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A Case for Distributing Intelligence Throughout the Signal Chain – Enabling Practical Wireless System Solutions

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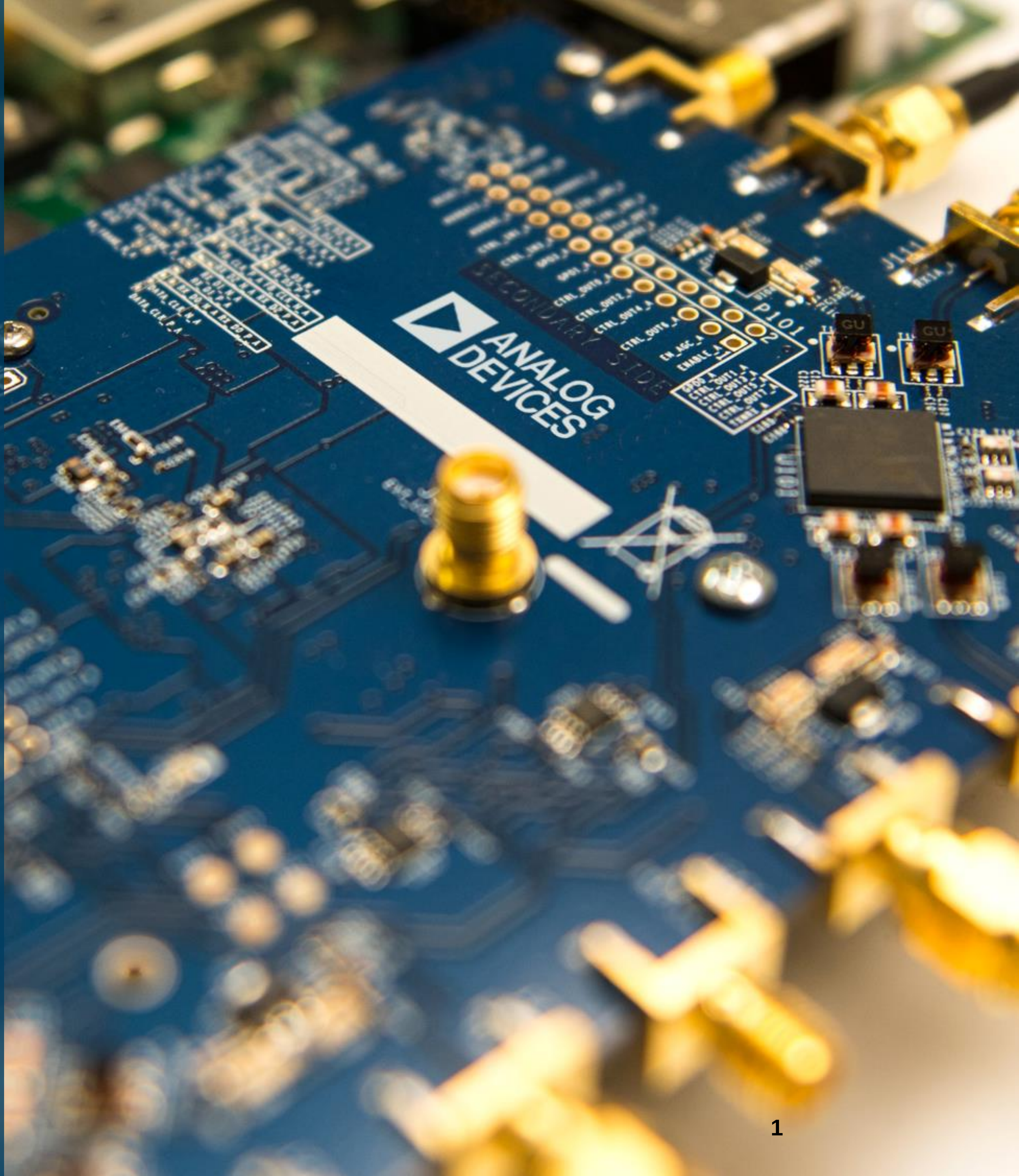


Agenda

- The Current Wireless Landscape
  - Scalability Challenges
- Digital Pre-Distortion (DPD) Perspective
  - What is it?
- Power Amplifier (PA) Perspective
  - State-of-the-Art
  - Challenges in PA & DPD co-design
- 2T2R System Specs
  - Figure of merit (FoM) for comparison
- Architecture Analysis & Comparison
- Conclusion
- Q&A

Current Wireless Landscape
What's all the fuss about?

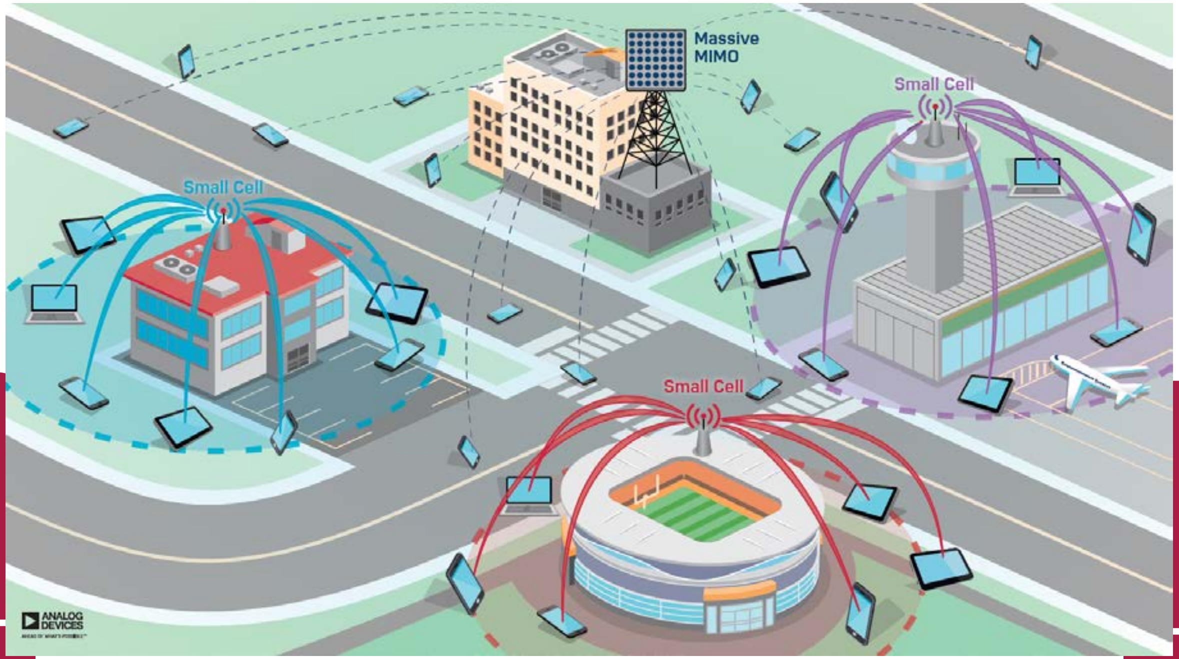
Coverage & Capacity Improvement

Spectrum Re-use

Small Cells

Network Densification

Indoor/Outdoor & Rural



5x Capacity Improvement

Spectrum Re-use through Beam-forming

Massive MIMO

Higher Data Rates

Dense Urban Areas

- How do we bridge these two pillars?
- How can we scale?
- Size Weight and Power = SWaP(-C)

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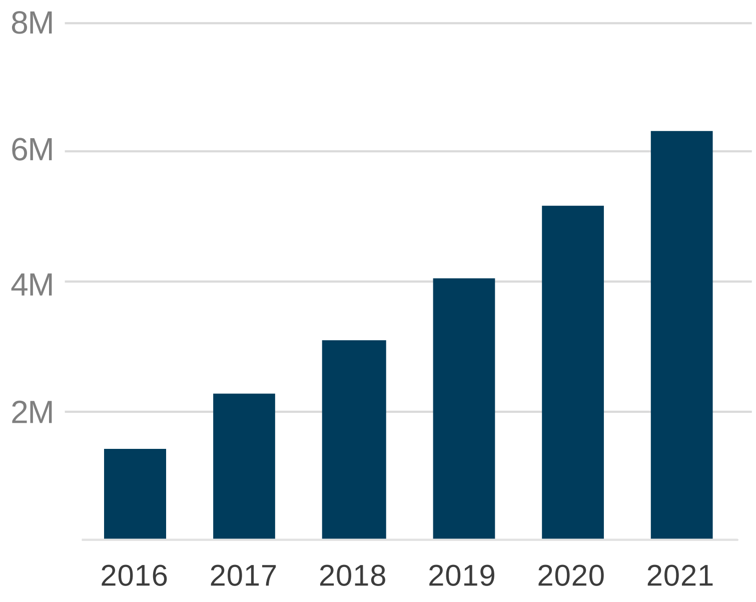
Current Wireless Landscape

