR
  - – Iterative Direct DPD provides this information

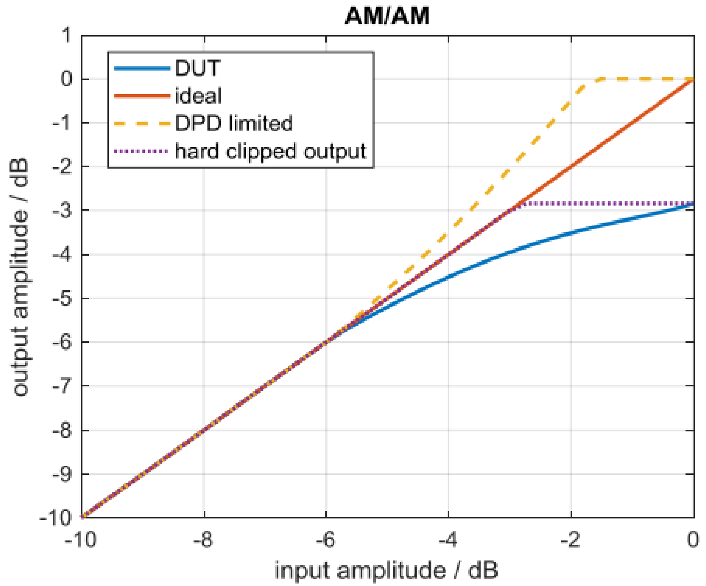
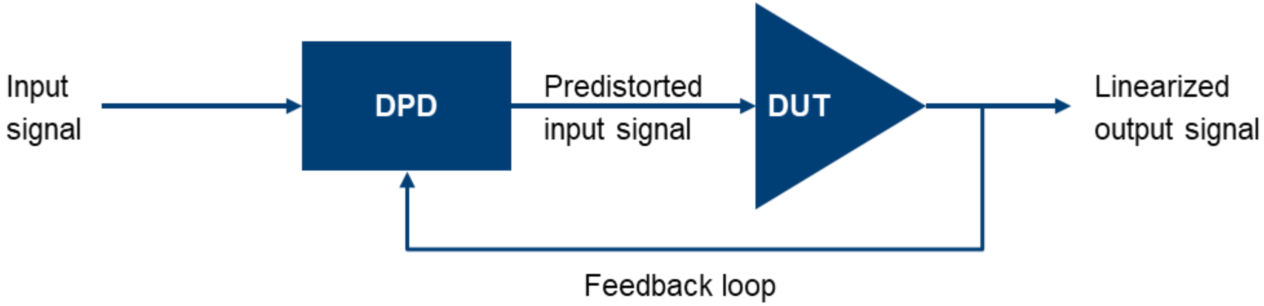
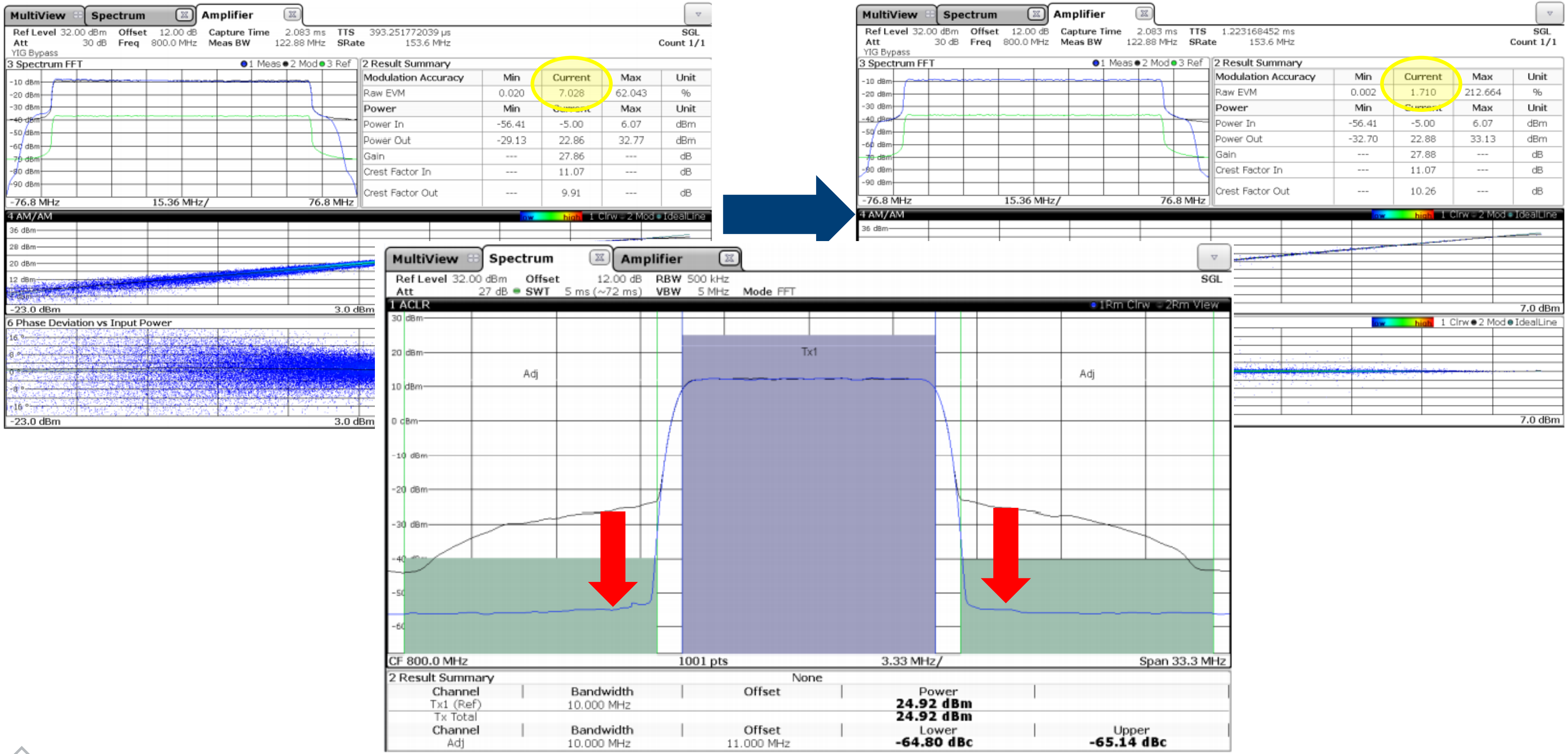


