Linear & Power Efficient RF Sub-Systems

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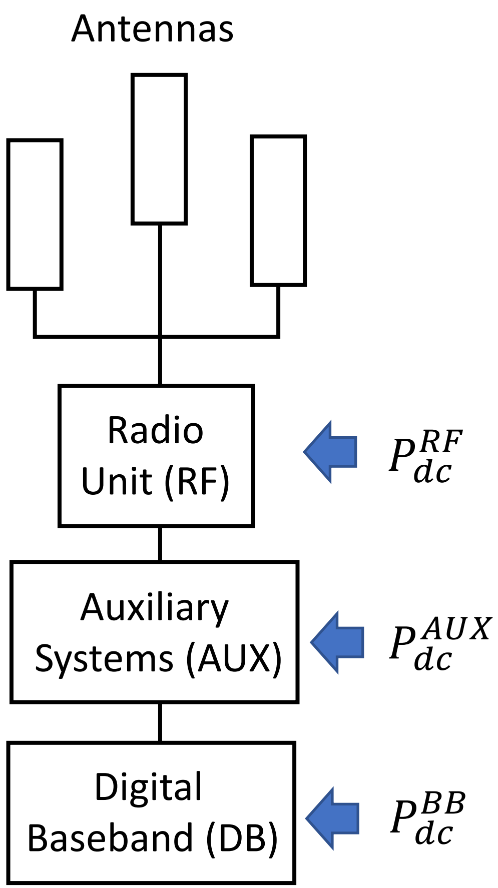
http://www.bristol.ac.uk/engineering/research/csn/

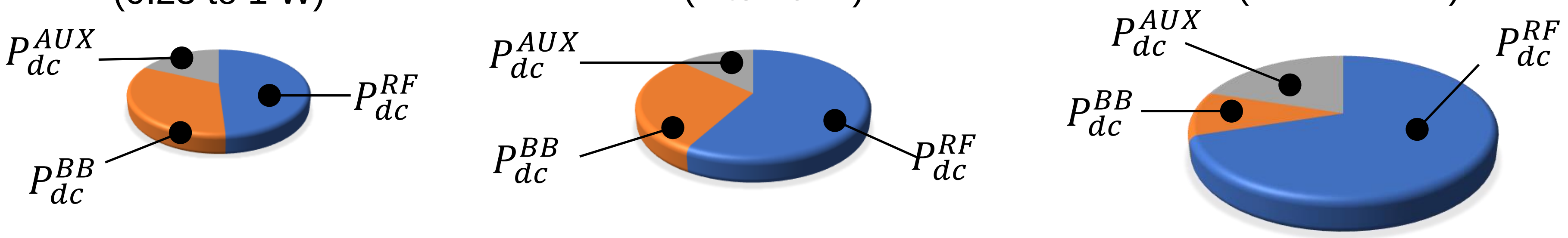
6G: Technology Enablers for Spectrum & Energy Efficient Wireless Access
University of Bristol with the support of DCMS/SPF, 26th May 2021

Base-Station Power Budget

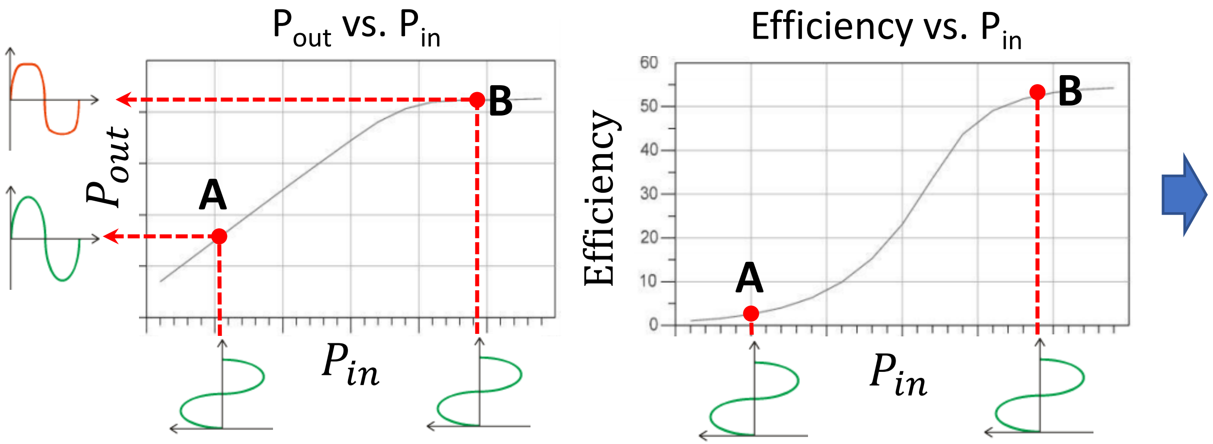
- Base-station transmitters are classified based on their output power required to cover a certain area.



Pico-cell BS (0.25 to 1 W) | **Micro-Cell BS** (1 to 10 W) | **Macro-Cell BS** (10 to >50 W)



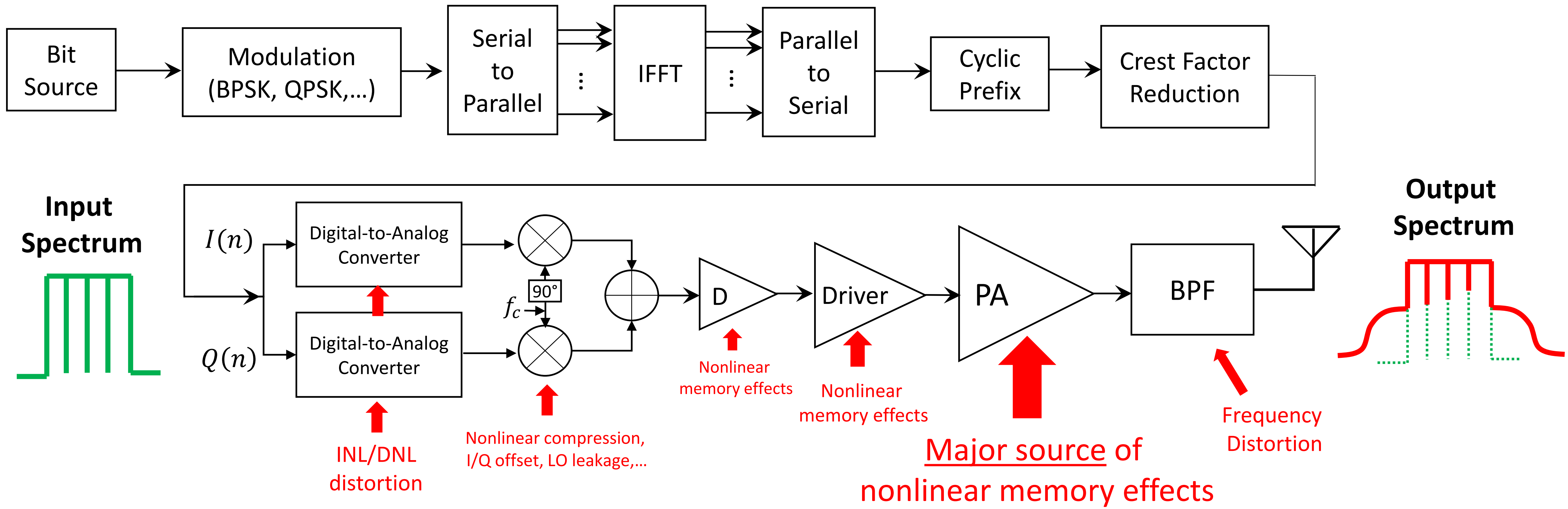
- BS overall power consumption is dominated by the RF radio unit.
- The RF power amplifiers (PAs) are the most power-hungry components in the radio.



Linearity-Efficiency Tradeoff

Linearity Impairments in the Transmitter

- Transmitter linearity and efficiency is limited by the RF frontend.

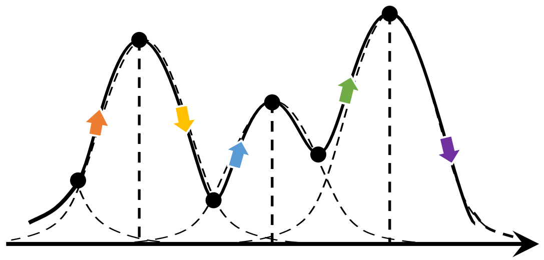


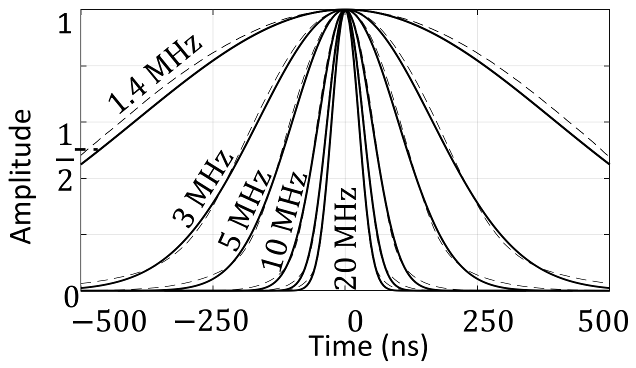
Starting from 4G, RF hardware capabilities are becoming more and more a performance limitation

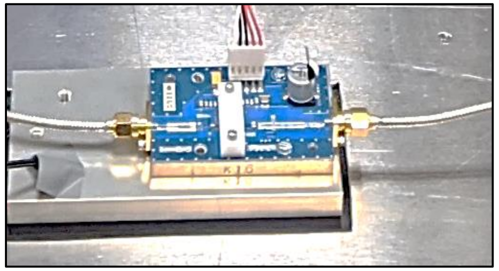
Hybrid Time-Frequency Transmitter Characterization

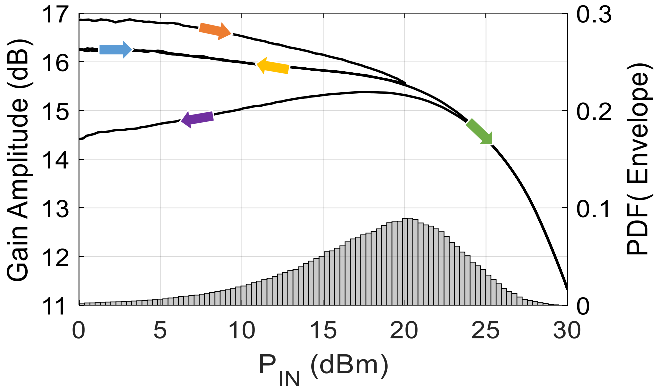
- It is necessary to rethink the way transmitters are characterized → hybrid time-frequency characterization.