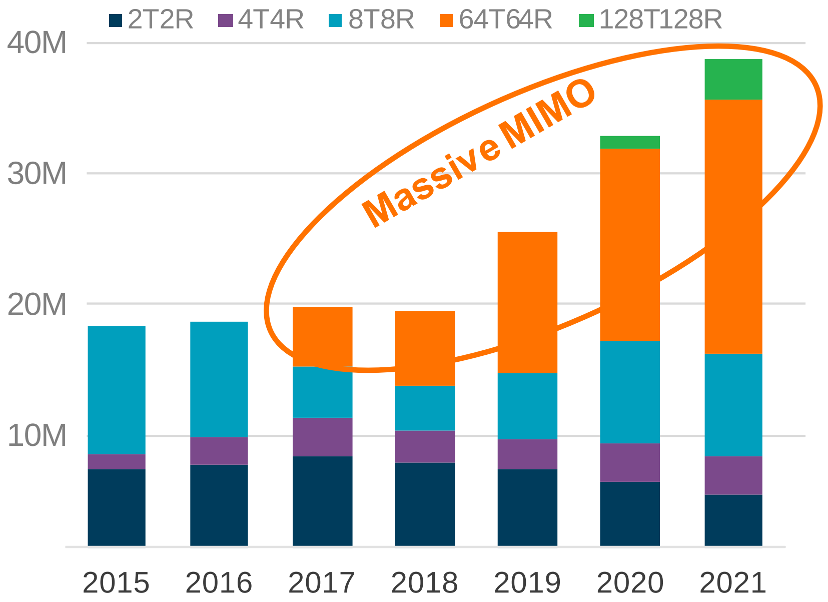
What's all the fuss about?

Small Cell BTS Forecast



Source: Mobile Experts Apr 2017. Excl Residential Femto

Macro BTS Transceiver Forecast



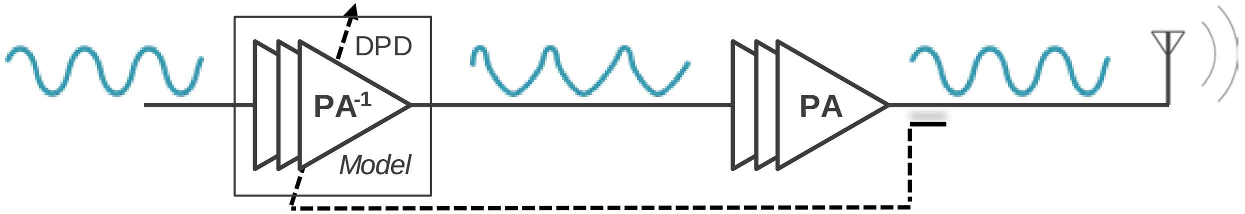
Source: Mobile Experts Apr 2017

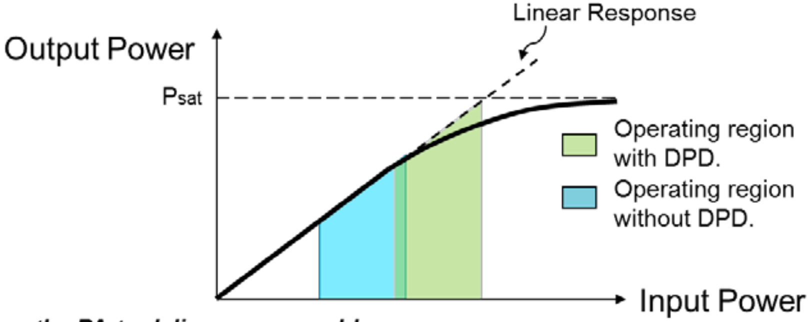
- These trends should mean $ for device and product vendors but usually ends up being a painful process in reality

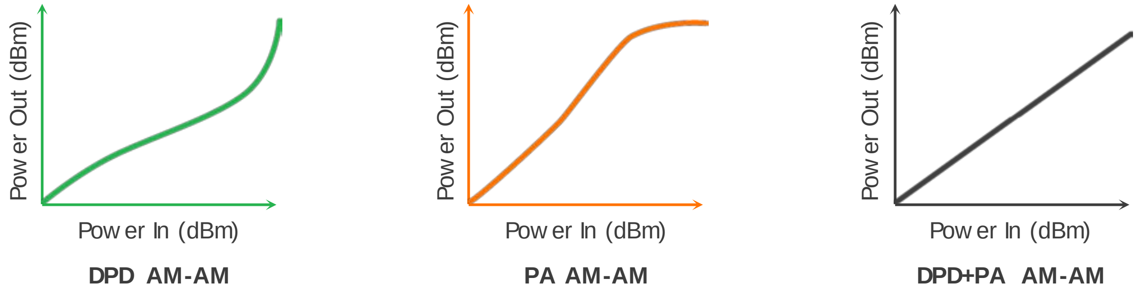
SWaP is a double-edged sword!

DPD Perspective

Digital Pre-Distortion
Overview

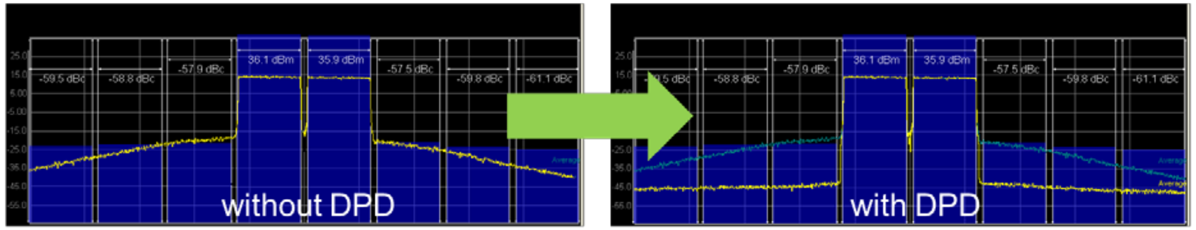






DPD allows the PA to deliver more usable power…

….while meeting spectral emission limits.



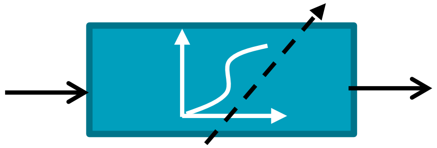
Power spectral density of 2x20 MHz LTE transmission shows improvement in adjacent channel leakage ratio. (ACLR)

SwaP!

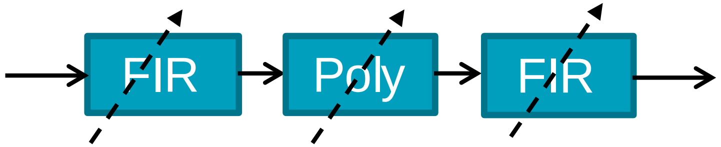
DPD Modeling Options

- **Physical PA Models (Discrete-time RF)**
  - Tuned-to specific PA model.
  - Difficult parameter learning.
  - Inverse model hard to compute!

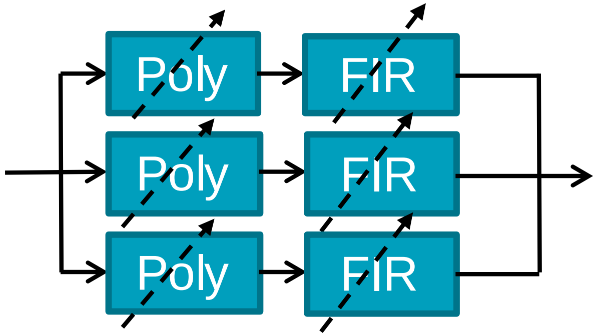
- **Behavioral Models**
  - Simple parameterized models.
  - Not physically meaningful.
  - Baseband model (3x-5x occupied bandwidth).



