Future Networks Webinar Series

Mitigating Thermal & Power Limitations to Enable 5G

Presented By –

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OVERVIEW

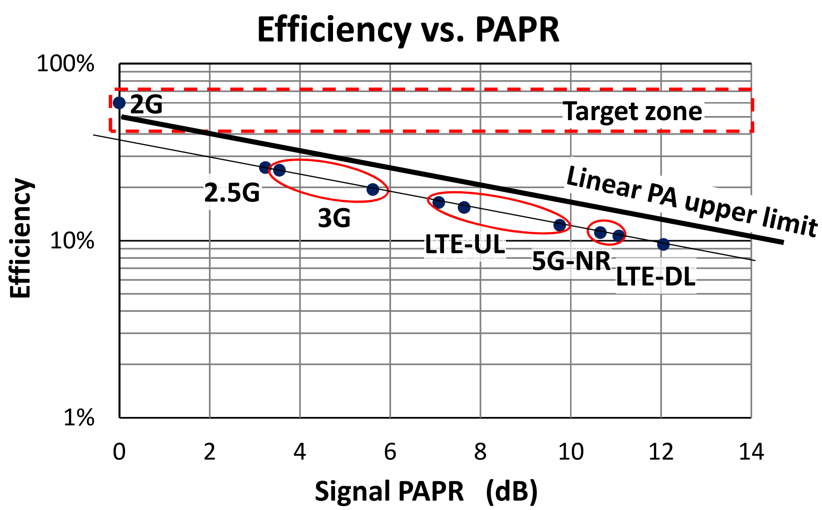
- **5G New-Radio modulation**
- **Heat flows in Transmitters and Arrays**
- **Physically available options**
- **Where we are now**
- **Paths forward**

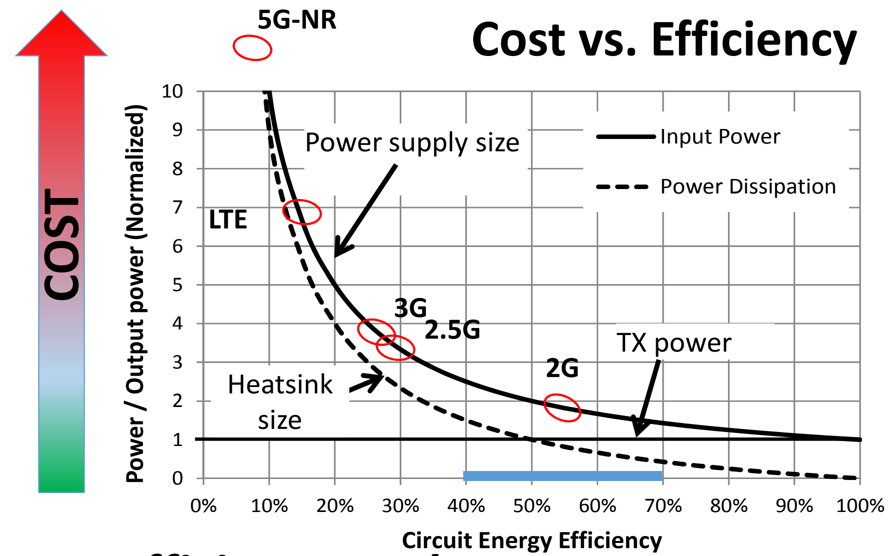
We are here because…

- **It is well known that linear amplifiers operate with low efficiency on OFDM-style signals**
- **The scale of 5G is unprecedented**
- **An inefficient network may be unsustainable**
- **The solution: use sampling theory instead of linear network theory**

Key 5G Parameters	
Latency in the air link	<1 ms
Latency end-to-end (device to core)	<10 ms
Connection density	100x vs. current 4G LTE
Area capacity density	1 (Tbit/s)/km^2
System spectral efficiency	10 (bit/s)/Hz/cell
Peak throughput (downlink) per connection	10 Gbit/s
Energy efficiency	>90% improvement over LTE