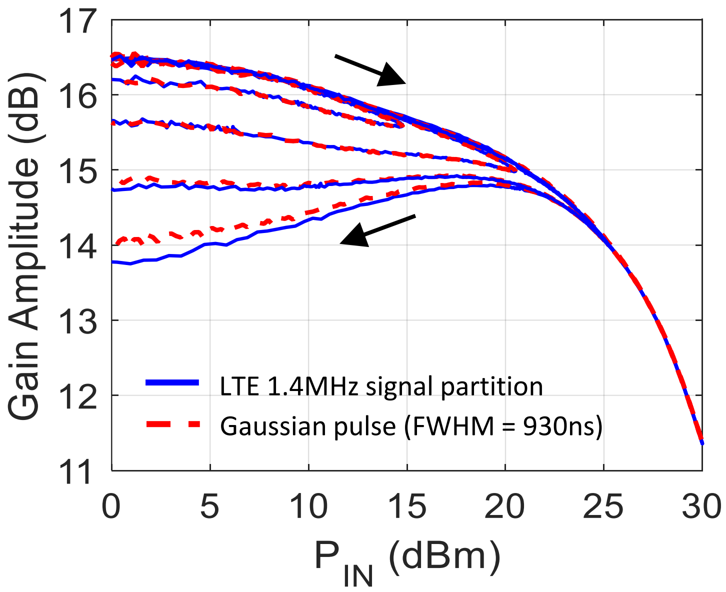
Gaussian decomposition [1]







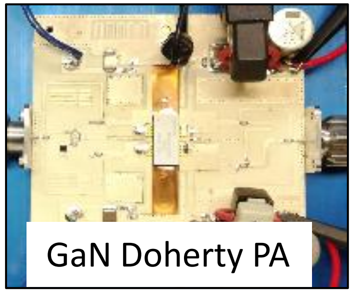




- Gaussian pulse decomposition is equivalent to the response with an LTE signal (not a-priori known).
- More powerful than the sinusoidal and time-domain techniques.
- **Gaussian pulse is optimal for capturing NL memory effects.**

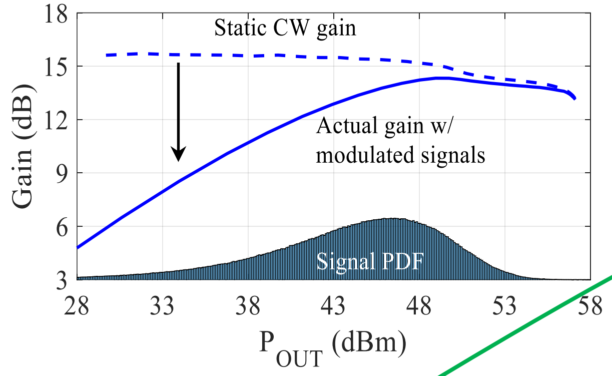
[1] T. Cappello, Z. Popovic, K. Morris and A. Cappello, "Gaussian Pulse Characterization of RF Power Amplifiers," in *IEEE Microwave and Wireless Components Letters*, April 2021.

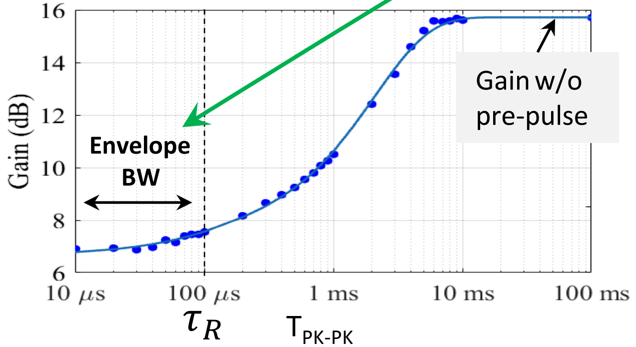
Trapping Effects in GaN Doherty PAs



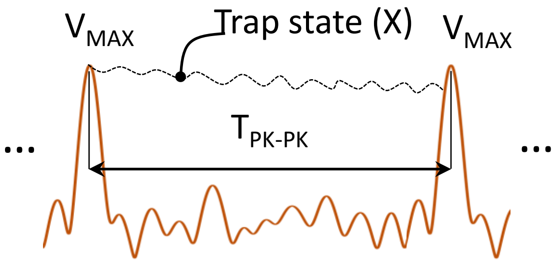
- GaN is a candidate technology to improve the bandwidth/efficiency of RF frontends.
- Doherty architecture is common in macro-cell base-stations.

- GaN PAs, however, are still affected by trapping effects

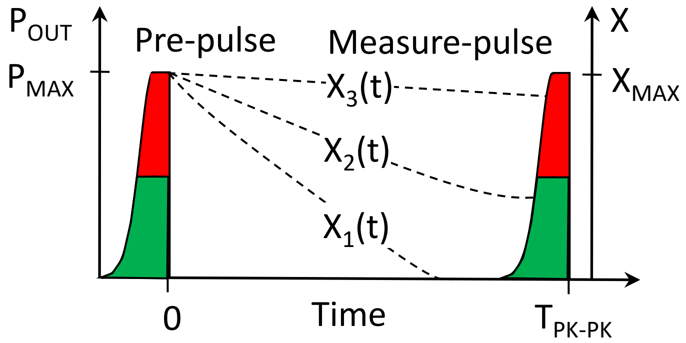


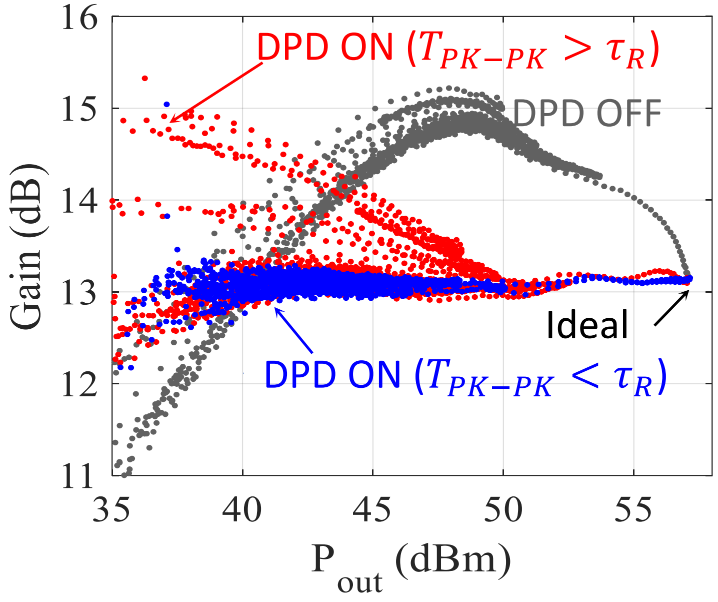


- This is particularly evident with high-PAPR signals (e.g., OFDM):



- New characterization technique that mimics the envelope signal



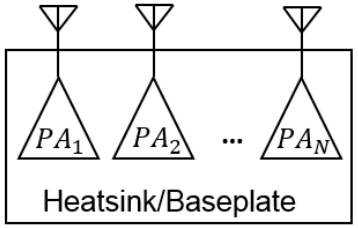


- **New finding [1]:** If T_{PK-PK} separation is longer than the dominating trap time constant (τ_R), a memory-less DPD is effective.

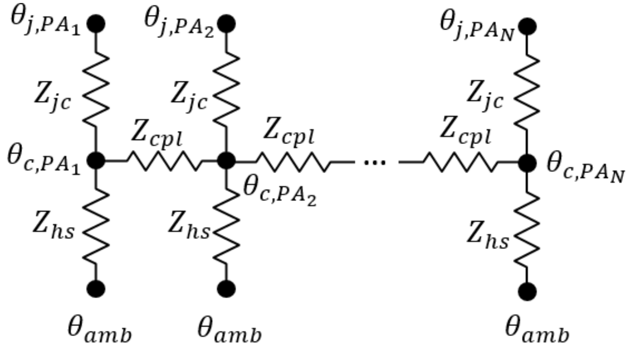
[1] T. Cappello, C. Florian, A. Santarelli and Z. Popovic, "Linearization of a 500-W L-band GaN Doherty Power Amplifier by Dual-Pulse Trap Characterization 26th May 2021," in IEEE Int'l Microw. Symp. (IMS), June 2019.

PA Digital Pre-Distortion (DPD) with Temperature Correction

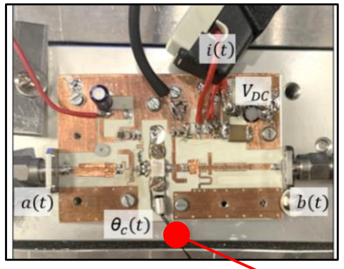
- Because of the high power density of GaN transistors, temperature effects are particularly evident.
- In MIMO arrays, large heatsinks are used and PAs experience wide temperature variations.