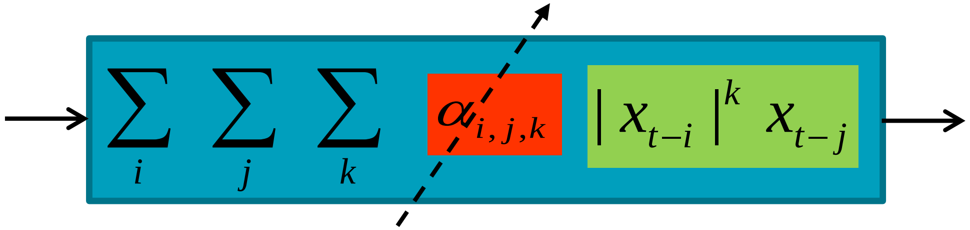
Simple Polynomial



Wiener-Hammerstein

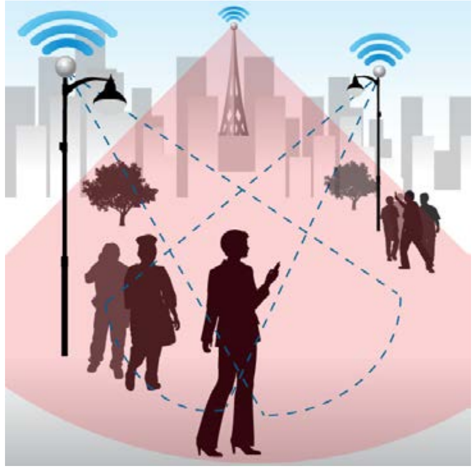


Parallel-Hammerstein



Generalized Memory Polynomial

Digital Pre-Distortion
The Small Cells Challenge



Small Cell Challenges

- Macro parity
- PoE+ power requirements
- Passive cooling
- Highly integrated
- 20, 40 MHz BW typical
- **630mW – 5W PAs**

Typical macrocell DPD Solution consumes 1-2W by itself.

50W PA @ 40% efficiency
…including DPD power:
50W/(125W + 2W) = ***39%***
…OK

630mW PA @ 31% efficiency
…including DPD power:
630mW/(1.9W + 2W)= ***14%***

Doesn't work for **small cell.**

Need a DPD solution that can scale down for small cell power amplifiers.

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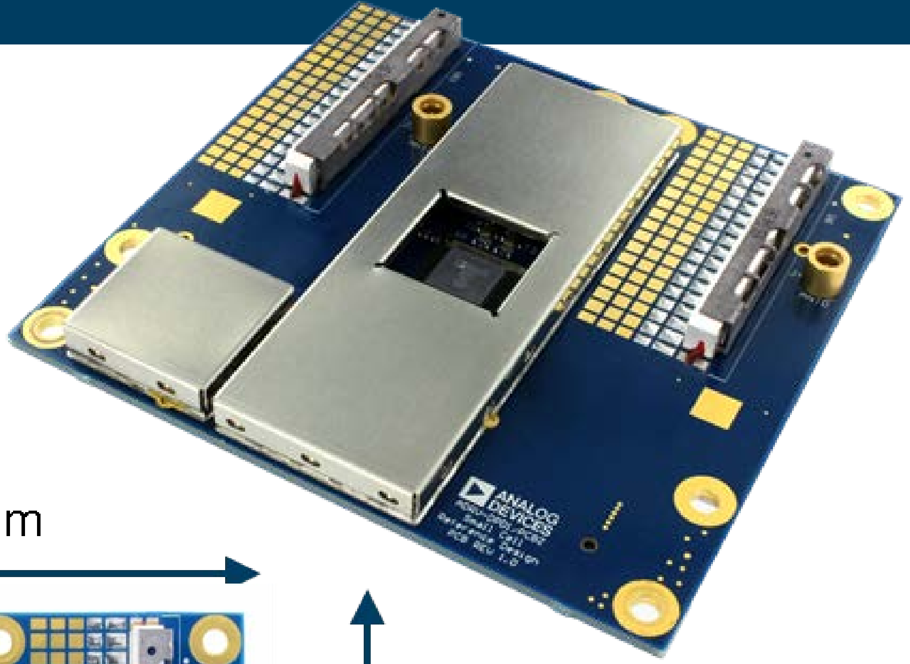
AD9375 Small Cell Radio Reference Design
with Integrated DPD!



Complete JESD204B to antenna design

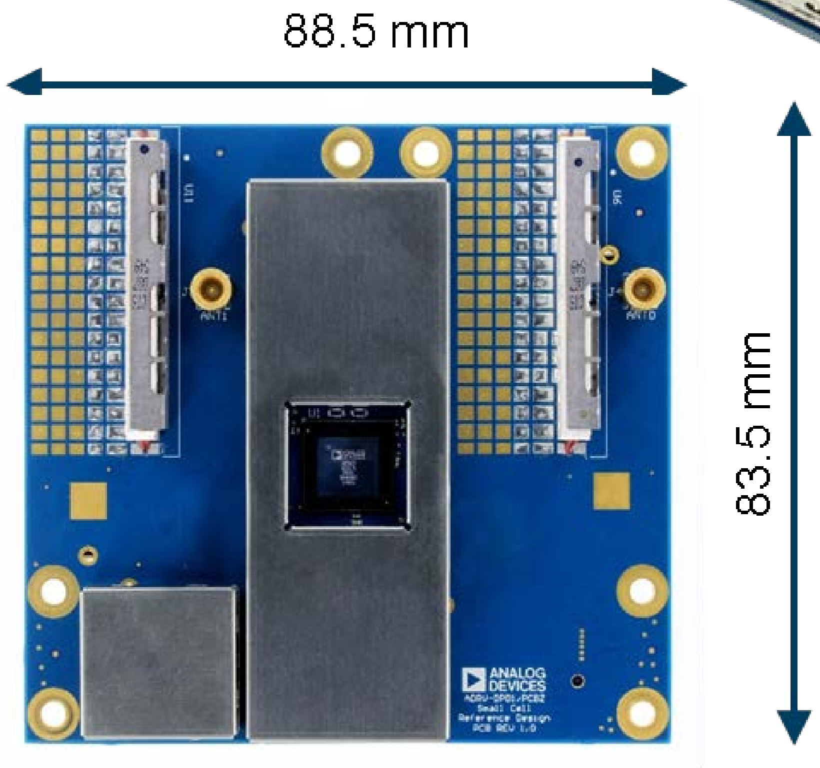
2x2 LTE 20MHz, 250mW output power per antenna, Band 7 FDD with integrated DPD

BOM Reconfigurable to other bands

Contains all components: Transceiver, Pas, LNAs, Filters, Power Solution

Power Consumption <10W

Evaluation Kit connects to baseband sub-system



PA Perspective

Power Amplifiers
State-of-the-Art for COMMS

Metric	LDMOS	GaAs	GaN
Operating Frequency	< 4 GHz	< 6 GHz	< 40 GHz
Process Maturity, Yield	Mature, high yield	Mature, high yield	Developing, lower yield
Typical Applications	Cellular infrastructure	Cellular Infrastructure, handsets	Switches, high-power saturated applications
Typical PAE	37%	30%	45%
Output RMS Power	<= 100 W	<= 50 W	<= 100 W (but higher power possible)
Memory Effects	Low	Low	High: charge trapping, thermal effects