Figure 4 Overview plot: measured AM/AM, ideal output, pre-distorted input signal, and target output signal (hard clipped)

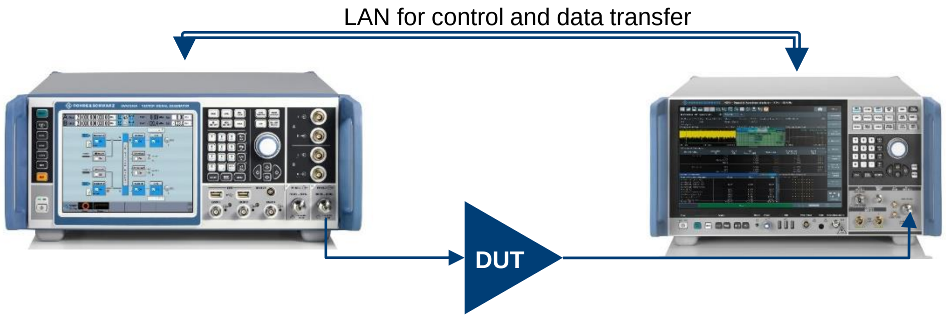


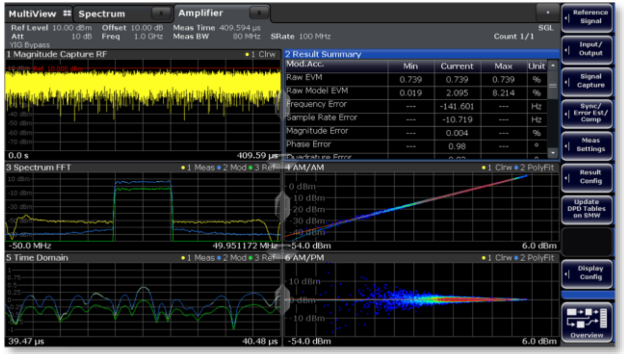
OPTIMIZATION EXAMPLE THROUGH DPD



Understand linearity improvement possibilities on a physical amplifier

DIGITAL PREDISTORTION ON A REAL POWER AMPLIFIER



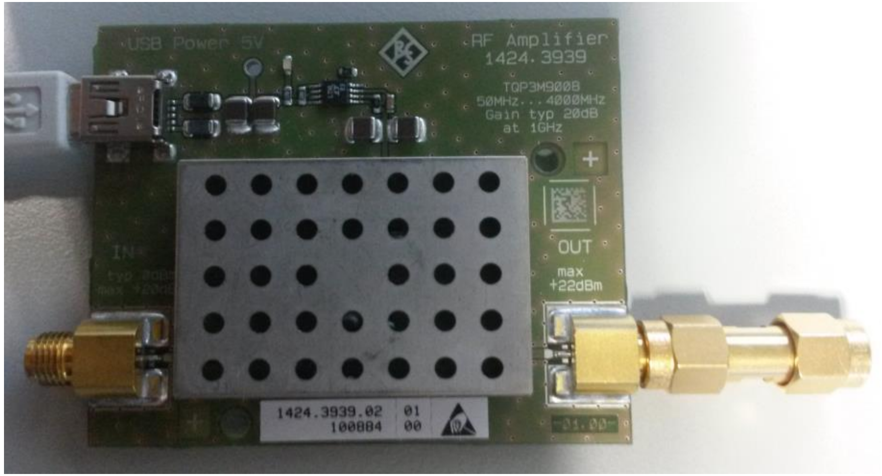


R&S®FSW-K18D Direct DPD

- Iterative approach
- Compensates for memory effects
- Excellent performance especially for amplifiers with memory effects

- Reference for best possible
  - Suppliers typically do not have access to DPD algorithms used by system integrators