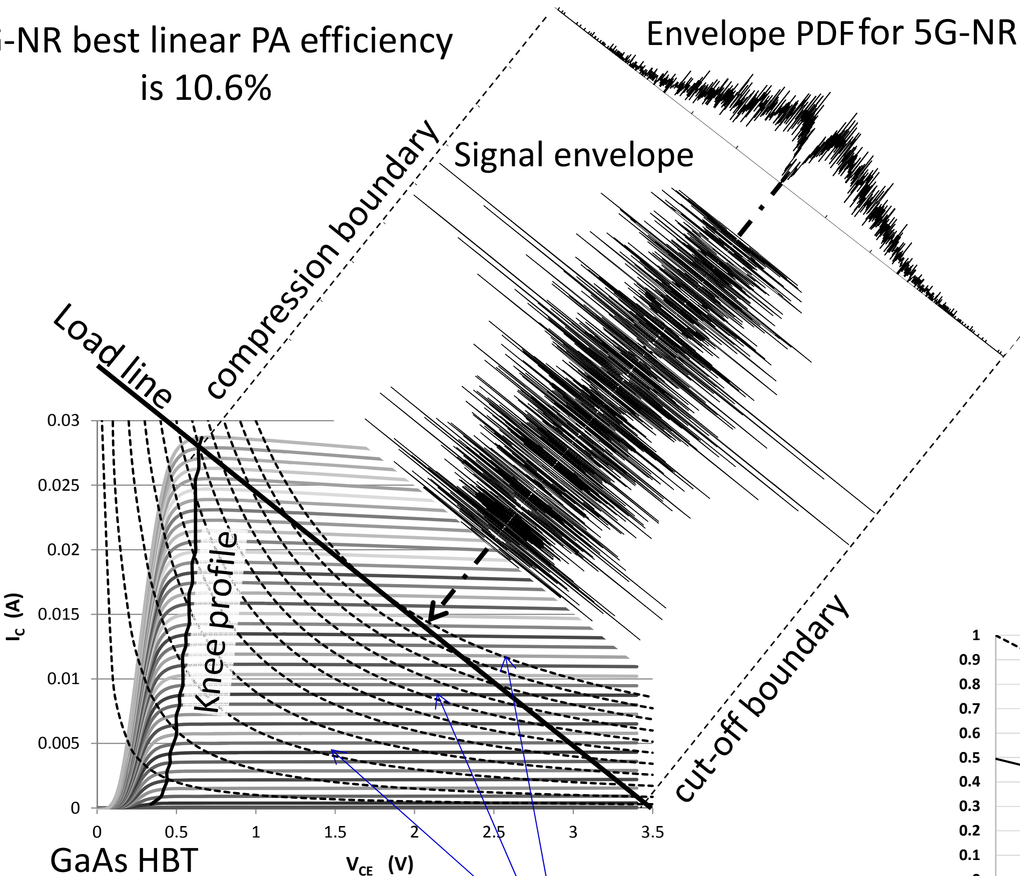
Linear PA Efficiency: Business Impact



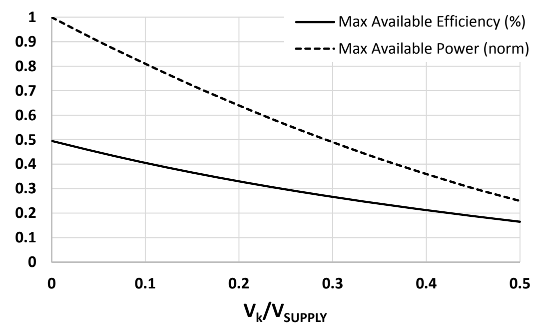


- **Signal design progression forces linear PA efficiency to *decrease***
- **First-cost and operating costs *increase***
  - Higher input power is required (larger power supply)
  - Thermal management of the PA heat (larger heatsink)
- **Preferred efficiency range by industry: between 40 to 70 %**
- **5G must be profitable to build and operate – or it will *fail***

Linear PA Efficiency Ceilings



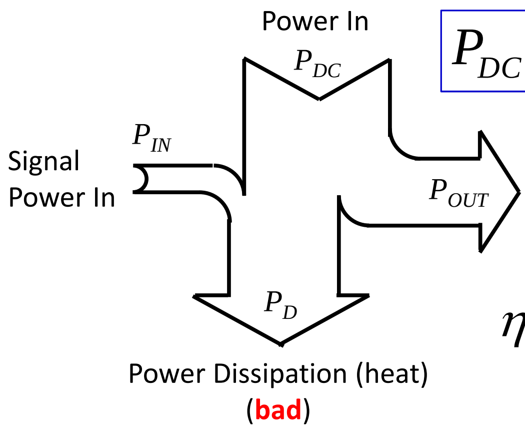
- **Entire output signal – *peak to peak* – must fit within the linear PA load line**
- **PA is scaled for signal *peak* power**
- **Signal *average* power sets communication range**
- **Low average power increases PA heat**
  - *Remains near the maximum power dissipation*