- Thermal coupling in the array

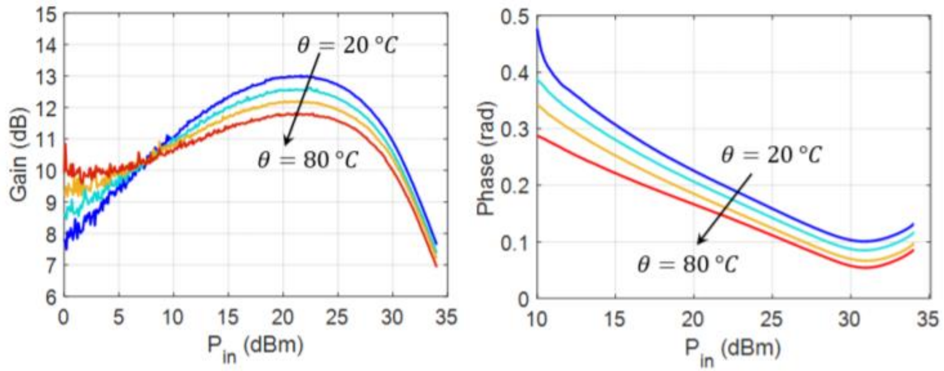


- GaN RF PA testbed (10-W Wolfspeed at 3.5GHz)

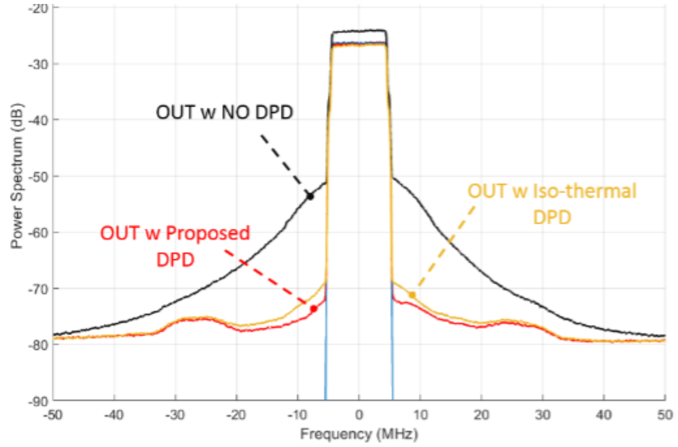


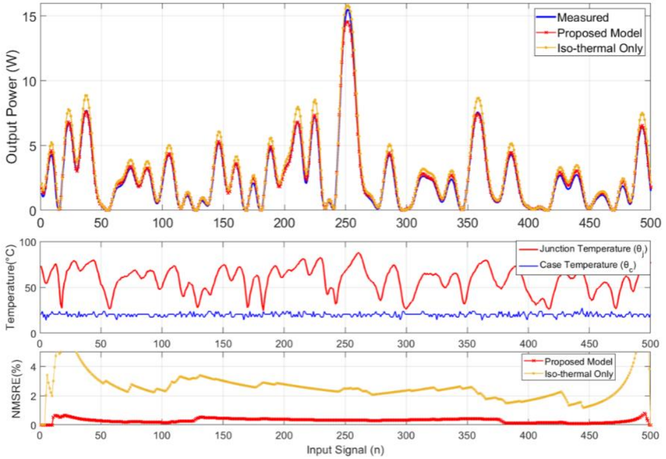
Temperature Sensor

PA gain amplitude and phase vs. temperature:



- Linearized PA with thermal correction:

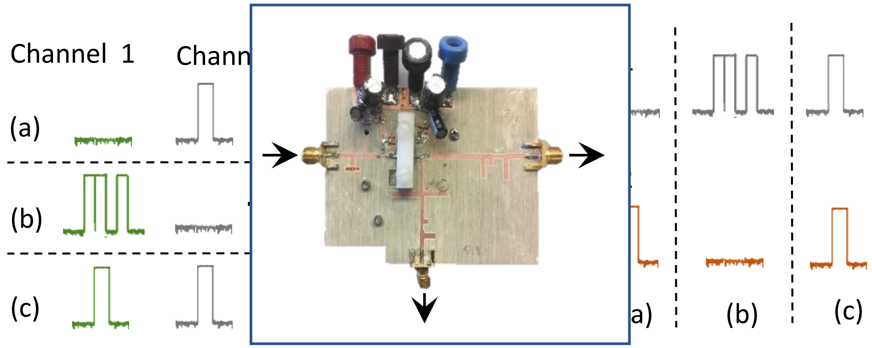




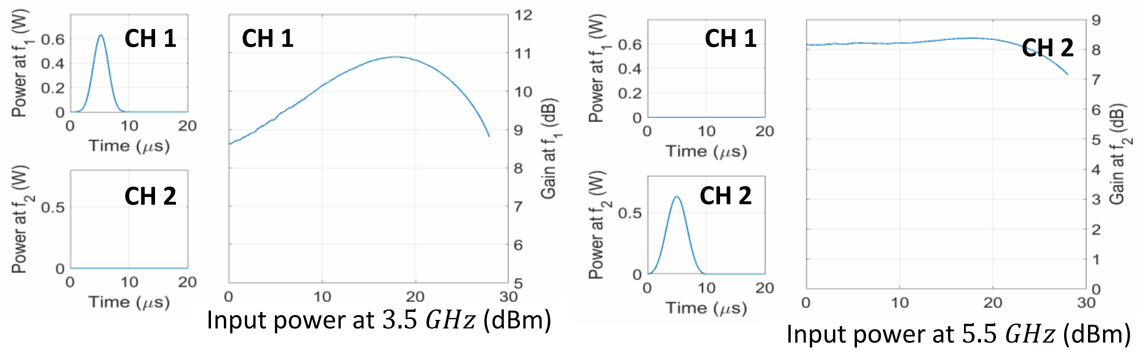
G. Jindal, G. Watkins, K. Morris, T. Cappello, "An RF Power Amplifier Behavioural Model with Low-Complexity Temperature Feedback for Transmitter Arrays," to be presented at IEEE Int'l Microw. Symp. (IMS), June 2021.

Multi-Band Power Amplification

- The congested spectrum requires flexible hardware solution capable to transmit on multiple bands.
- Normally, a PA for each band is required. The DB-PA allows to transmit on multiple bands simultaneously:

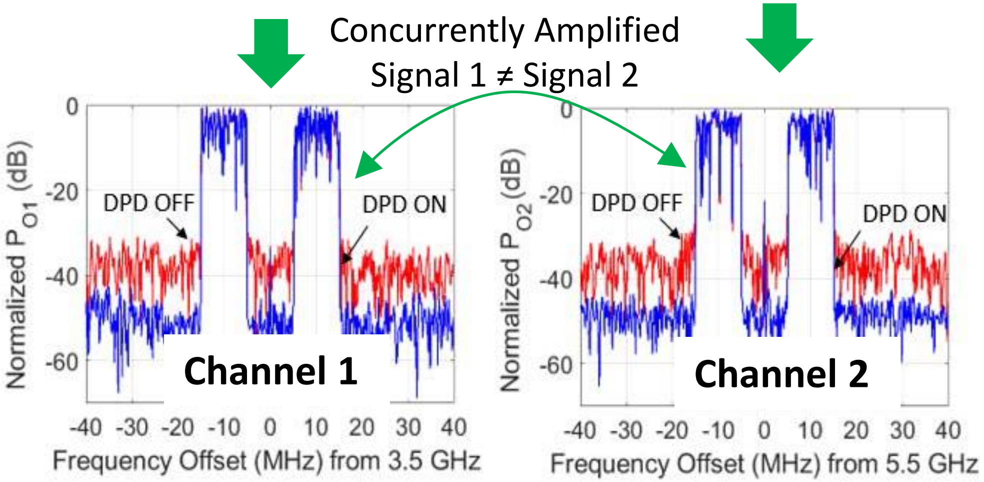


- Characterization of the channel cross-Modulation



- Linearity is recovered with 2-D Digital Pre-Distortion*

$$\begin{cases} z_{1,n} = \sum_{m=0}^{M}\sum_{i=0}^{K}\sum_{j=0}^{i} c_{1,m,i,j}\, x_1(n-m)\,|x_1(n-m)|^{i-j}\,|x_2(n-m)|^{j} \\ z_{2,n} = \sum_{m=0}^{M}\sum_{i=0}^{K}\sum_{j=0}^{i} c_{2,m,i,j}\, x_2(n-m)\,|x_2(n-m)|^{i-j}\,|x_1(n-m)|^{j} \end{cases}$$



* S. A. Bassam, "2-D digital predistortion (2-D-DPD) […]," *IEEE TMTT,* 2011.

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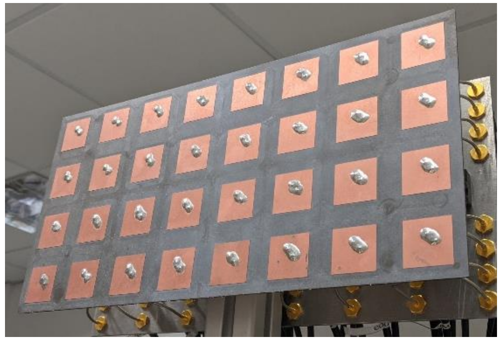
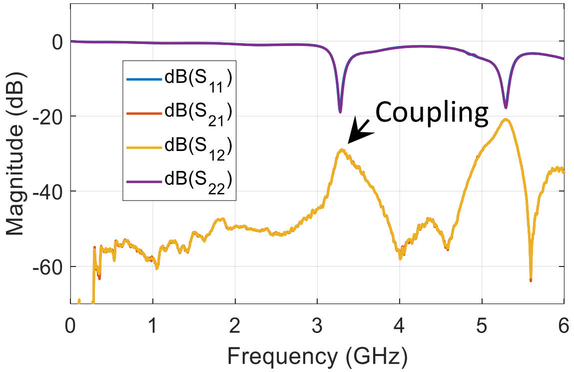
T. Cappello, A. Duh, T. W. Barton and Z. Popovic, "A Dual-Band Dual-Output Power Amplifier for Carrier Aggregation," in *IEEE Transactions on Microwave Theory and Techniques*, July 2019.