DEMO PA

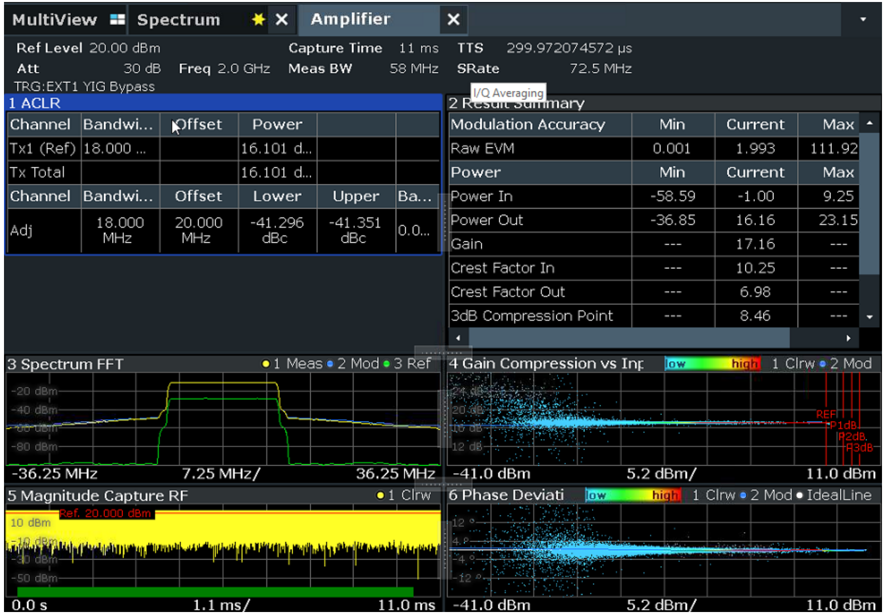


- 20 MHz OFDM signal
- 2 GHz
- Generator power: -1 dBm

RUNNING DPD

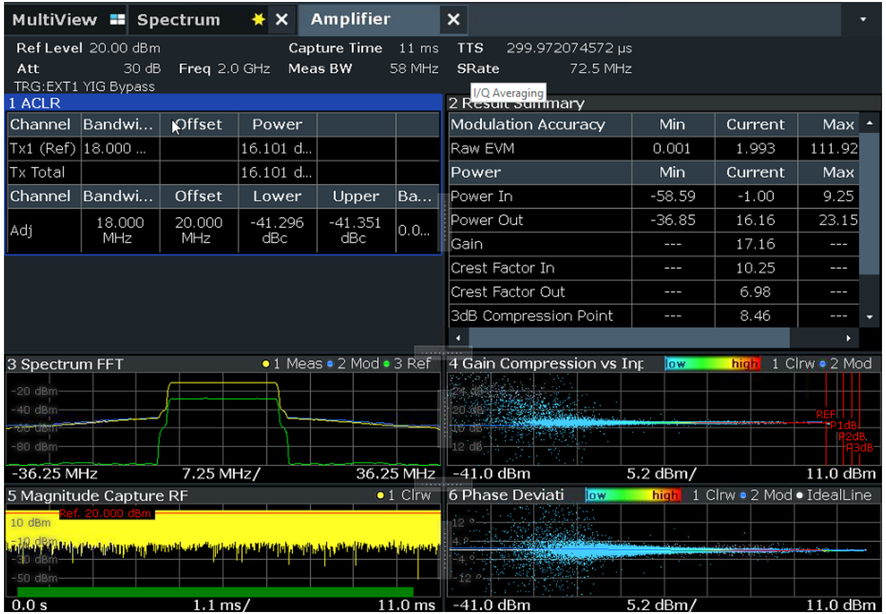
Before DPD

Run K18D, 0 dB Gain Expansion, 10 iterations (default setting)

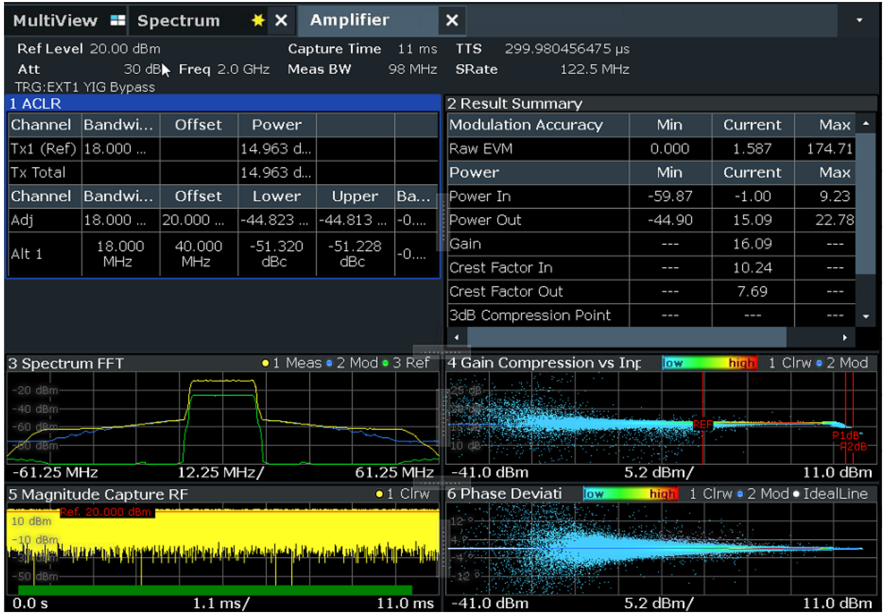


GAIN EXPANSION

Run K18D, 0 dB Gain Expansion, 10 iterations (default setting)