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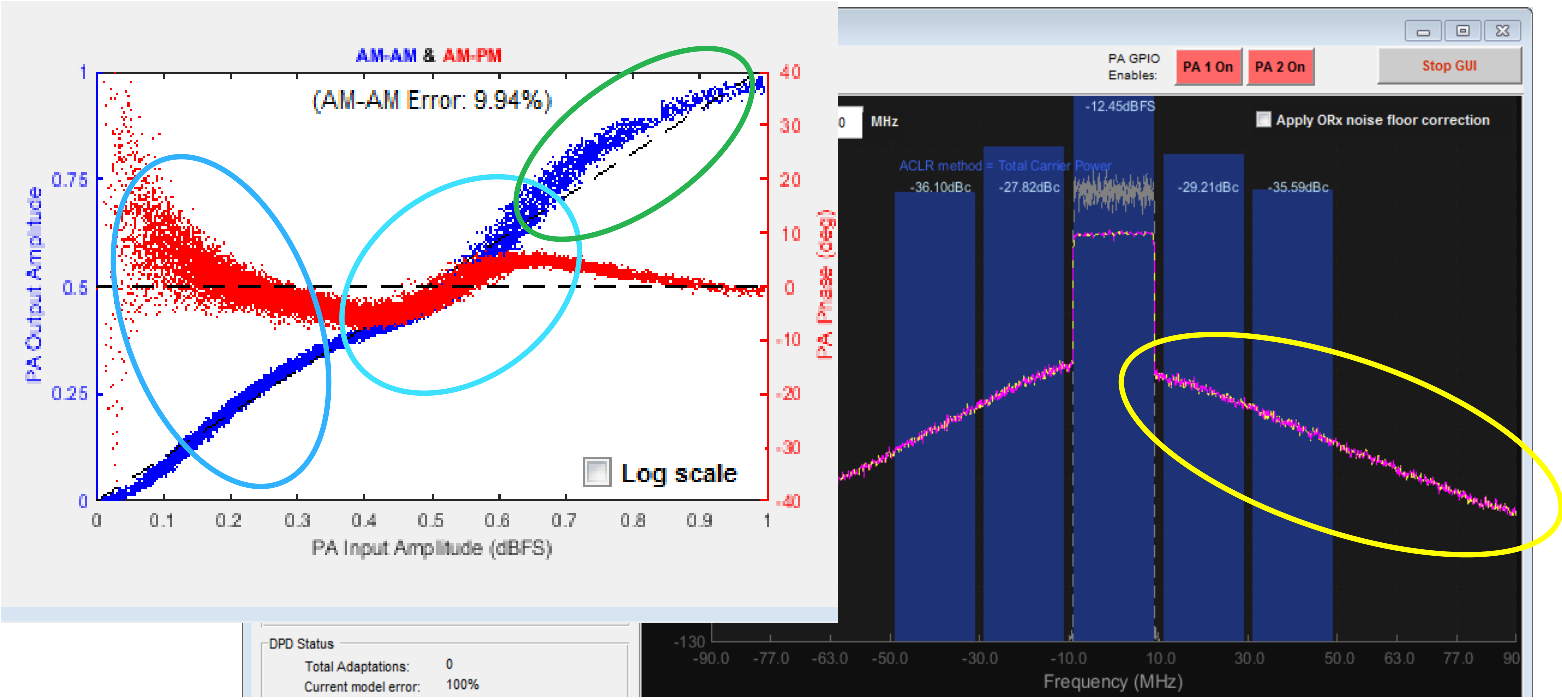
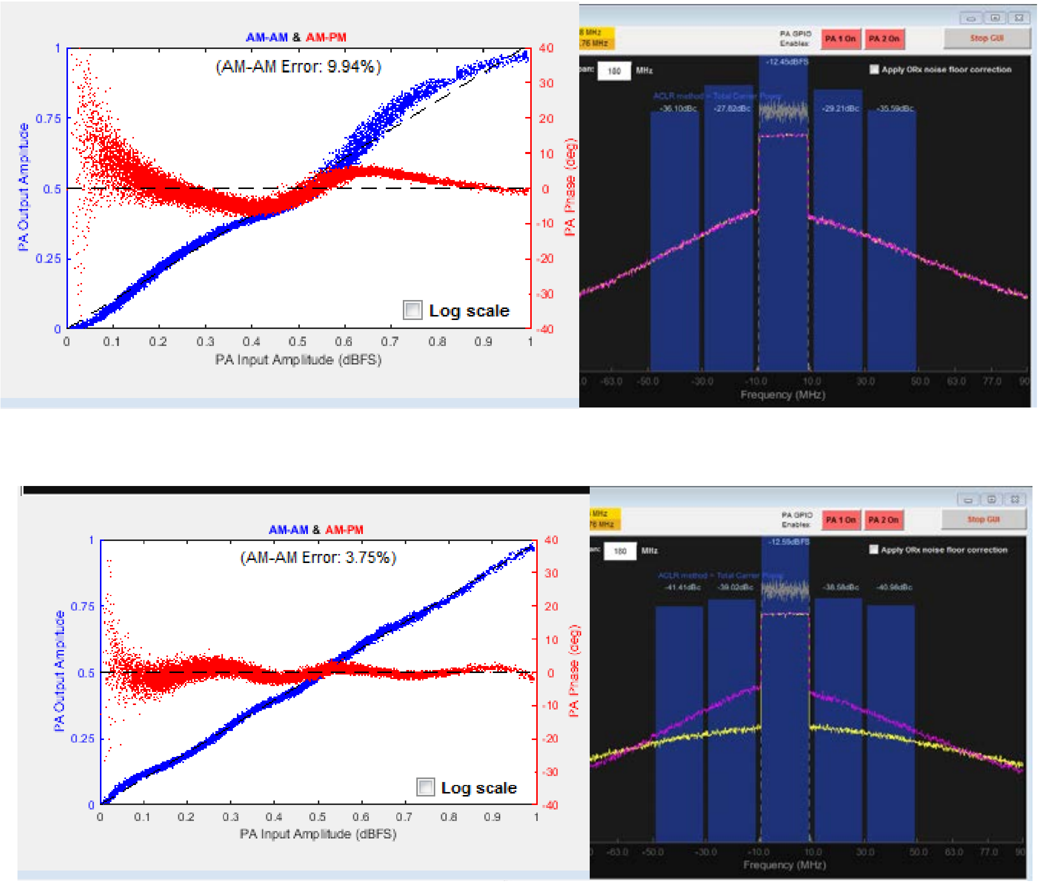
Typical PA Design Considerations - I

Predicting DPD Performance with AM-AM and AM-PM Curves - I

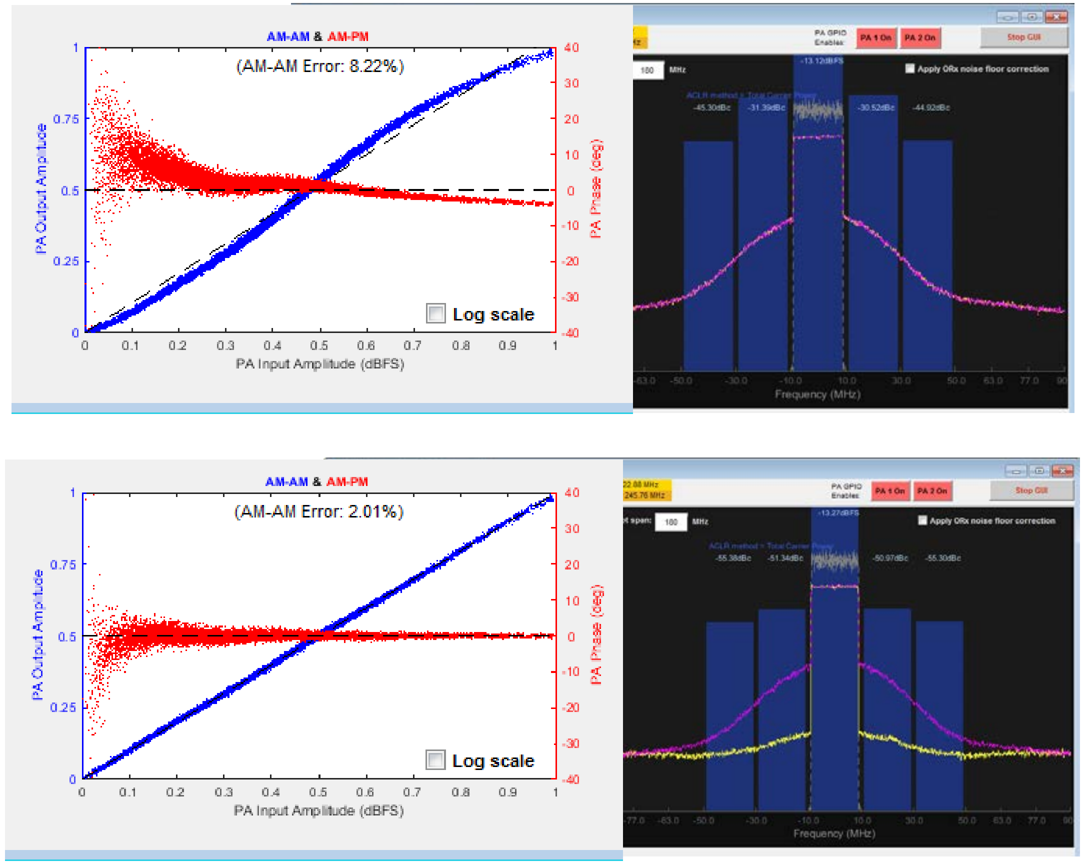
- Highly compressed PA gain stages can pose a problem for most DPD solutions, as such non-linearities typically use higher-order correction terms that increases the complexity of the DPD model



Typical PA Design Considerations - I
Bias Tuning



Before Tuning



After Tuning

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Typical PA Design Considerations - II
Memory Effects

- "Memory effects" typically manifest as 'spreading' on the AM-AM and AM-PM curves and are used as a blanket term in the industry to mean any time-dependent process in a PA
  - Encapsulated in a DPD system's delay terms
  - Delay terms cost more computational resources!