Antenna Coupling in MIMO Arrays

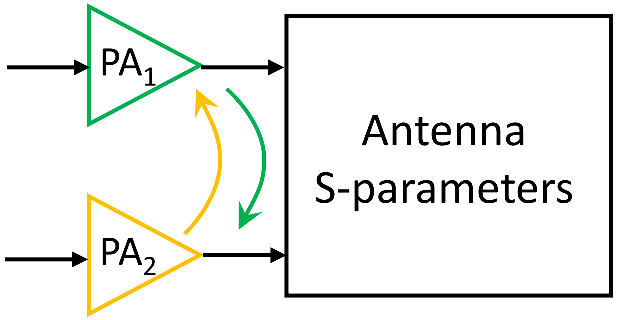
- MIMO is used for high-capacity data links and it requires an high number of antennas in small volume.
  - Typical MIMO antenna array



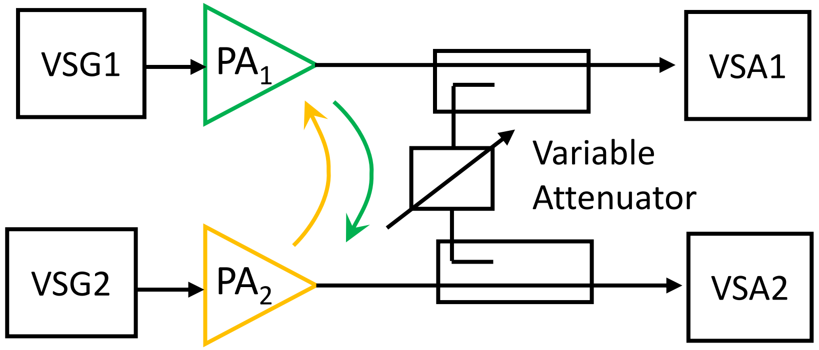
- Coupling (|S21|) between two nearby elements



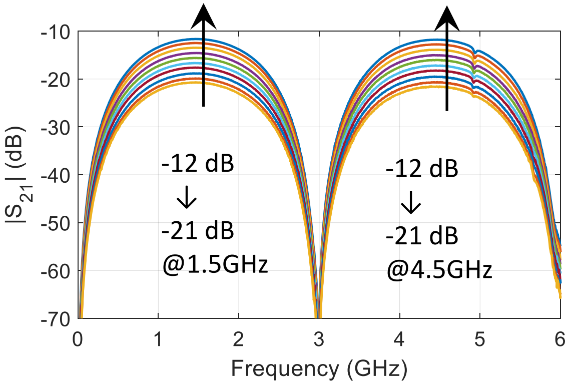
- The PAs experience active load-pulling because of the coupling between the antenna elements [1].



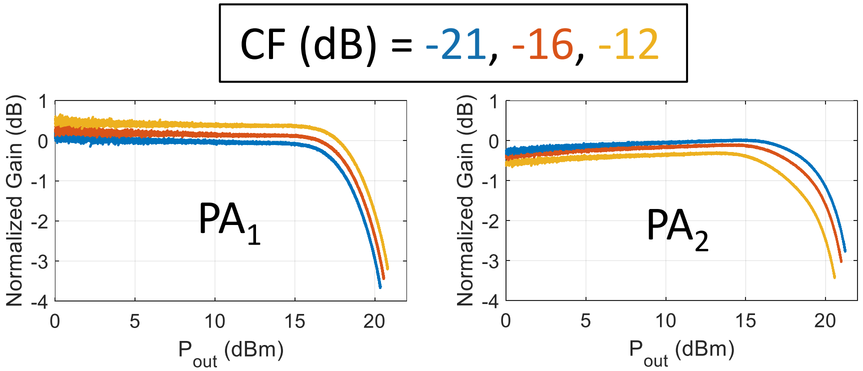
- Antenna coupling hardware simulator (most PAs are not available in simulators).



- Synthesizable coupling factors (S21):



- PA gain variation for varying coupling:

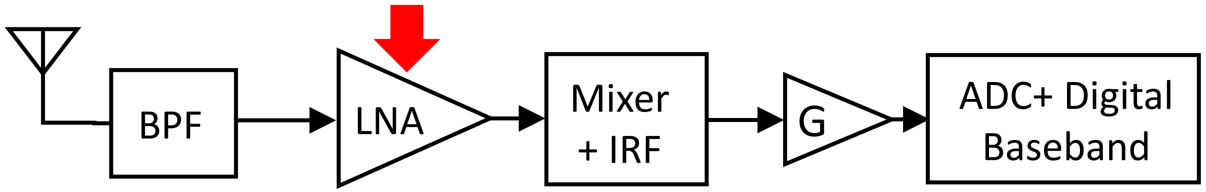


[1] F. M. Barradas, P. M. Tomé, J. M. Gomes, T. R. Cunha, P. M. Cabral and J. C. Pedro, "Power, Linearity, and Efficiency Prediction for MIMO Arrays With Antenna Coupling," in *IEEE Transactions on Microwave Theory and Techniques*, Dec. 2017.

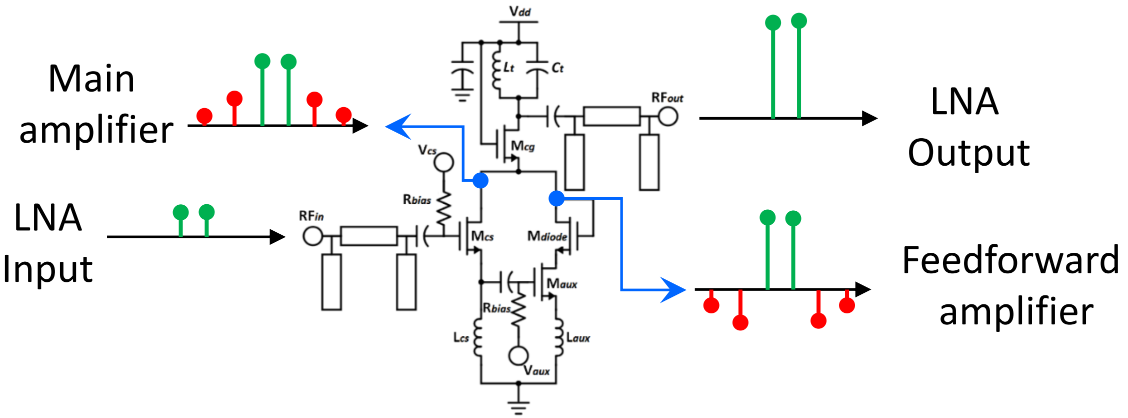
LNA Linearization with Analogue Techniques

- Similarly to the RF transmitter, where the main limiting factor is the linearity-efficiency tradeoff in the PA, in receivers the LNA sets the sensitivity-efficiency limit.

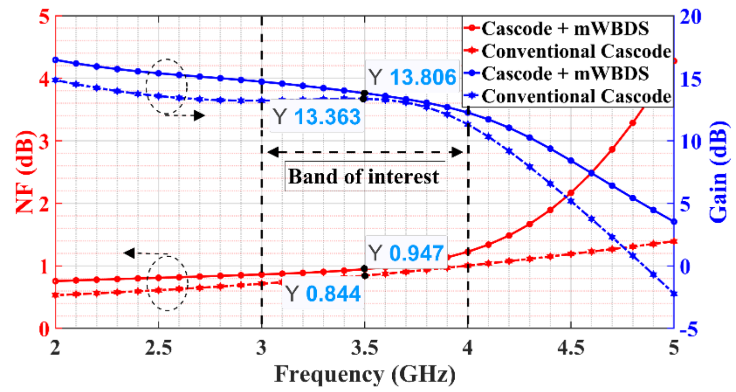
Main source of non-linearities/noise



- LNA with feedforward linearization is a candidate architecture to improve linearity without extra digital complexity.

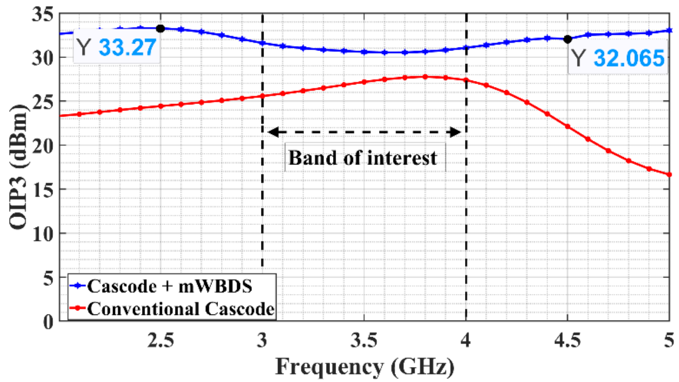


- LNA w/ feedforward performance (NF and OIP3):