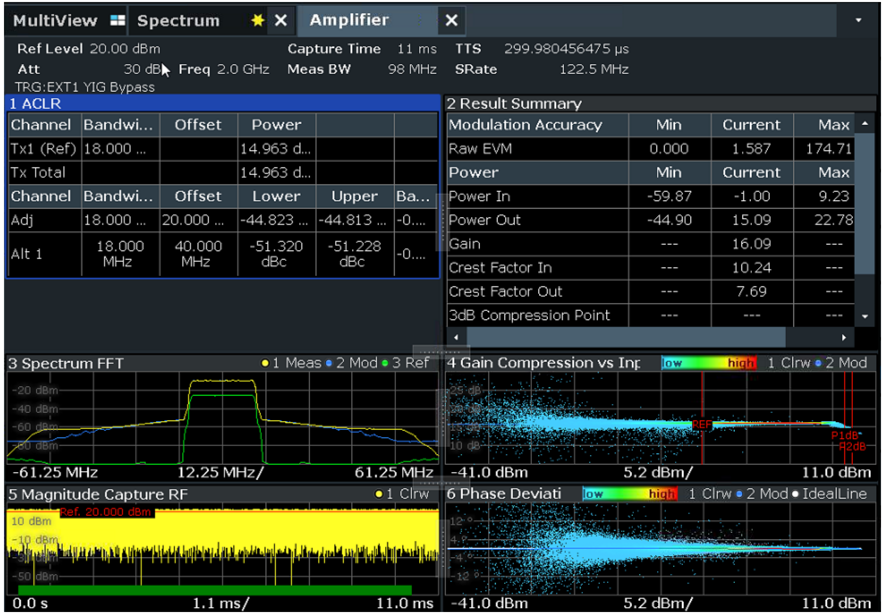


5 dB Gain Expansion, 2 adjacent channels in ACLR

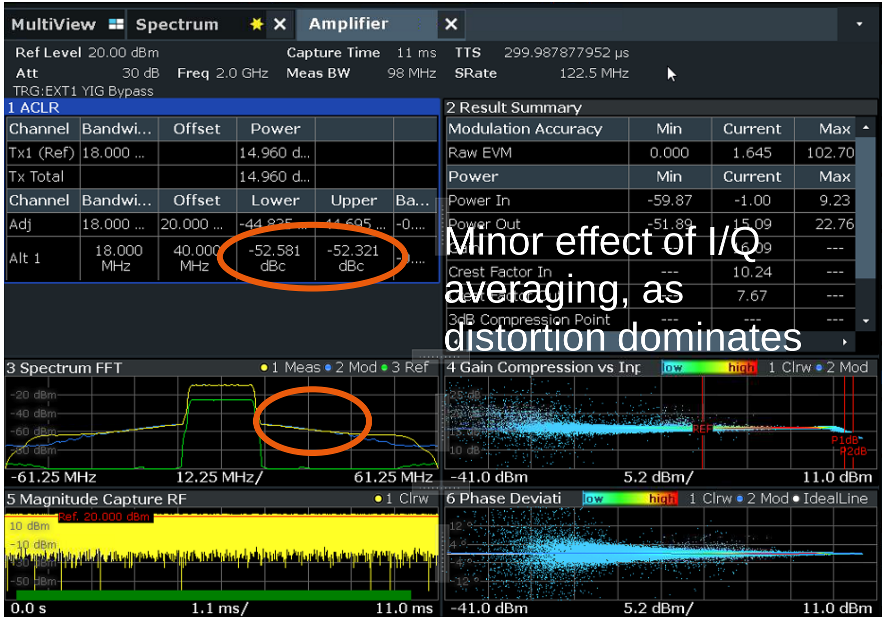


GAIN EXPANSION PLUS I/Q AVERAGING

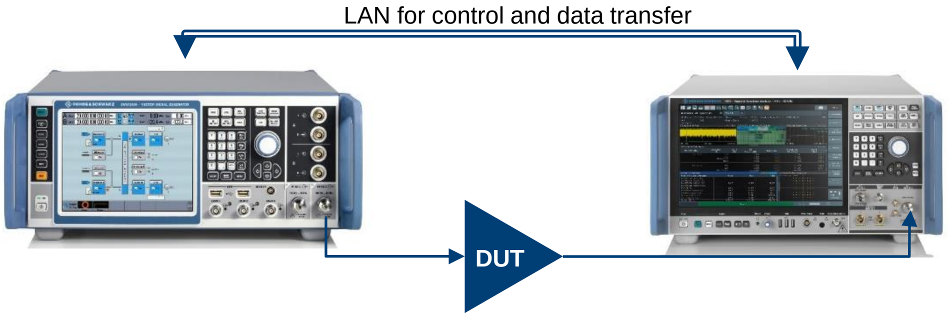
5 dB Gain Expansion, 2 adjacent channels in ACLR

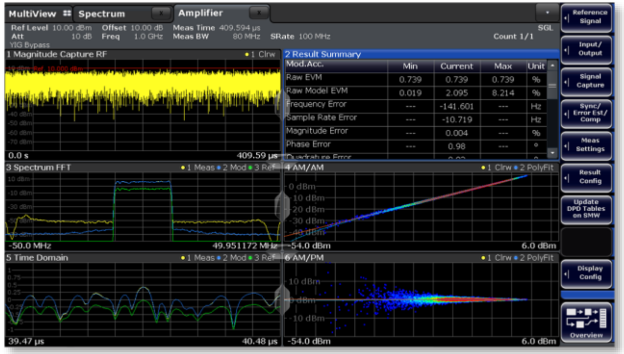


5 dB Gain Expansion, 10 I/Q Averages, 2 adjacent channels in ACLR



CREATING A DPD MODELL





R&S®FSW-K18D Direct DPD

- Iterative approach
- Compensates for memory effects
- Excellent performance especially for amplifiers with memory effects

- Reference for best possible
  - Suppliers typically do not have access to DPD algorithms used by system integrators

R&S®FSW-K18M memory polynomial

- Memory polynomial model or Hammerstein model based on Direct DPD result
- Modeling can be adopted in order and memory depth
- Model verification on DUT

- Proves easy linearization of RFFE solution

MEMORY POLYNOMIAL MODEL

- Derive an algorithm based memory DPD, as described in Application Note 1EF105
- We use a memory polynomial DPD

$$\tilde{P}(nT) = \sum_{p=1}^{P} \sum_{m=1}^{M} k_{p,m} A(nT - \tau_m) \, |A(nT - \tau_m)|^{p-1}$$

- We use the result of K18D to directly derive the coefficients, rather than modeling the DUT and inverting the model