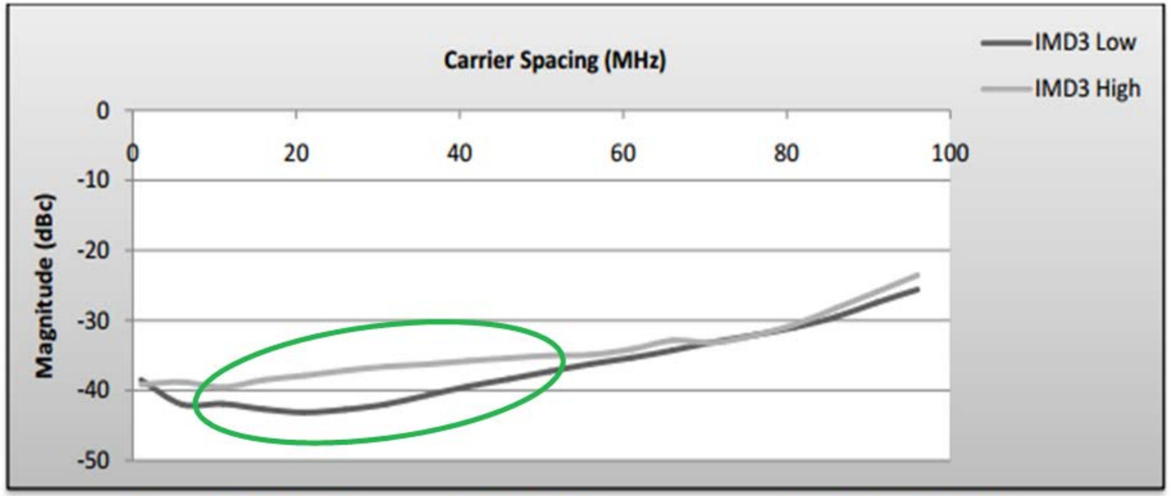


Figure 54: IMD3 performance of NXP's design (carrier sweep from 1960 to 2060MHz)

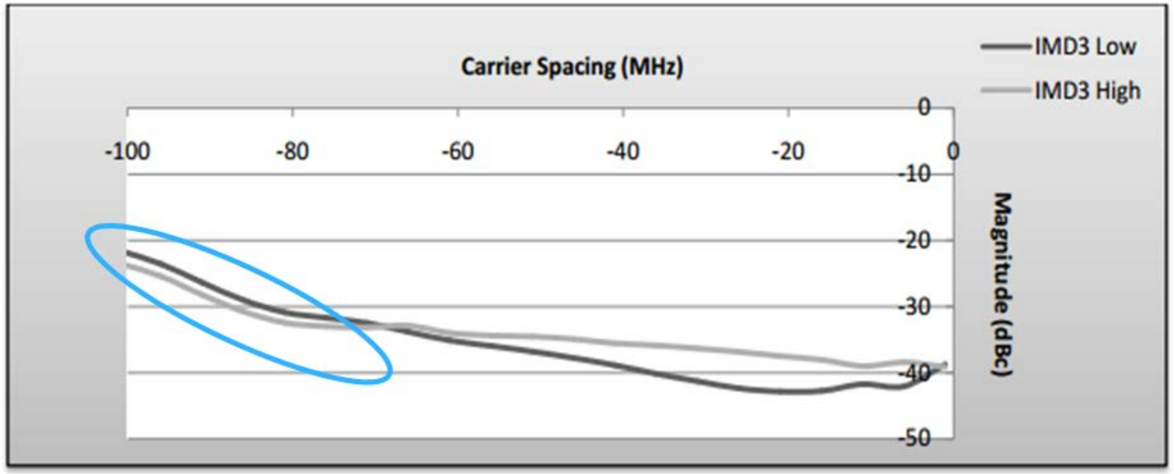
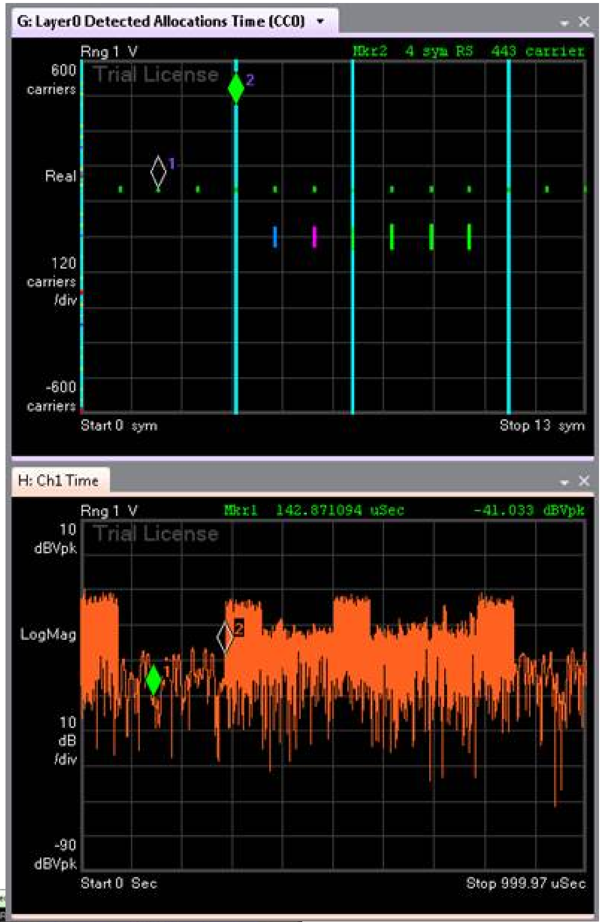


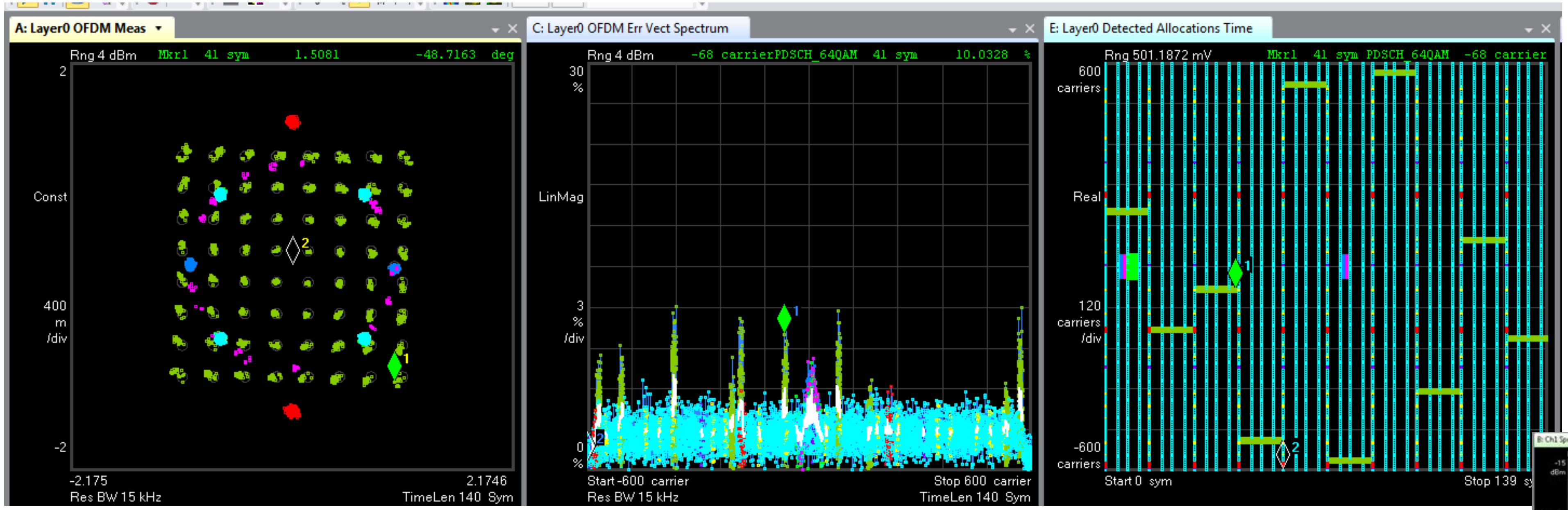
Figure 55: IMD3 performance of NXP's design (carrier sweep from 1960 to 1860MHz)

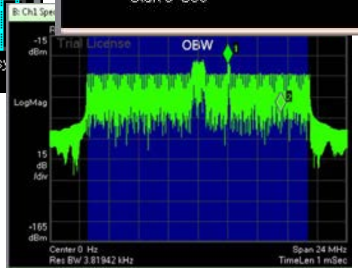
Typical PA Design Considerations - III

PA Process Characteristics with E-TM2-like pulsed waveforms

- In LTE, the PDSCH (data) for an E-TM2 waveform corresponds to low power but is concentrated in a few subcarriers (1 RB = 12 subcarriers bunched in frequency); it's the RS (pilots) that are the larger time-domain pulses but spread out over the entire available spectrum.