$$\eta_{MAX} \leq \eta_0 \cdot 10^{\frac{PAPR_{dB}}{20}}$$

	Vk/Vs	η_0
Theory	0	0.5
GaAs HBT	0.17	0.35
CMOS	0.29	0.27

Power Flow in Transmitters

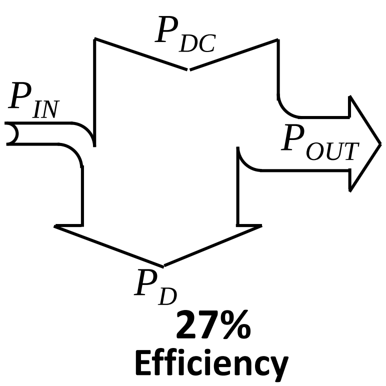


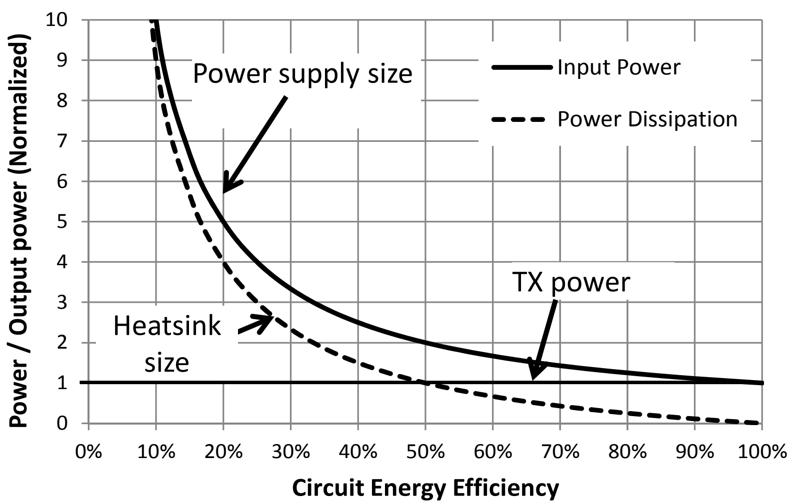
$$P_{DC} + P_{IN} = P_{OUT} + P_D$$

Conservation relation

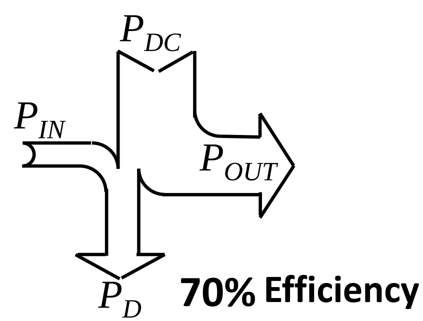
$$\eta \equiv \frac{P_{OUT}}{P_{DC} + P_{IN}} \simeq 1 - \frac{P_D}{P_{DC}} \quad \text{for small } P_{IN}$$

Minimize P_D for best efficiency

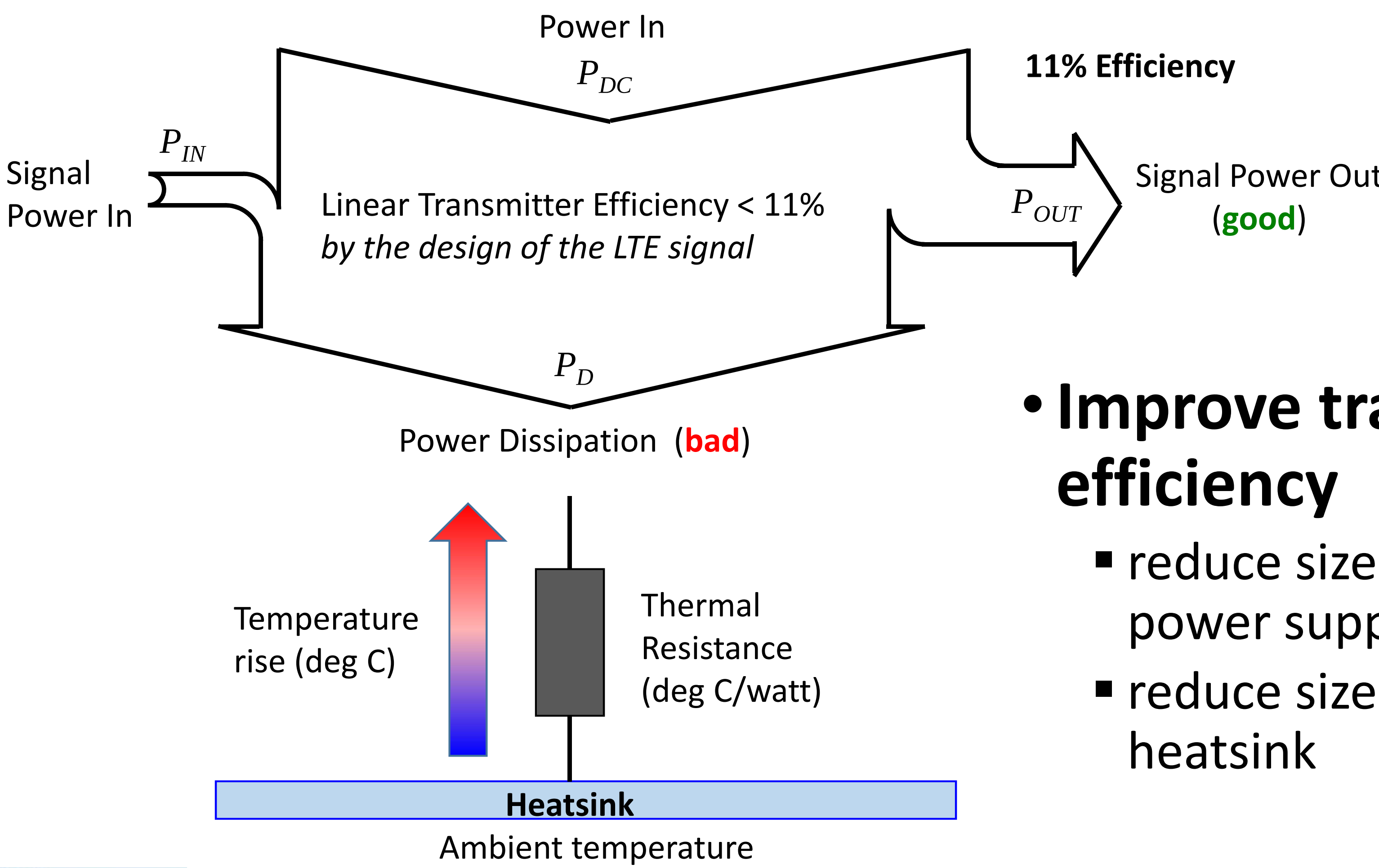




- **“Conservation of Power” actually models Conservation of Energy**
- **Output power is specified**
  - Normalize to P_{OUT}
- **Power dissipation (P_D) is not wanted**
- **Design to minimize P_D**