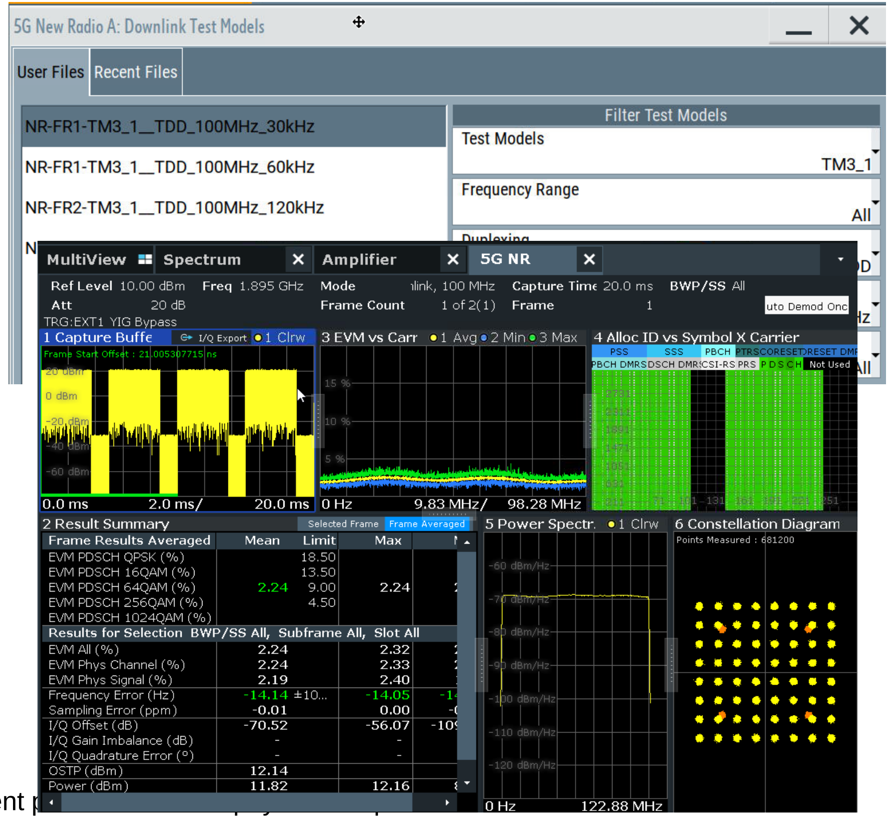
HAMMERSTEIN MODEL

- Predistortion according to the Hammerstein model, is applied to the IQ sample stream by first applying a non-linear polynomial, followed by a convolution

- Easier to be applied in real-time to any IQ stream
- Much less complex → less power needed to apply
- But a bit less efficient in EVM & ACLR improvement

CHARACTERIZE DUT AND DERIVE DIRECT DPD

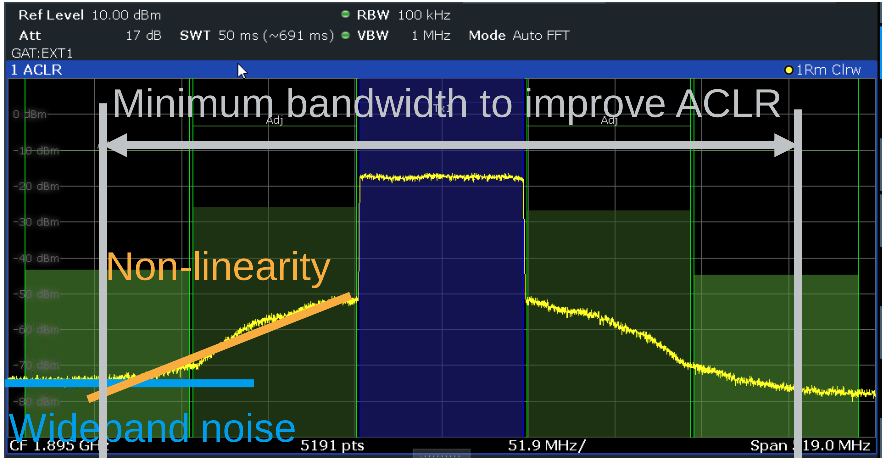
- Either use the real-world signal or
- Or use „Generate Own Signal“ with a bandwidth and crest factor similar to your real-world signal
- Example: 5G FR1, TDD, 100 MHz, 30 kHz



REQUIRED DPD BANDWIDTH

- ► Significant ACLR that we need to correct
- ► We‘ll need 4-5 x TX bandwidth for DPD

➔ Huge capture to process – maybe one want to use a much shorter representative signal