3-4 GHz bandwidth

14 dB gain



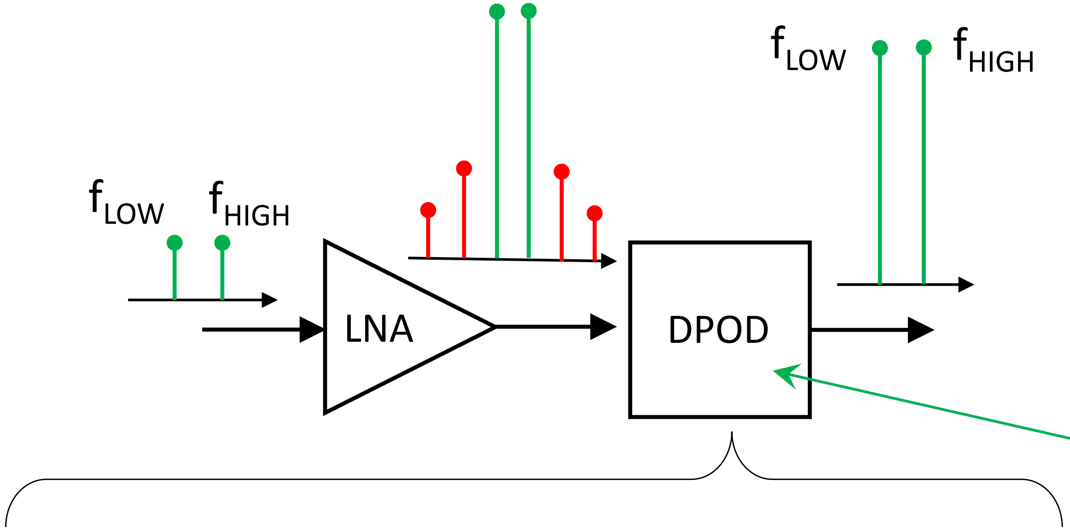
NF <1.2 dB

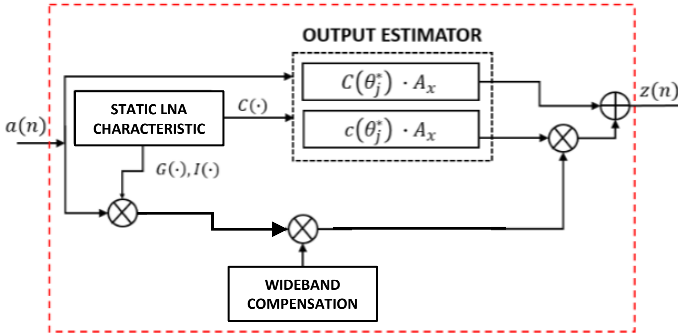
OIP3 > 30dB

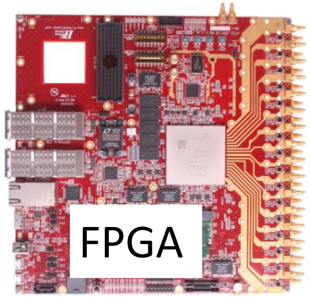
S. Ozan, M. Nair, T. Cappello and M. A. Beach, "Low-Noise Amplifier with Wideband Feedforward Linearisation for Mid-Band 5G Receivers," *IEEE Asia Pacific Conference on Circuits and Systems (APCCAS)*, 2020.

LNA Linearization with Digital Techniques (DPD)

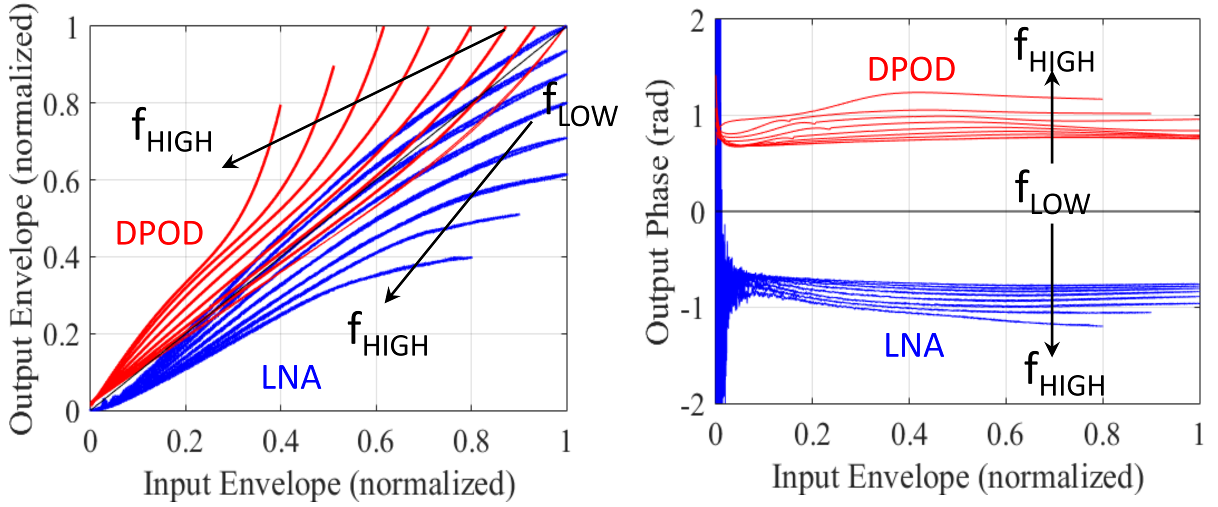
- When extra digital complexity can be afforded, digital post-distortion (DPOD) can be used to simplify the RF hardware.







- Wideband linearization can be achieved without the addition on noise by characterizing the LNA from f_{LOW} to f_{HIGH}.

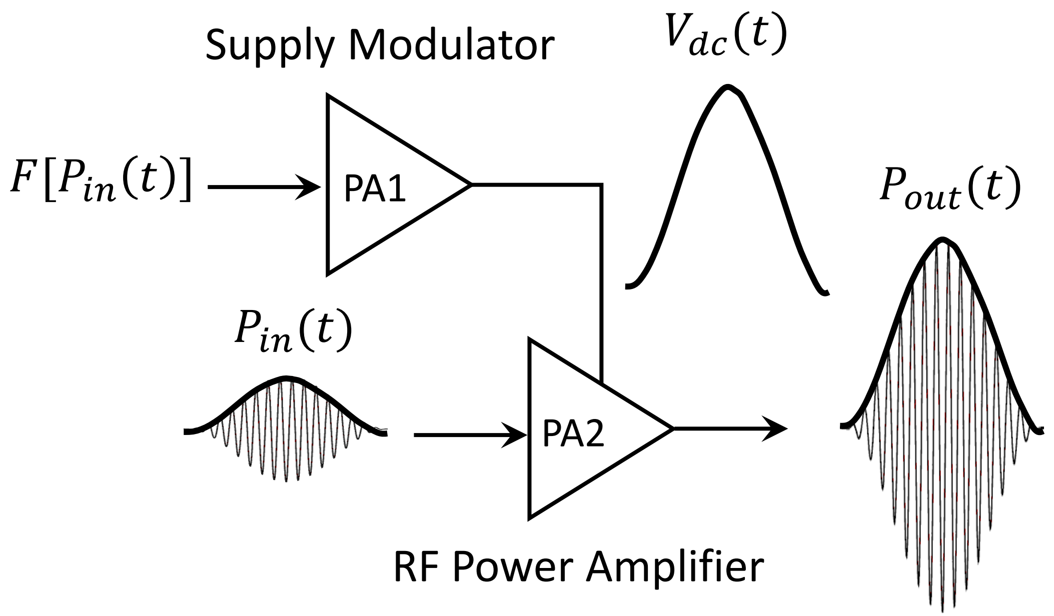


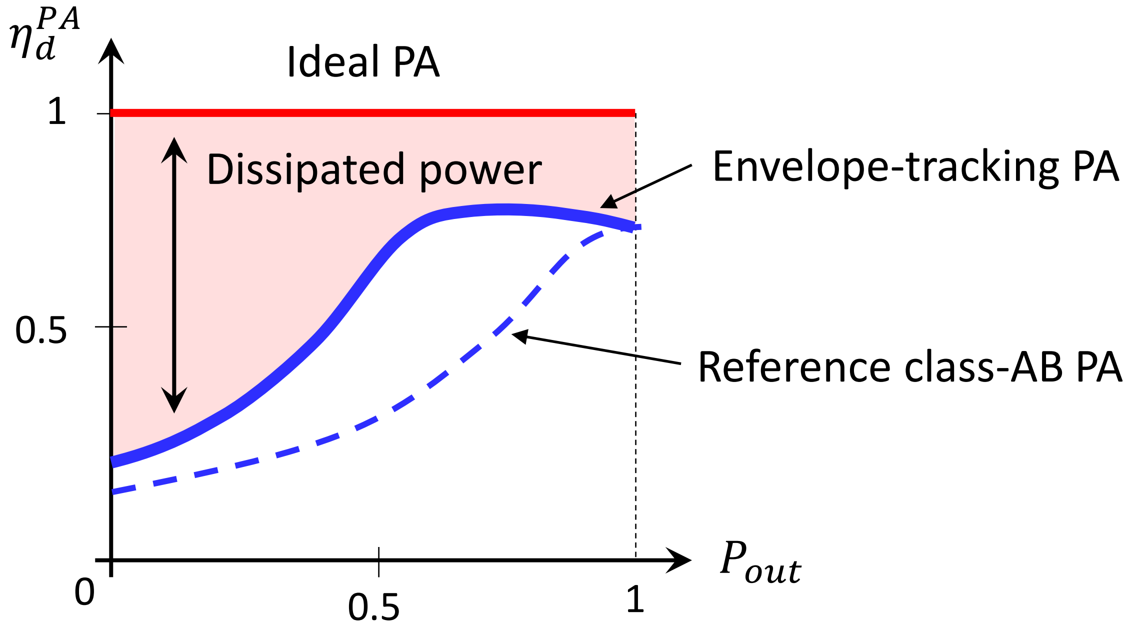
- Digital complexity requirements and added power consumption need to be carefully investigated.

A. Katz, J. Wood and D. Chokola, "The Evolution of PA Linearization: From Classic Feedforward and Feedback Through Analog and Digital Predistortion," in *IEEE Microwave Magazine*, Feb. 2016.

Envelope-Tracking (ET) PA Architecture

- ET is candidate for improving the linearity-efficiency limitations of next generation transmitters.
- Unlike Doherty, ET can enhance the efficiency of very broadband PAs because the supply modulator operates at low frequencies and so independent from the RF carrier.