Let’s Design a System!

2T2R SMALL CELL TO 64T64R SYSTEM EVOLUTION

2T2R System Requirements
Key Specs

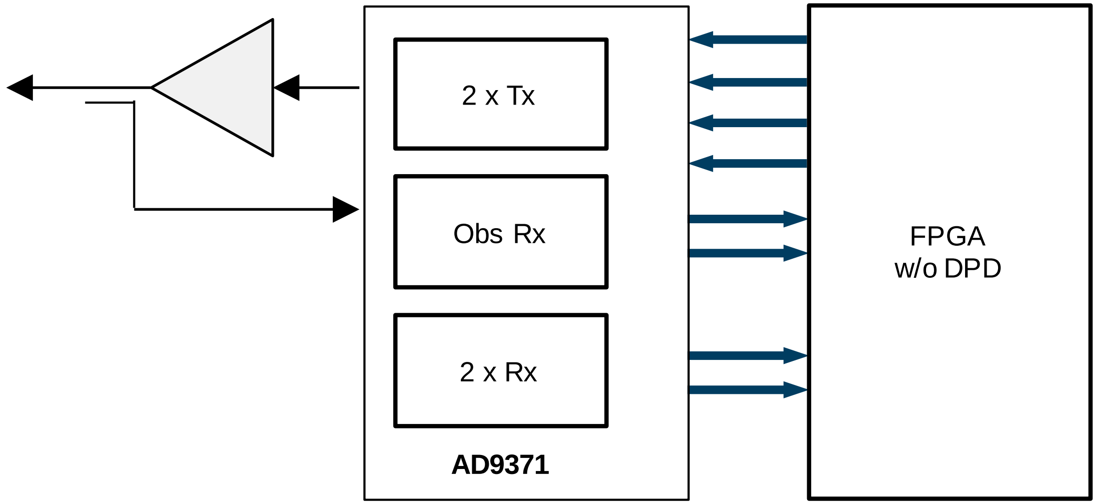
- PA Pout = 1 W, 30 dBm (27 dBm at 1x antenna, 30 dBm system output power)
  - Assume 3 dB post-PA IL with isolator, couplers, duplexer, and trace loss
- -45 dBc ACLR + 5 dB margin = -50 dBc
  - *Note that SEM targets and other requirements such as FCC/ETSI can also drive this figure*
- Cost/unit
  - <$1,000/unit preferred for 10k units volume
- Power Consumed
  - POE+ specs 25.5 W or less power consumed by a Type 2 device
- Frequency of operation = 2.6 GHz
- 2T2R minimum for small cell
  - Explore: Can this be made scalable to a 64T64R M-MIMO system?
- FigureOfMerit_$ = CapEx <Cost/unit, NRE> + 2 years OpEx <power, cooling>
  - Assume 2 years as minimum product lifetime

2T2R System Requirements
Assumptions

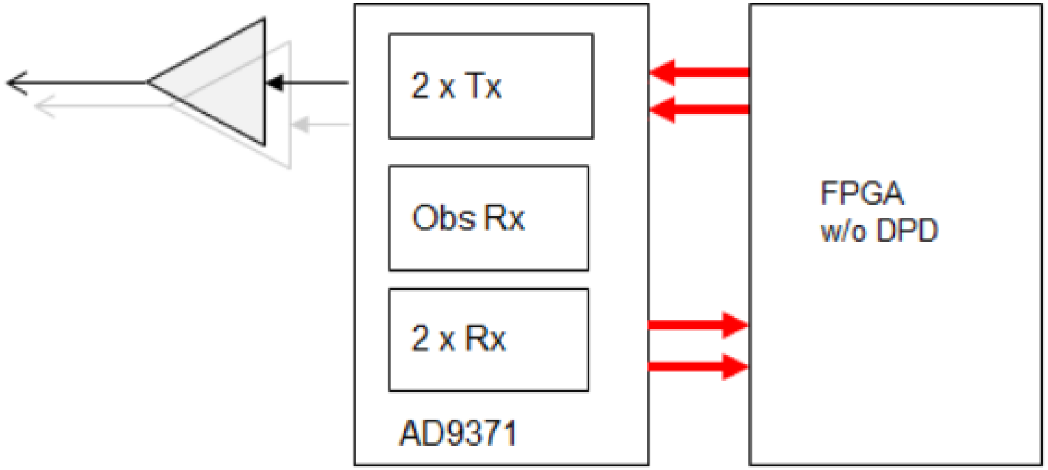
- Since we are focusing on DPD, it makes sense to be focusing on the big 3 power-hungry parts in a system – namely the FPGA/BBP, RF transceiver/converter, and the PA that will act as independent variables for our analysis. However, other non-zero power and cost hits do exist and must be taken into consideration while designing a full system
- Power management solution
  - This is a critical piece of the system that scales both the cost and power requirements of a system dramatically ($1.29/1ku+ for LDOs like ADP1704)
- Clocking and synchronization solution
  - Another critical piece that increases in complexity as you scale to M-MIMO ($8.25/1ku+ for clock chips like AD9528)
- Duplexer and filtering
  - Can be expensive when output power and frequency increase ($7.8/1ku+ for UPD007A)
  - Special care needed in certain bands to handle SEM requirements (LTE-U and WiFi co-existence - B46)
- Spec Compliance Testing
- Board area, layout, form factor, and cooling (…priceless?!)
  - Scale in complexity with more signal chains and can impose further restrictions on total system design

Case 0:
Backed-Off PA

- Back off needed due to high PAR in OFDM communications
- Larger PA required and some arbitrary upper limit on Pout exists due to heat sinking limitations
  - NOT a viable solution in modern day communications!
- PA efficiency is reduced and is ~ 10% or less