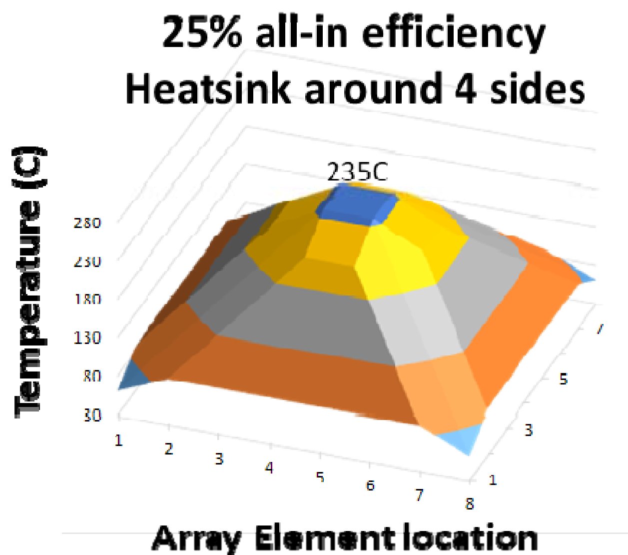


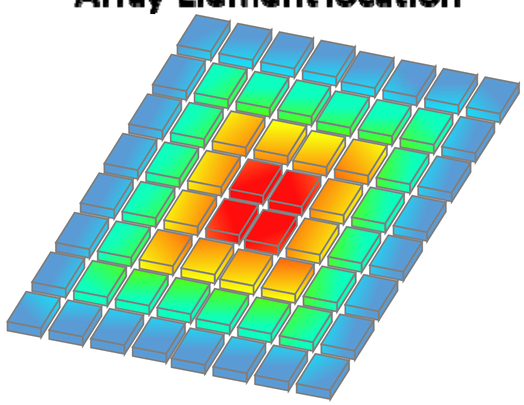
LTE Downlink Case (to scale)



- **Improve transmitter efficiency**
  - reduce size (and cost) of the power supply
  - reduce size (and cost) of the heatsink

Active Antenna Array Challenge





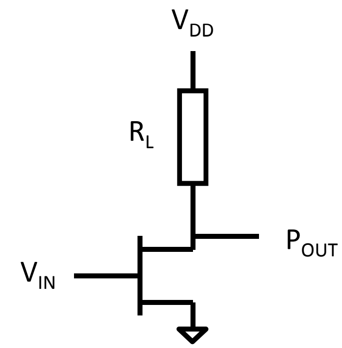
HEAT

- **Outer transmitters are "electric blankets" to the inner transmitters**
- **Center elements get very hot**
- **Constrains the achievable size of active antenna arrays**

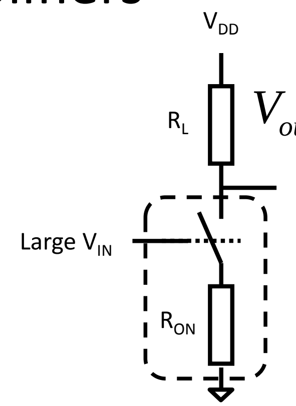
Options – Look to Physics

- **Actual transmitter objective:** ***modulation accuracy at-power***
- **Traditional approach: Linear Network Theory**
  - Modulate at small signal levels
  - Increase signal power with linear amplifiers
  - Maintains modulation accuracy, as long as all amplifiers remain linear (mathematical sense)

$$V_{out} = I_D \cdot R_L$$



- ***Alternative approach*****: Sampling Theory**
  - At-power sampling of the output waveform