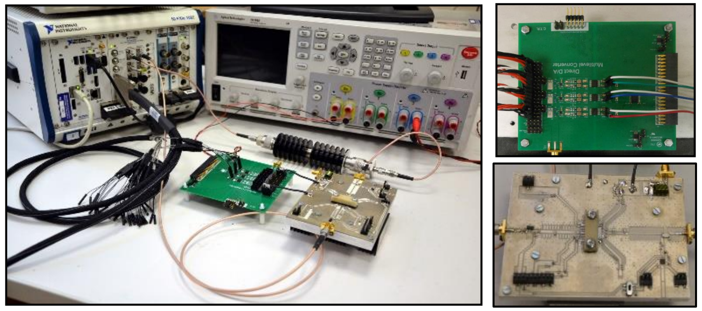


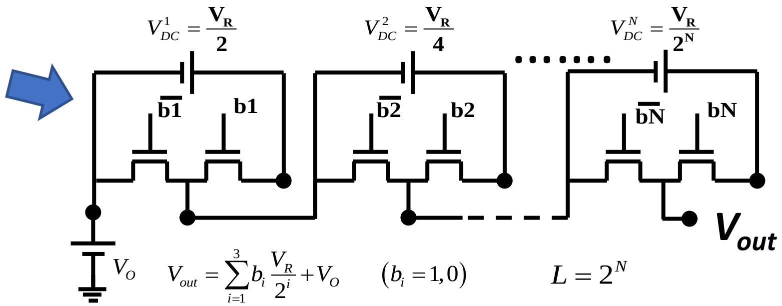


- Still research needs to be done to improve the supply modulator bandwidth.

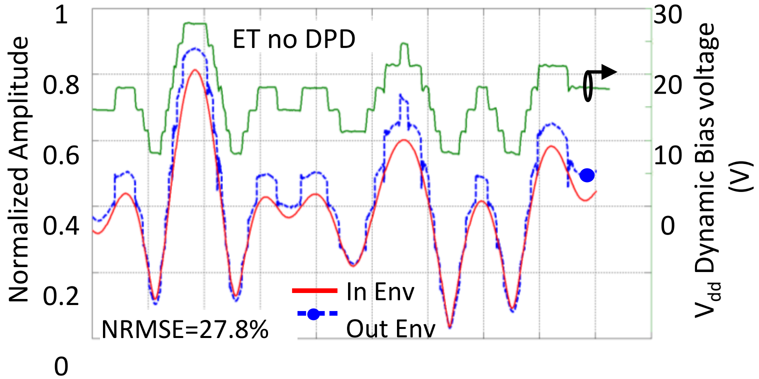
ET-PA for Base-Station Transmitters (5G)

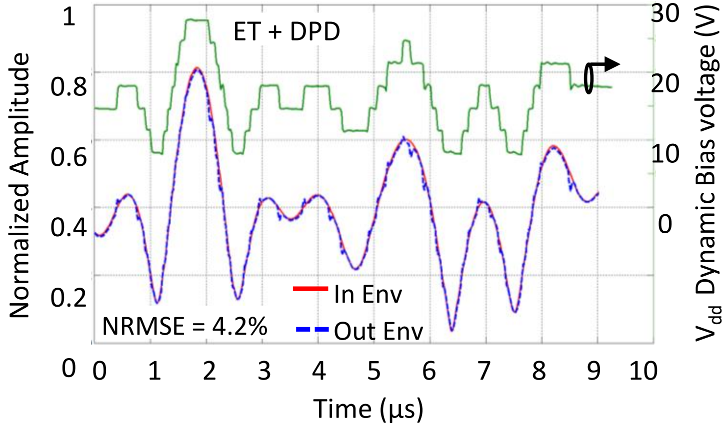
- ET PAs are suitable for medium to high power PAs in the sub-6GHz spectrum.
- LTE compliant ET-PA @ 1.84GHz using the Power-DAC supply modulator [1].



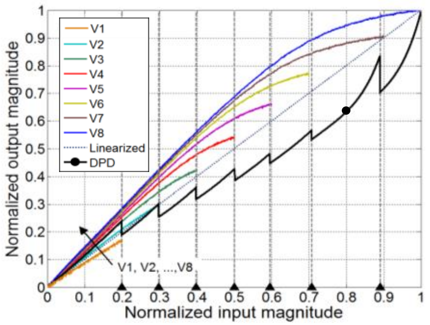


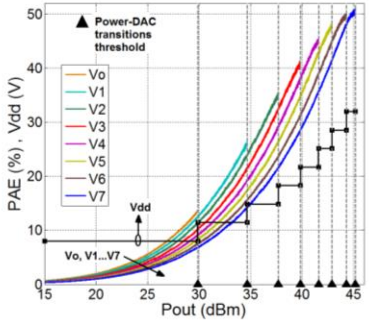
- LTE waveforms with and without DPD



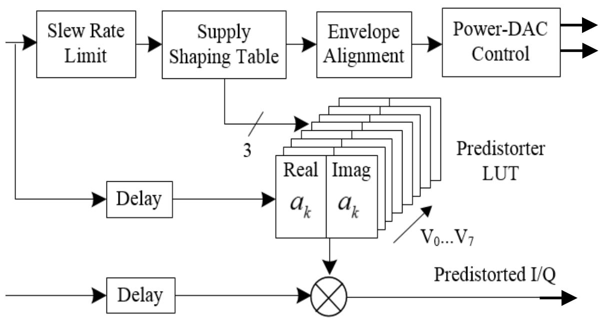


- PA characteristics at variable supply level





- FPGA DPD and ET control



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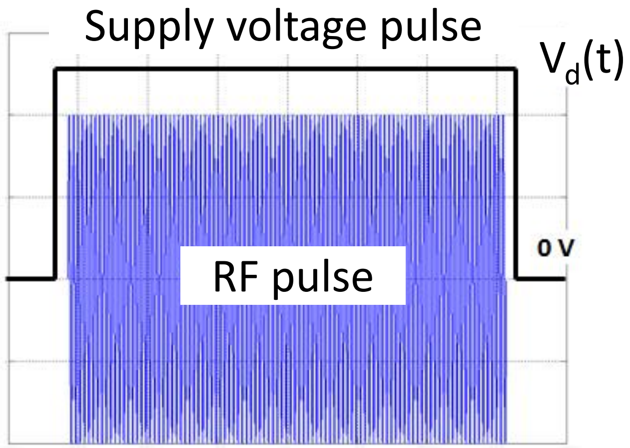
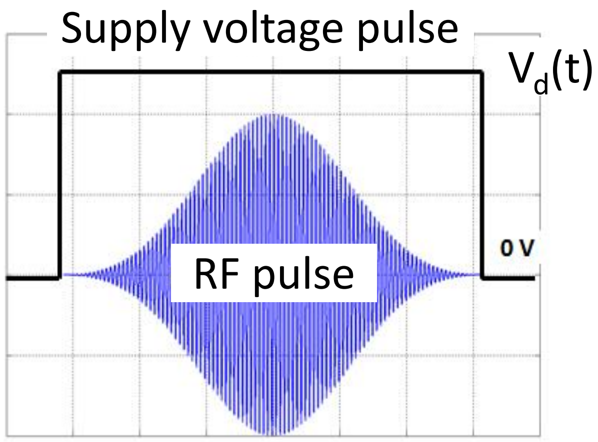
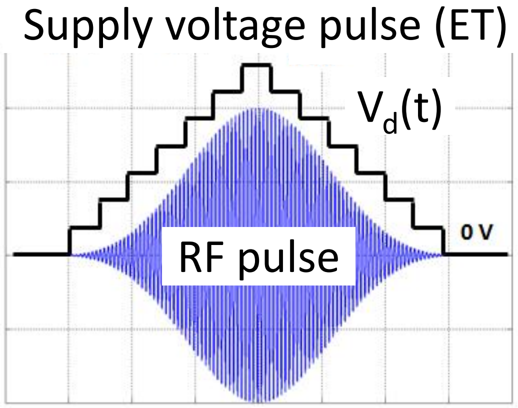
[1] T. Cappello, P. Pednekar, C. Florian, S. Cripps, Z. Popovic and T. W. Barton, "Supply- and Load-Modulated Balanced Amplifier for Efficient Broadband 5G Base Stations," in *IEEE Transactions on Microwave Theory and Techniques*, July 2019.

Radar Pulse Shaping

- Pulse shaping in radars is used to reduce the detectability and/or allow the radar operation in a congested spectrum.



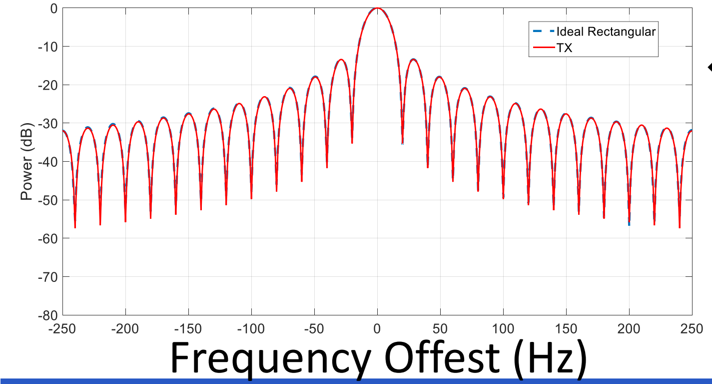




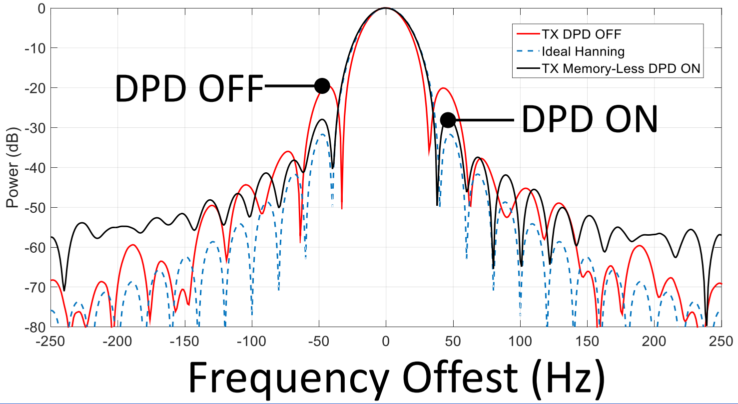
High PAE

Low PAE

Recovered PAE



← 1st sidelobe at -13dB (high spectral leakage)