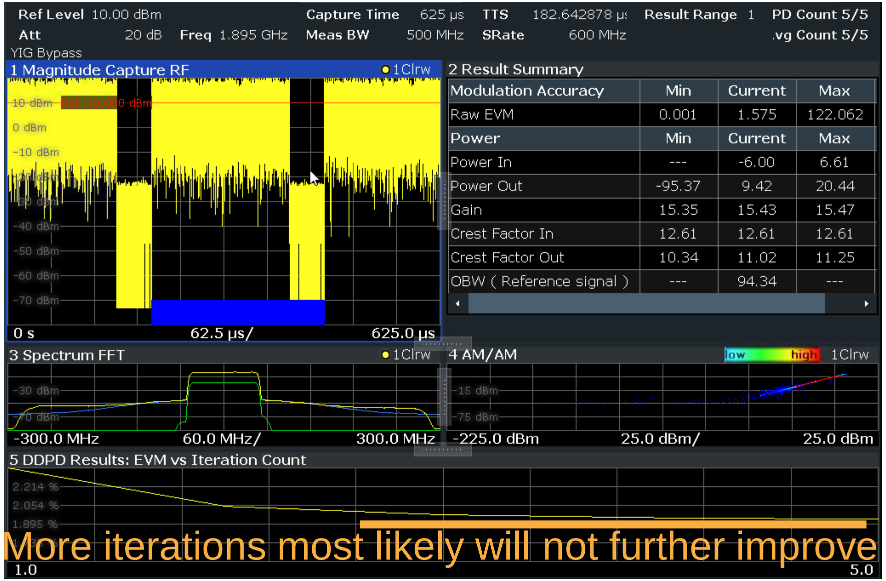


Channel	Bandwidth	Offset	Power			
Tx1 (Ref)	98.280 MHz		12.19 dBm			
Tx Total			12.19 dBm			
Channel	Bandwidth	Offset	Lower Abs	Upper Abs	Lower Rel	Upper Rel
Adj	98.280 MHz	100.000 MHz	-25.93 dBm	-26.89 dBm	-38.13 dBc*	-39.09 dBc*
Alt1	98.280 MHz	200.000 MHz	-43.40 dBm	-44.81 dBm	-55.59 dBc	-57.00 dBc

EVALUATE DIRECT DPD RESULT

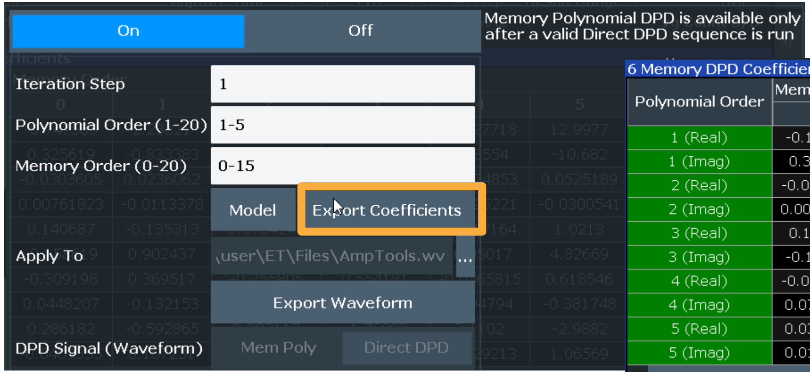
- Have a look at the DDPD Results window – if it flattens out to the right, more iterations will most likely not make it better

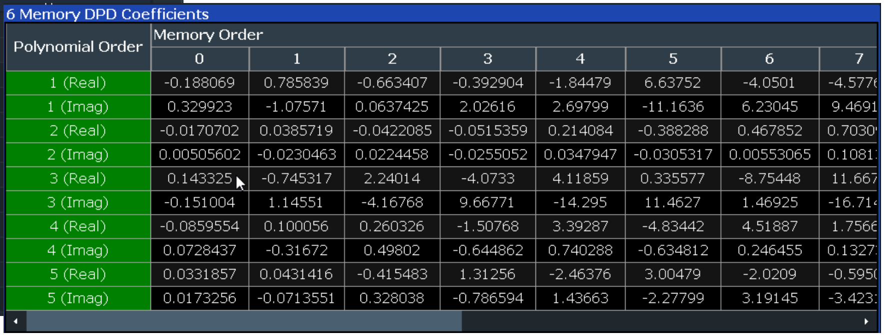
- Double check if noise affects the K18D result, if so – increase I/Q averaging count



MODELLING PROCESS

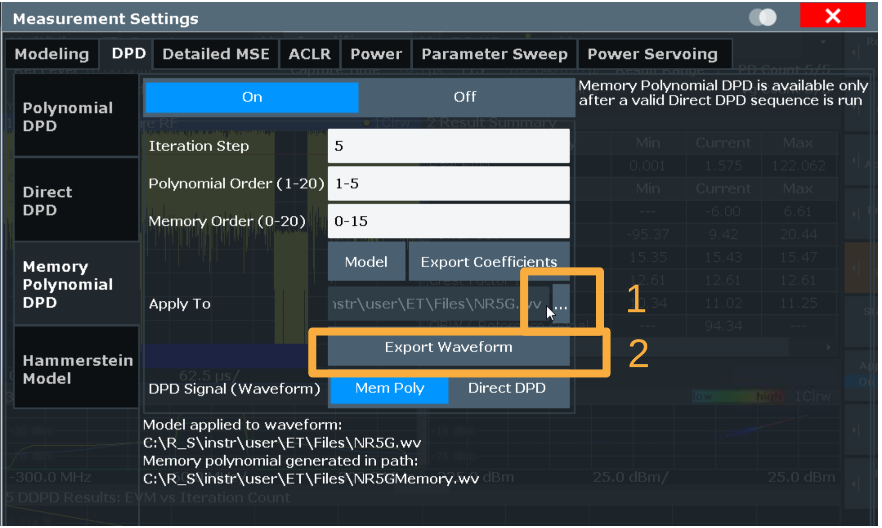
- ▶ Iteration step: last iteration is typically best, but check Direct DPD Result window for best iteration
- ▶ Memory Depth: may require a bit of experimenting, high oversampling typically requires more memory depth