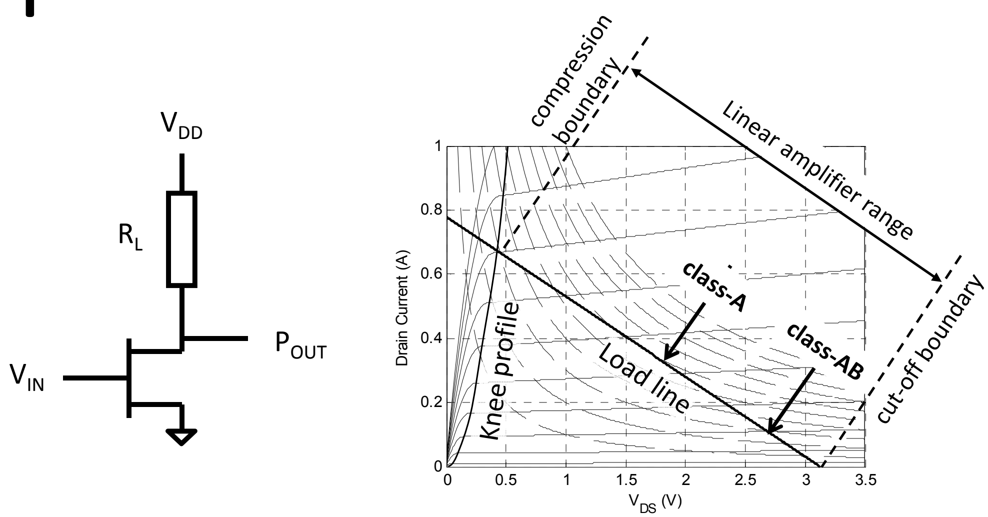


$$V_{out} = \frac{V_{SUPPLY}}{R_L + R_{ON}} \cdot R_L$$

Sampling Theory in Transmitters

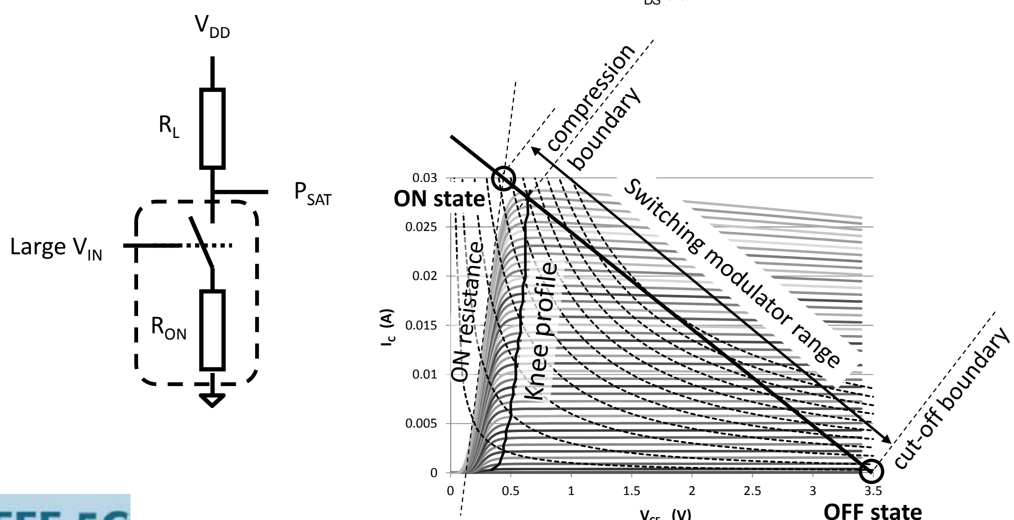
- **Nyquist showed how sampling is used to maintain waveform accuracy**
- **Sampling circuitry is inherently nonlinear**
  - *Exactly* what Ohm's Law requires to achieve energy efficiency
- **Fourier theory still applies**
  - Circuit speed must be sufficiently fast to properly resolve the samples

Implementation Differences



Linear Operation

- Output range is bounded by the knee voltage
- Signal always stays on the load line

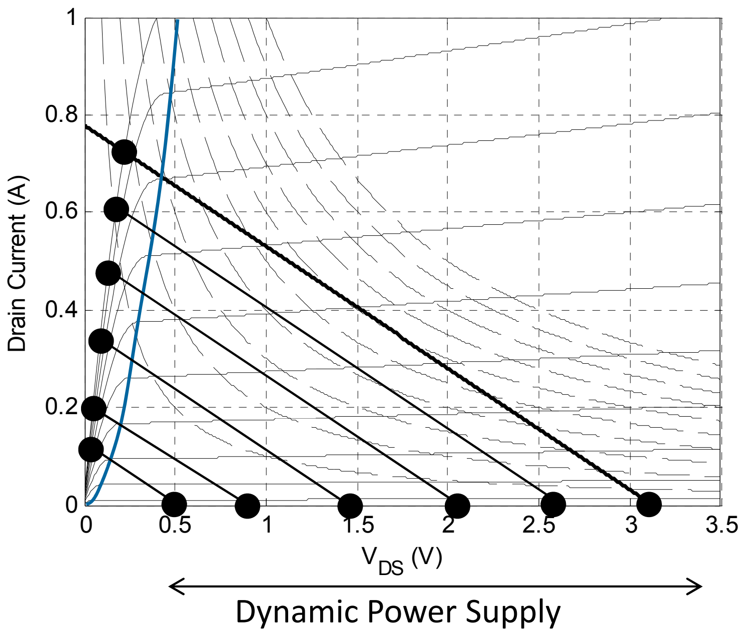


Switching Operation

- Output range is bounded by the transistor ON resistance
- Circuitry operates at the endpoints of the load line
- Power dissipation decreases
  - ***Efficiency increases***