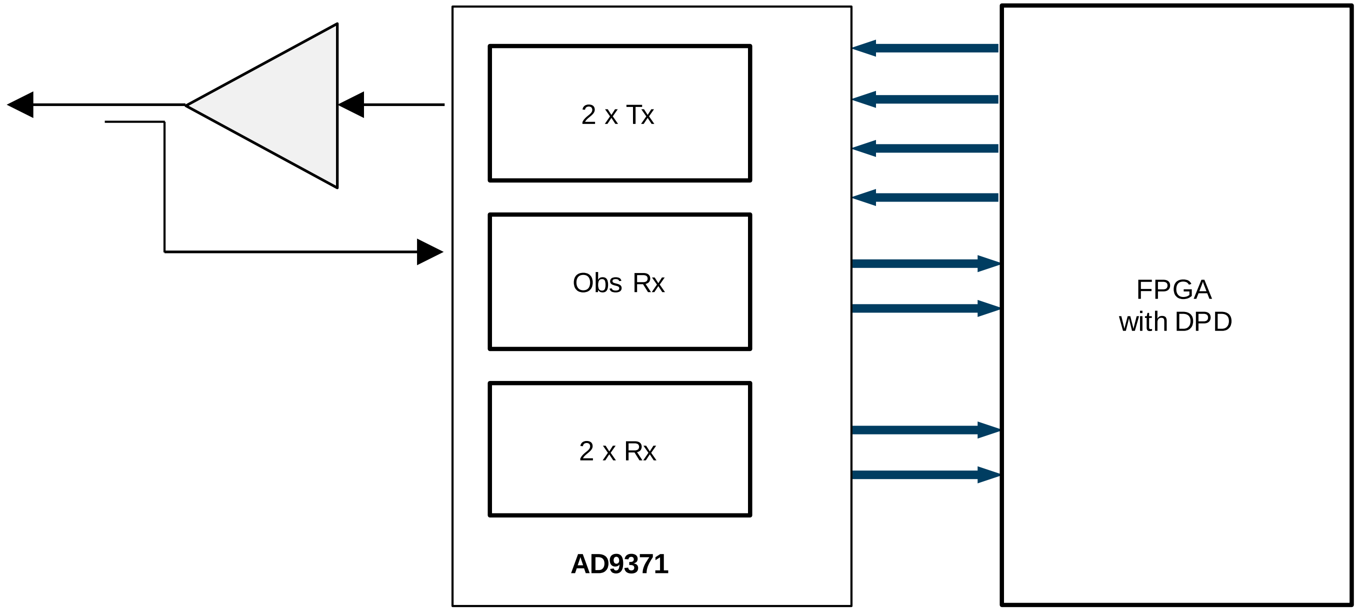
8 x SERDES lanes



4 x JESD204B lanes

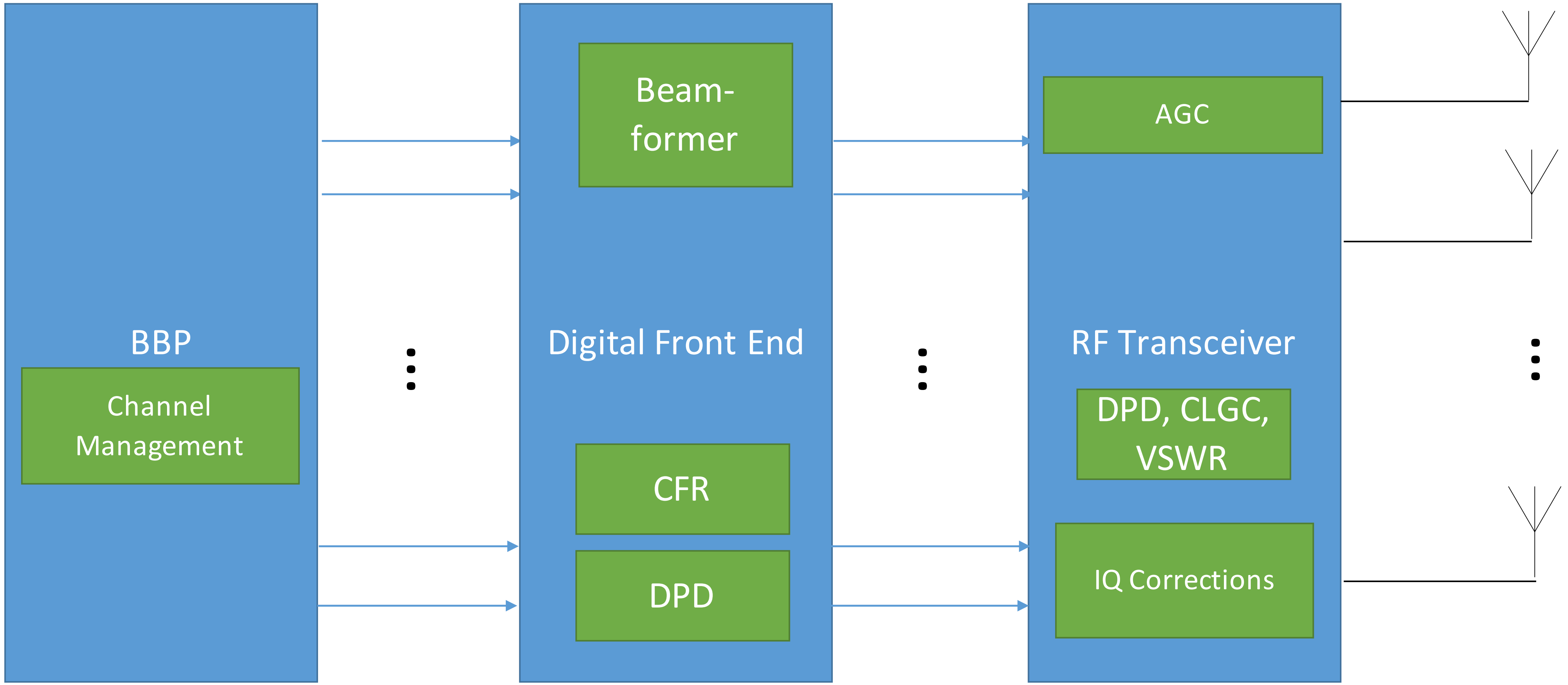
Case 1:
Non-linear PA + FPGA DPD

- Choose a traditional FPGA like Xilinx ZC7030 with own or vendor DPD IP
- Choose some zero-IF RF transceiver like AD9371
- PA efficiency is higher ~ 35% to 40%
- Scalable but costs more



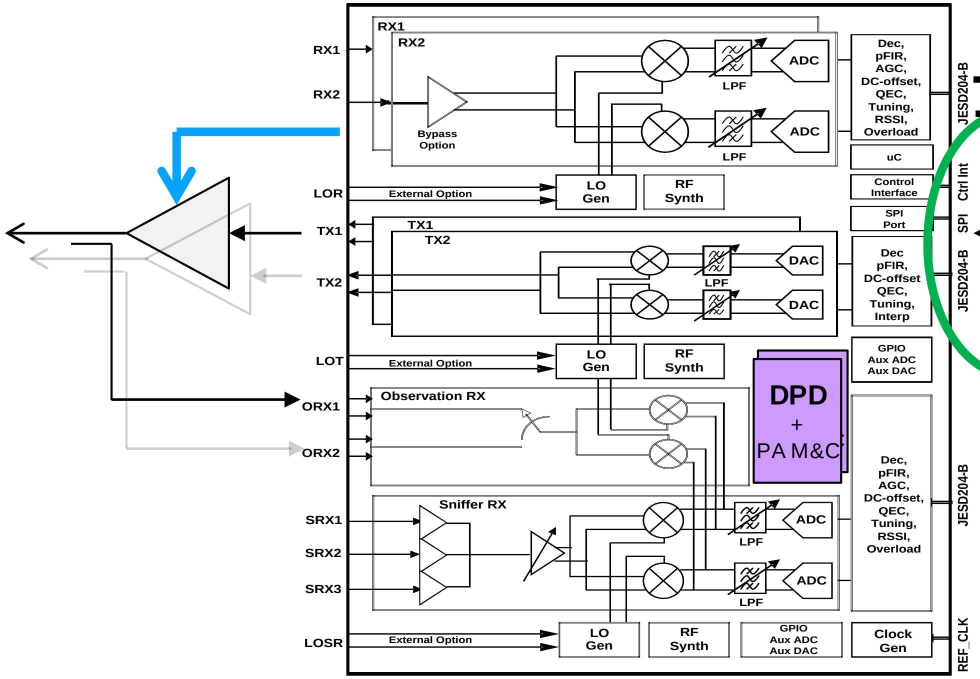
8 x SERDES lanes

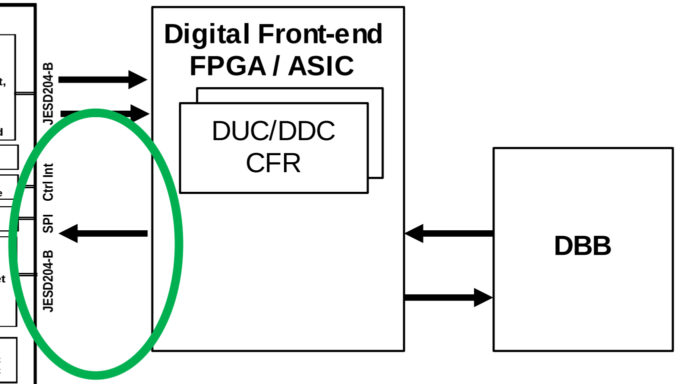
Integrated TRx:
A Growing Systems Solution



AD9375 Small Cell Transceiver

Integrated DPD - Benefits

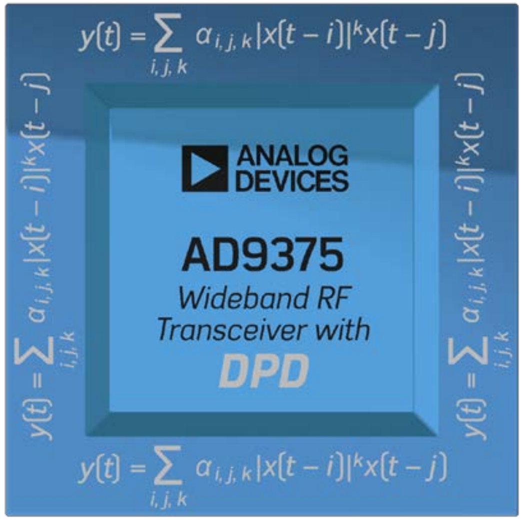




Eliminating JESD 204-B Lanes…

	Separate DPD in DFE		AD9373 Integrated DPD	
	Interface Rate (MSPS)	**JESD204-B Lanes Required**	**Interface Rate (MSPS)**	**JESD204-B Lanes Required**
CH1 Tx	245.76	2 lanes	61.44	0.5 lane
CH2 Tx	245.76	2 lanes	61.44	0.5 lane
ORx	245.76	2 lanes	0	0 lanes