6 Memory DPD Coefficients

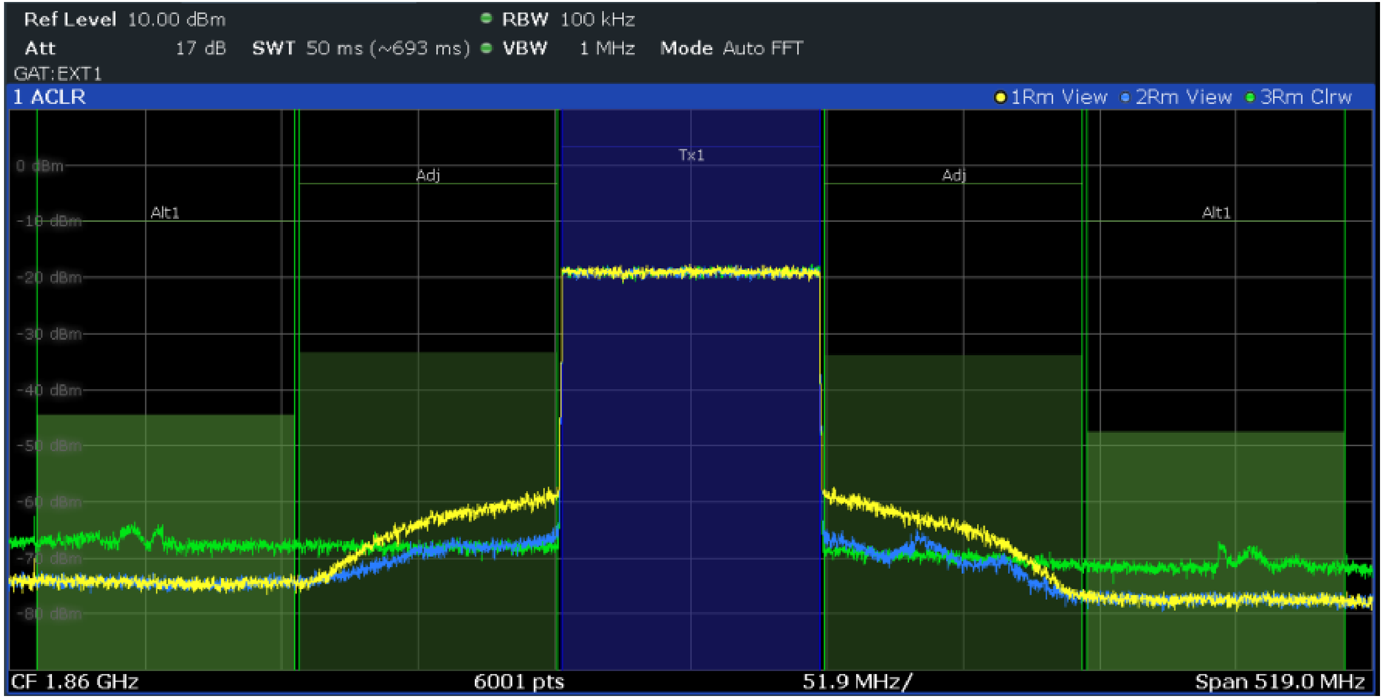
Polynomial Order	Memory Order 0	1	2	3	4	5	6	7
1 (Real)	-0.188069	0.785839	-0.663407	-0.392904	-1.84479	6.63752	-4.0501	-4.577
1 (Imag)	0.329923	-1.07571	0.0637425	2.02616	2.69799	-11.1636	6.23045	9.4691
2 (Real)	-0.0170702	0.0385719	-0.0422085	-0.0515359	0.214084	-0.388288	0.467852	0.7030
2 (Imag)	0.00505602	-0.0230463	0.0224458	-0.0255052	0.0347947	-0.0305317	0.00553065	0.1081
3 (Real)	0.143325	-0.745317	2.24014	-4.0733	4.11859	0.335577	-8.75448	11.667
3 (Imag)	-0.151004	1.14551	-4.16768	9.66771	-14.295	11.4627	1.46925	-16.71
4 (Real)	-0.0859554	0.100056	0.260326	-1.50768	3.39287	-4.83442	4.51887	1.7566
4 (Imag)	0.0728437	-0.31672	0.49802	-0.644862	0.740288	-0.634812	0.246455	0.1327
5 (Real)	0.0331857	0.0431416	-0.415483	1.31256	-2.46376	3.00479	-2.0209	-0.595
5 (Imag)	0.0173256	-0.0713551	0.328038	-0.786594	1.43663	-2.27799	3.19145	-3.423

REALITY CHECK: APPLY CREATED MODEL TO ORIGINAL SIGNAL



COMPARISON OF MODELS

- Green: Memory Polynomial
- Blue: Hammerstein Model
- Yellow: reference w/o any DPD

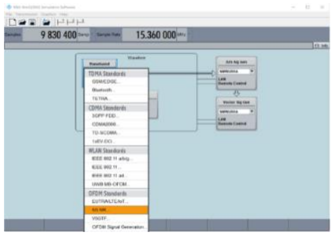


COMPARISON OF MODELS

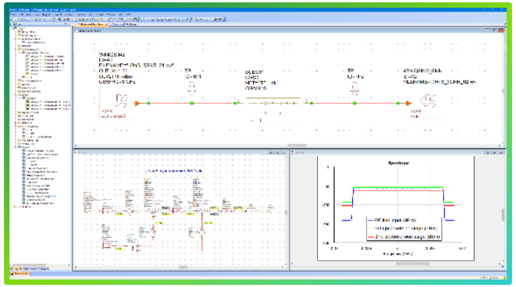
Predistortion Approach	Measurement Time	EVM Improvement (In-band)	ACLR Improvement (Out-of-band)
Polynomial Model	✓✓✓	✓	✓
Direct DPD (with Meas Bandwidth = Signal Bandwidth)	✓✓✓	✓✓	✓
Direct DPD (with increased Meas Bandwidth)	✓✓	✓✓	✓✓
Direct DPD (with increased Meas Bandwidth and IQ Averaging)	✓	✓✓✓	✓✓✓
Memory Polynomial Model	✓✓	✓✓	✓✓
Hammerstein Model	✓✓	✓✓	✓