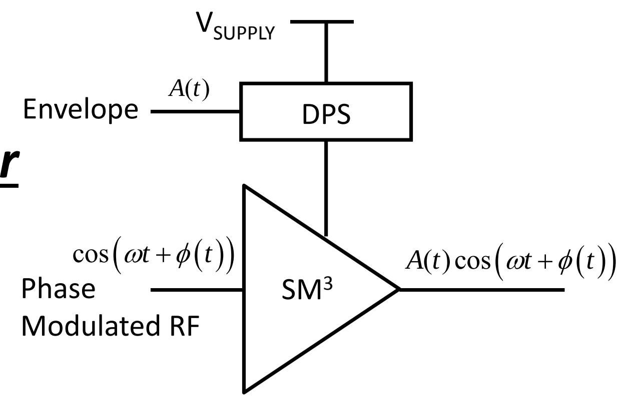
Sampling Transmitter Operation

$$V_{out} = \frac{V_{SUPPLY}}{R_L + R_{ON}} \cdot R_L$$



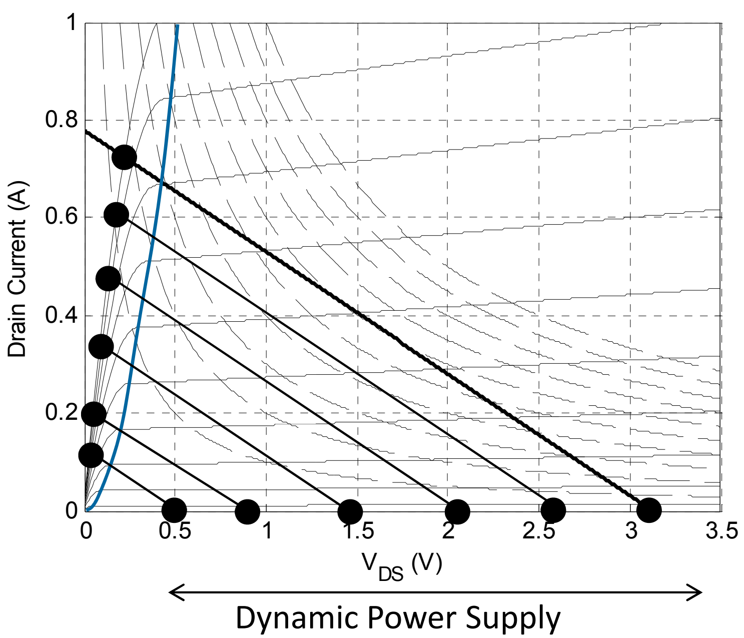
- **Phase modulated carrier samples the signal envelope**
- **Dynamic Power Supply (DPS) sets the instantaneous envelope value**
- **Switch-mode mixer modulator (SM^3) does the sampling at-power**

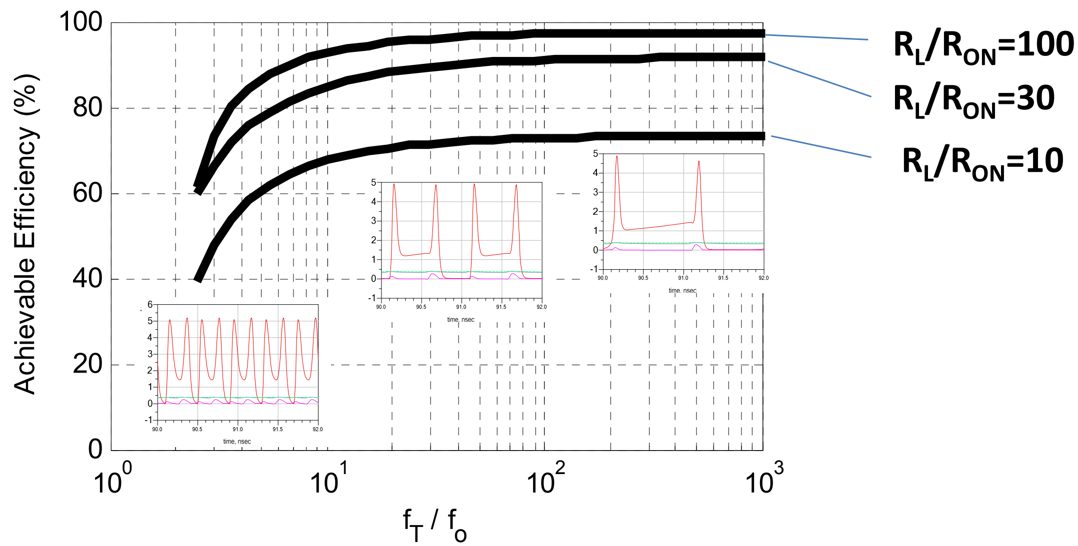
- ***Switching forces use of polar signal processing***