← 1st sidelobe at -30dB (low spectral leakage)

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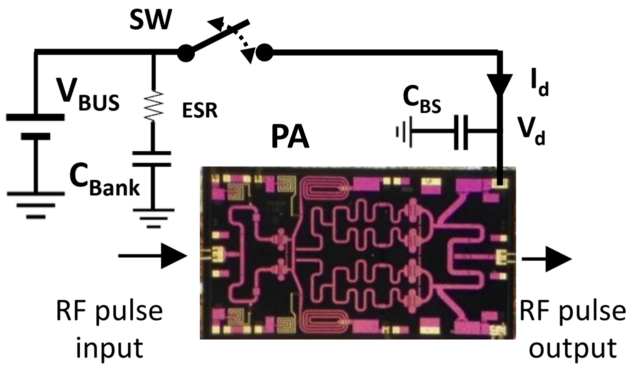
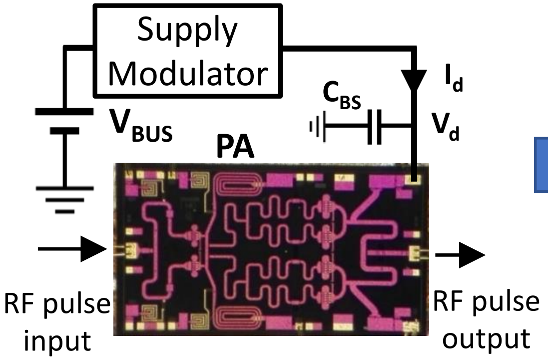
ET for Radar Pulse Shaping

- ET is an effective candidate to increase the efficiency of standalone or array PAs used with pulse-shaped waveforms.
- Typical and proposed way for PA supply

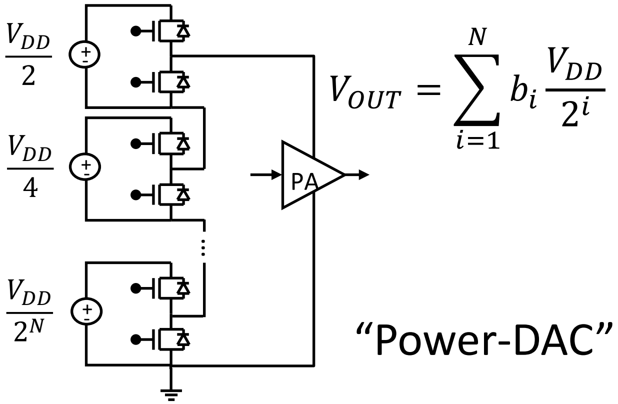
a. Rectangular supply voltage pulse



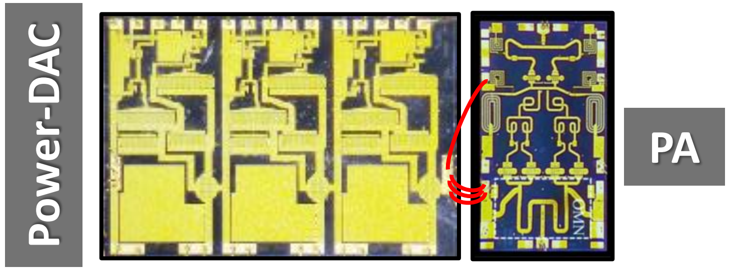
b. Shaped supply voltage pulse



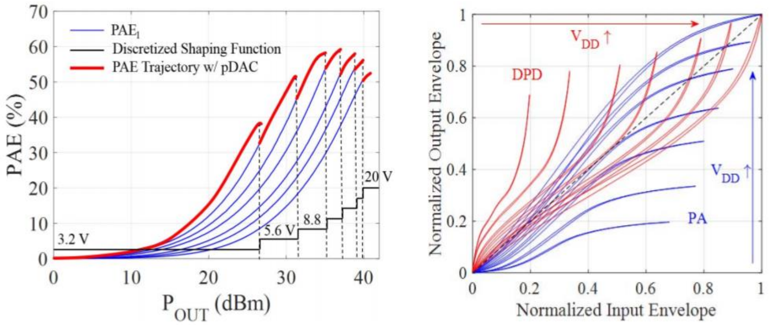
- High-efficiency supply modulator



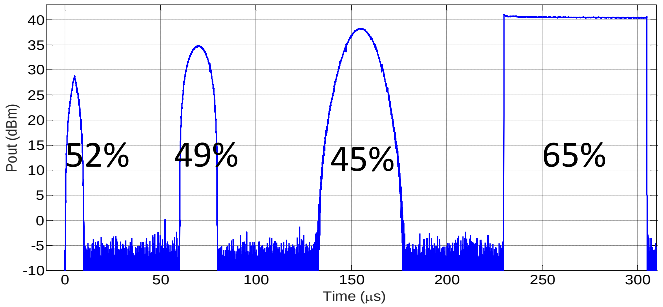
- Integrated MMIC in Qorvo GaN 0.15µm [1]



- PA characterization and DPD



- Arbitrary radar pulses generation with high efficiency



Dr. Tommaso Cappello
University of Bristol

T. Cappello, C. Florian, D. Niessen, R. P. Paganelli, S. Schafer and Z. Popovic, "Efficient X-Band Transmitter With Integrated GaN Power Amplifier and Supply Modulator," in *IEEE Transactions on Microwave Theory and Techniques*, April 2019.

Conclusions & Take Aways

- Since 4G, hardware performance are becoming more and more a limiting factor.

Solutions to move forward:

III-V semiconductor technologies (GaN/GaAs)

- Superior transceiver bandwidth, linearity, efficiency, noise figure, and operating frequencies compared to Silicon technologies.

RF architectures (multi-LNA, multi-PA, ET,…)

- Improve the single device technological limits by using multi-transistor architectures to achieve the required specifications.

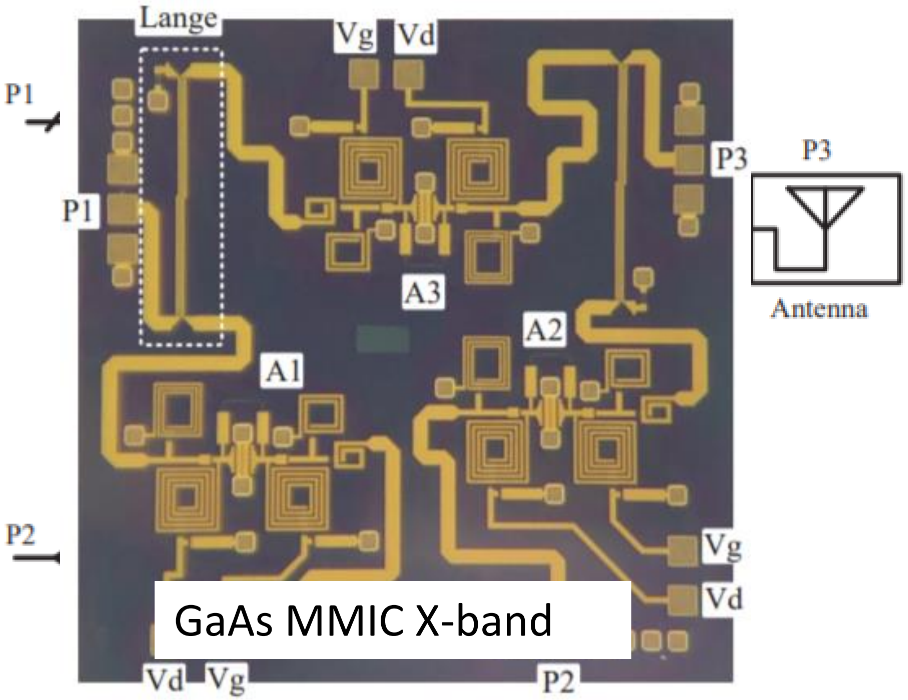
DPD-friendly RF hardware

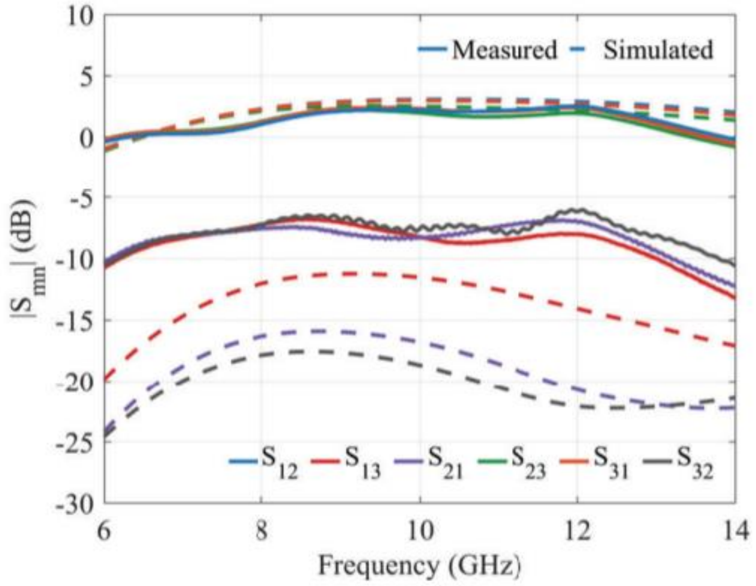
- Most effective way to achieve large bandwidths and linearity.
- Reconfigurable and 'upgradable' RF hardware performance.

Fundamental research is required to develop next generation RF transceivers

Active Circulator mm-Wave Front-Ends

- Magnetic circulators cannot be integrated in MMIC circuit operating at mmWaves.
- A possible alternative is to exploit the isolation introduced by transistors.