DESIGN: USING EDA TO PIN OUT EXPECTED PERFORMANCE WITH DPD

- ► Simulate as close to reality for risk mitigation
- ► Use Microwave Office for DUT with E-PHD or Cadence TDNN approach

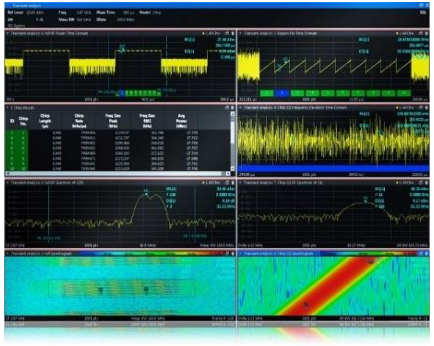


R&S WinIQSIM2
Signal Generation

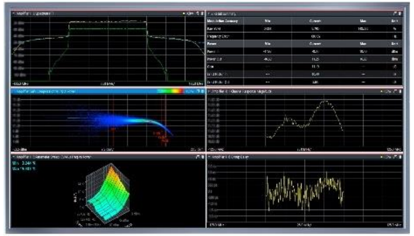


Cadence Visual System Simulator (VSS)
RF Design/Analysis

R&S VSE
Signal Analysis



Direct DPD
Linearization



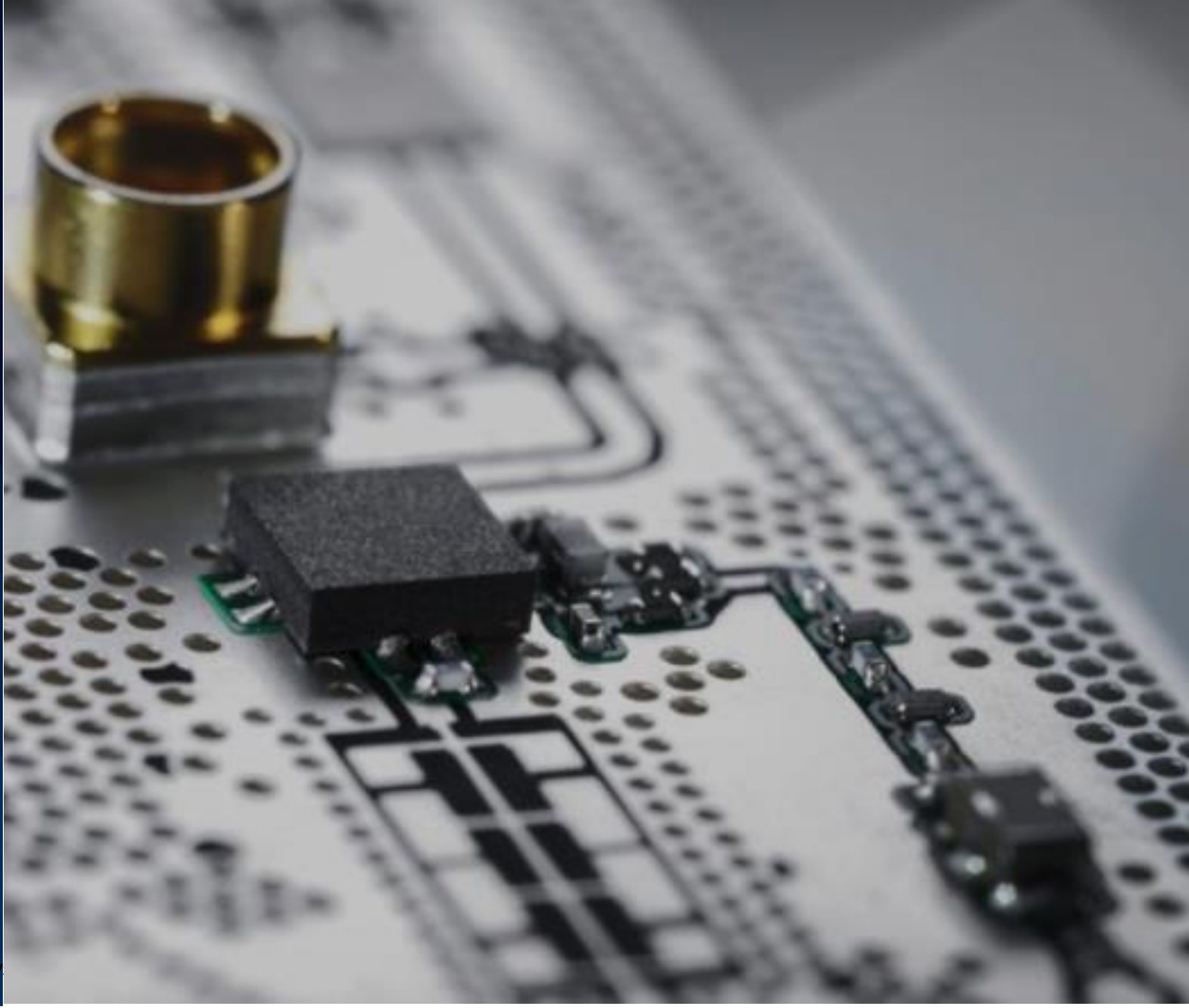
Understand linearity improvement possibilities on a physical amplifier

CONCLUSION

- There is an easy way to understand what is possible
- Works with any non-linear device and any signal
- Various models can be derived

- Works with physical hardware and even in EDA while design

Understand linearity improvement possibilities on a phy



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Make ideas real