Sampling Transmitter Operation

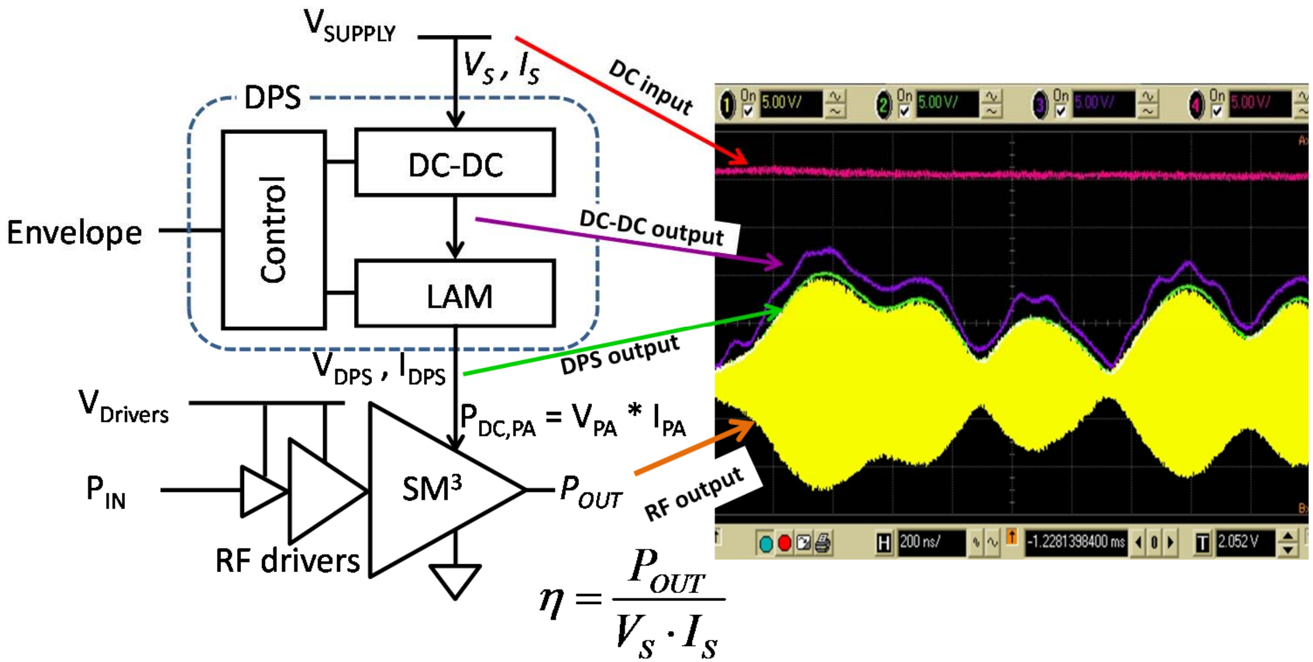
$$\eta_{MAX} = \frac{R_L}{R_L + R_{ON}}$$





- **Power is dissipated as the transistor state transitions the load line**
- **Transition time must be <5% of the carrier period (cycle time)**

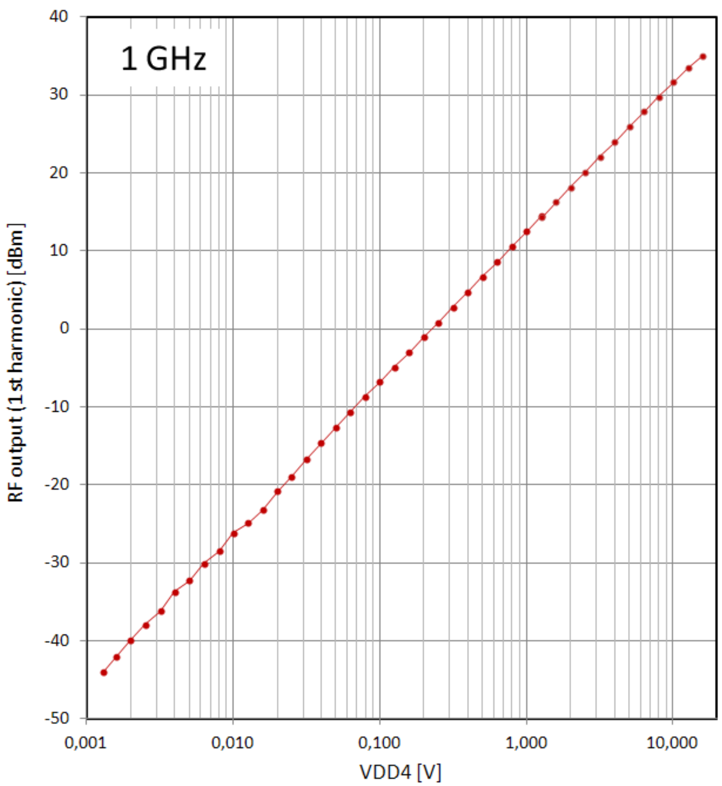
Sampling TX In Action



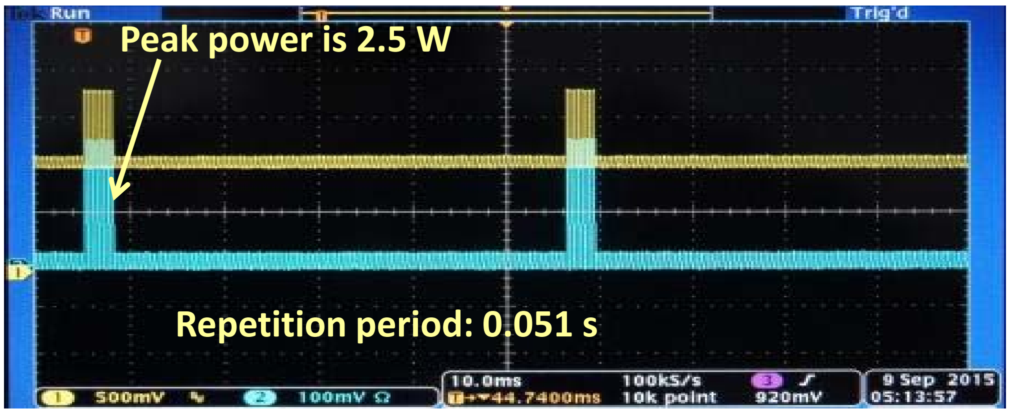
- **DPS has a DC-DC converter and linear regulator (LAM) in series**
- **LAM stays efficient because the voltage drop across it remains very small**