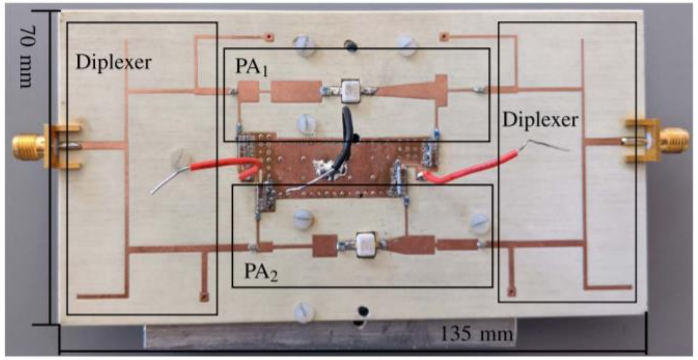
3dB gain Between 8-12GHz

7dB isolation over a very large bandwidth (simulation predicts >10dB)

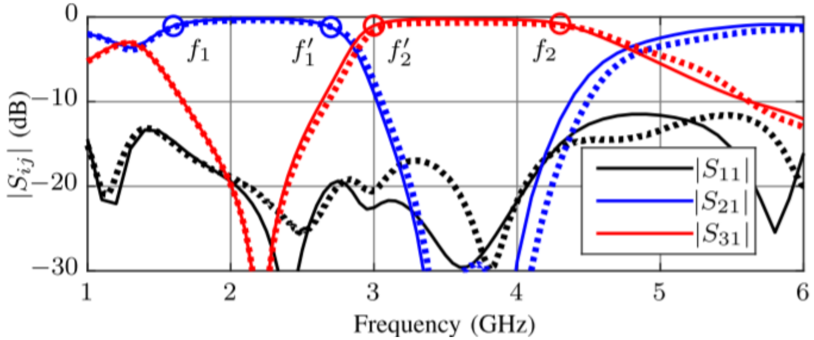
L. Marzall, S. Verploegh, T. Cappello, M. Roberg and Z. Popović, "Active MMIC Circulator Performance in a Phased-Array-Like Environment," *2020 50th European Microwave Conference (EuMC)*, 2021

Multi-Band Power Amplification

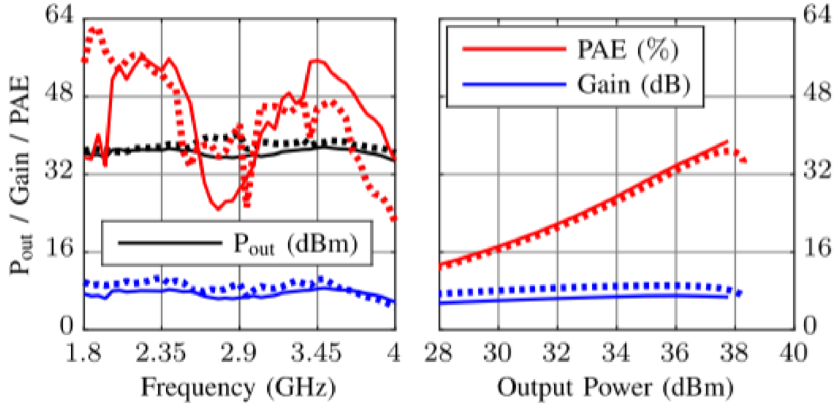
- When two PAs can be afforded, diplexed PA architecture is an alternative to improve the bandwidth



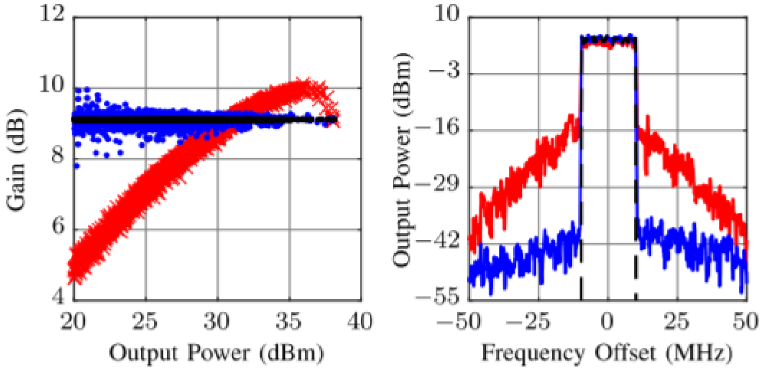
- Input and output diplexer need to be designed accordingly



- High efficiency over an extended bandwidth is achieved



- Because of the isolation between the two PAs introduced by the diplexer, a simple 1-D pre-distortion is sufficient:

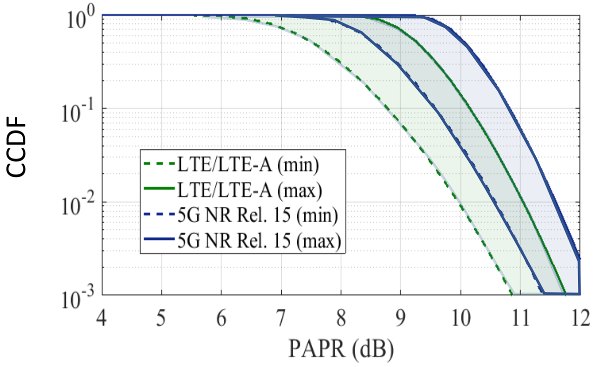


P. Zurek, T. Cappello and Z. Popovic, "Broadband Diplexed Power Amplifier," in *IEEE Microwave and Wireless Components Letters*, Nov. 2020

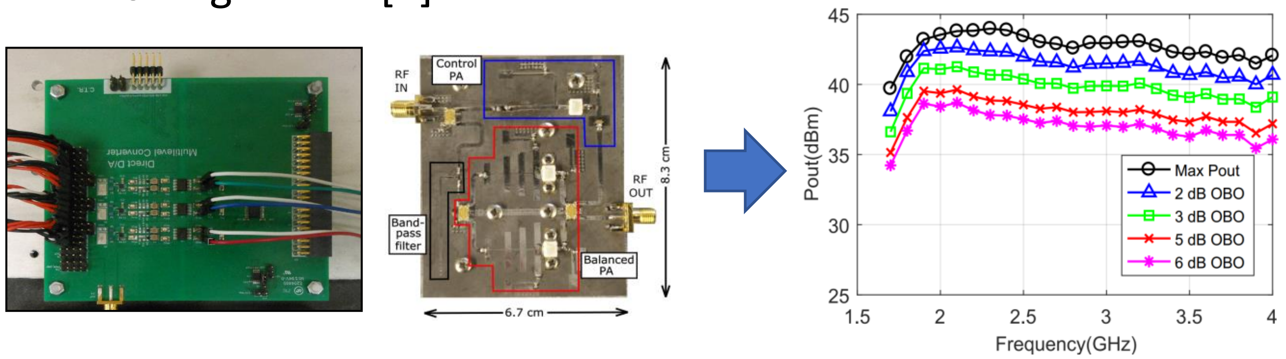
ET-PA for Base-Station Transmitters (5G)

- With 5G, base-station PAs need to achieve wider bandwidths and efficiency with high PAPR signals.

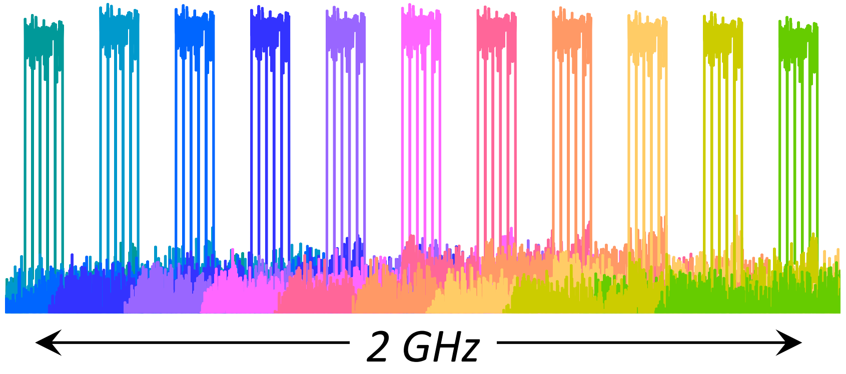
- PAPRs 1-2dB higher than in LTE/LTE-A



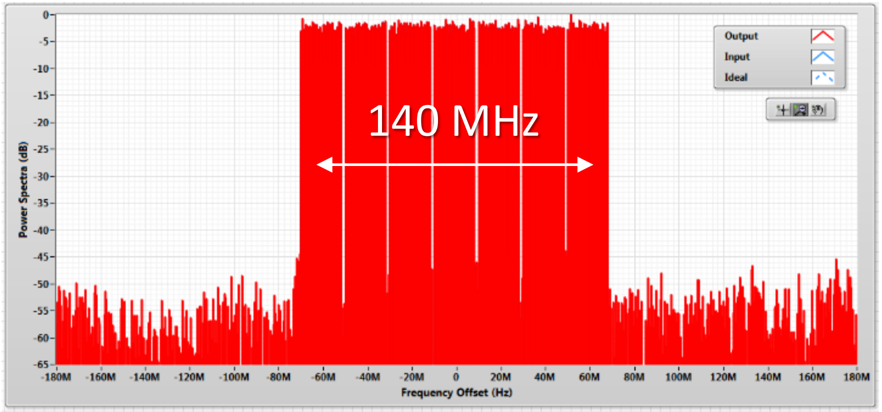
- Solution: load-modulated balanced amplifier (LMBA) for bandwidth + ET for high PAPR [1]



- >20W between 1.8-3.8GHz with >40% average efficiency



- Record instantaneous bandwidth of 140MHz in ET mode



[1] T. Cappello, P. Pednekar, C. Florian, S. Cripps, Z. Popovic and T. W. Barton, "Supply- and Load-Modulated Balanced Amplifier for Efficient Broadband 5G Base Stations," in *IEEE Transactions on Microwave Theory and Techniques*, July 2019.