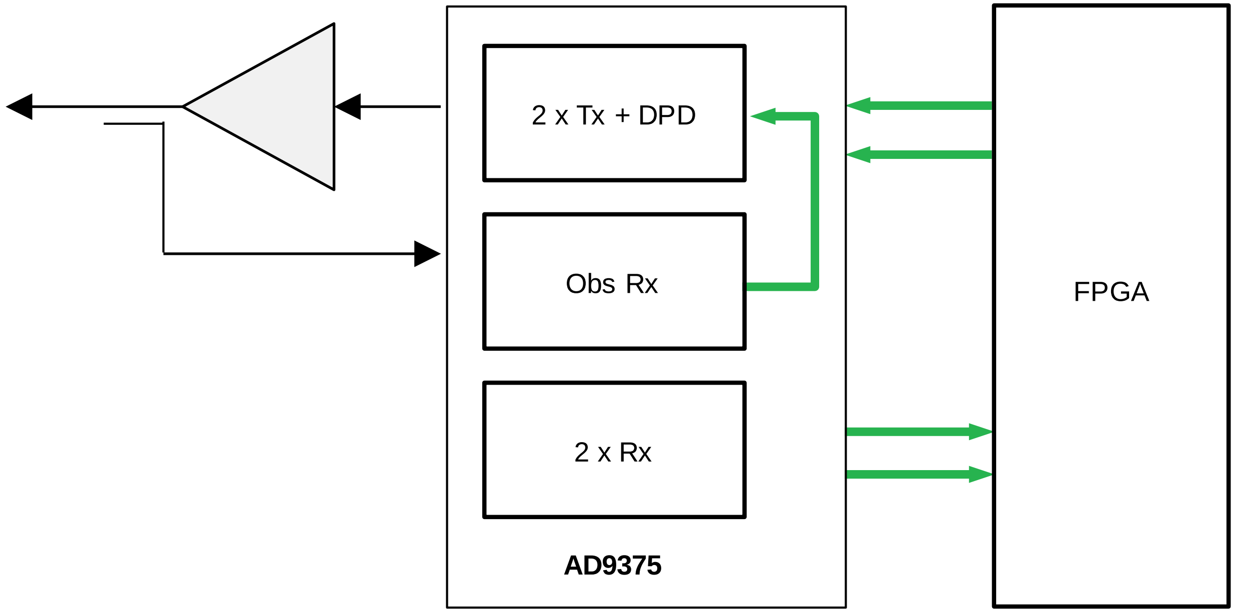
Eliminates 5 JESD 204-B Lanes
(saves ~**500mW** total on both ends)



Pin compatible with AD9371

Case 2:
Non-linear PA + TRx DPD

- Choose a traditional FPGA like Xilinx ZC7030(-1?) with integrated TRx DPD IP
- RF transceiver example: AD9375
- PA efficiency is higher ~ 35% to 40%
- Saves on system power, cost

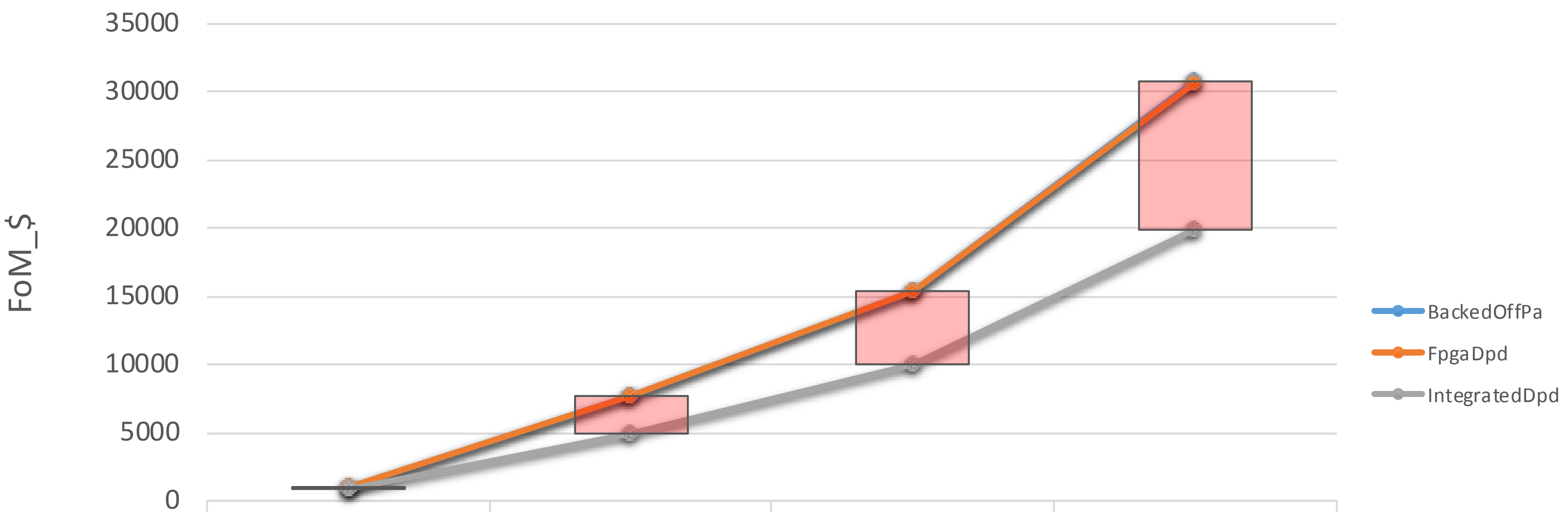


4 x SERDES lanes

How Scalable are these Architectures?
Scaling to 64T64R

- Think FPGA re-use with unused resources, lanes saved with integrated DPD
  - Assume 2 TRx per FPGA (4T4R) in the case of non-integrated DPD
  - Assume 4 TRx per FPGA (8T8R) in the case of integrated DPD
- FoM_$ is a *measure* of total cost of ownership

Figure of Merit for Architectures



	2	16	32	64
BackedOffPa	966.22064	7704.53632	15409.07264	30818.14528
FpgaDpd	962.2546971	7668.603977	15337.20795	30674.41591
IntegratedDpd	850.2574171	4970.523337	9941.046674	19882.09335

System #Tx

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Conclusion

- System Complexity
  - DPD Complexity and tradeoffs: Wider bandwidths will require a larger DPD solution space
    - PA+DPD co-design and system tradeoff is becoming a necessary fact of life
  - PA Design Criteria and tradeoffs
    - GaN poses unique challenges but is poised to be a dominant PA manufacturing process for 5G systems
- Evolving Business Models in the COMMS Industry
  - Top-tier COMMS OEMs increasingly looking for increased functionality and *product solutions*
  - Increases co-development between Transceiver and PA vendor manufacturers
- Scalability
  - System design is focused more on design reuse to realize faster TTM and lower BOM cost
- Know your spec!
  - Not just about best ACLR
  - Not just about best EVM
  - Think 3GPP spec compliance, product scalability, and TTM

So, what can the GNU Radio community do?

- Encourage more full signal chain algorithm development
  - Use reference designs from vendors?
- Lack of LTE support is a bit of a problem in COMMS system development
  - LTE signal analysis through GNU Radio?
- Not everything is Software-defined…YET!
  - There are some hardware designs (and tradeoffs) that will help simplify your software!

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Thank you!

Q&A

What are YOUR roadmap challenges?

COME TALK TO US AT BOOTH #1

Further References

- System performance and efficiency calculator: http://beta-tools.analog.com/dpdcalculator/
- PA + AD9375 DPD reports: http://analog.com/radioverse-dpd
- SWaP and Transceivers:
  - http://www.analog.com/en/analog-dialogue/articles/rf-transceivers-provide-breakthrough-swap-solutions.html
  - http://www.analog.com/en/analog-dialogue/articles/where-zero-if-wins.html
- Xilinx Small Cell Baseband Solution: https://www.xilinx.com/applications/wireless-communications/baseband/small_cell_baseband_design_example.html
- NanoSemi Resource Utilization Tool: http://www.nanosemitech.com/technology/