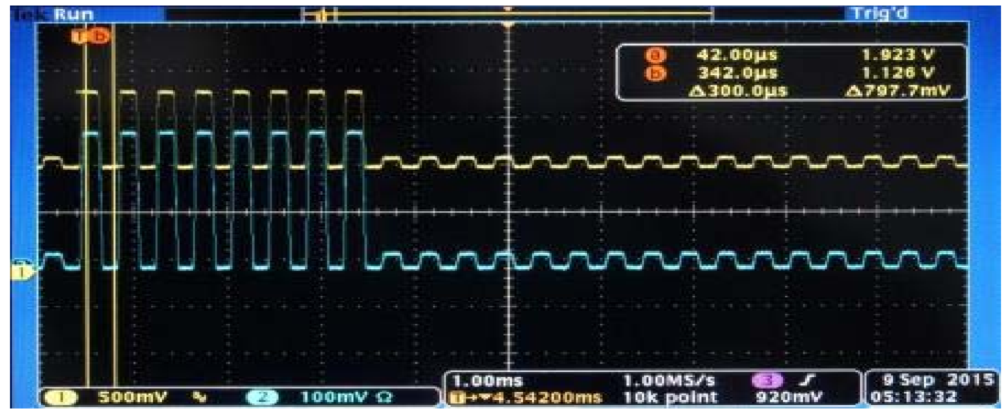
Keys to Success: Magnitude Dynamic Range

- **Now have >80dB direct envelope control**
  - Prior polar controlled envelope dynamic range was ~35 dB
  - Path to 130dB
- **“Good enough” $\rho(t)$ = 0**
  - Enables QAM & LTE
  - Enables <u>very</u> high order QAM & LTE



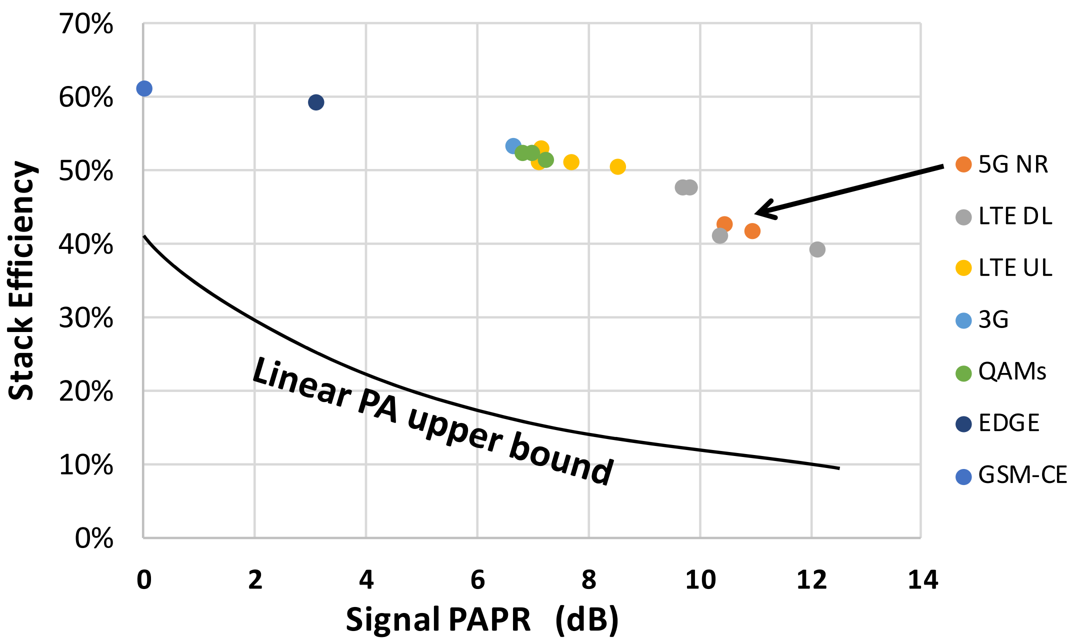
Keys to Success: Drain-lag Solved





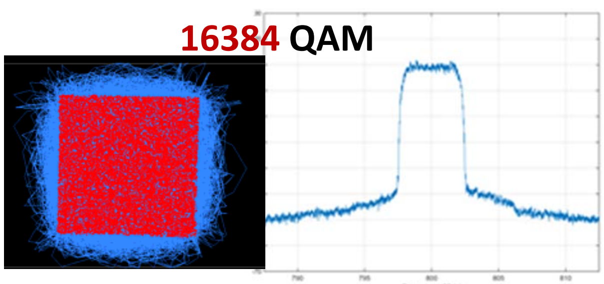
- **Both long-term and short-term effects are moved outside of the SM³ operating area**
- **Requires modification of the FET devices**

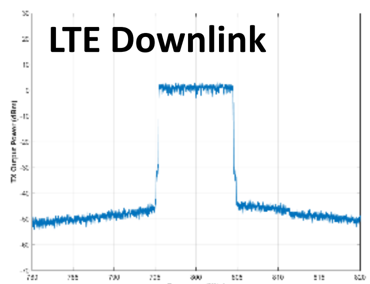
Measured Efficiency vs. Signal PAPR

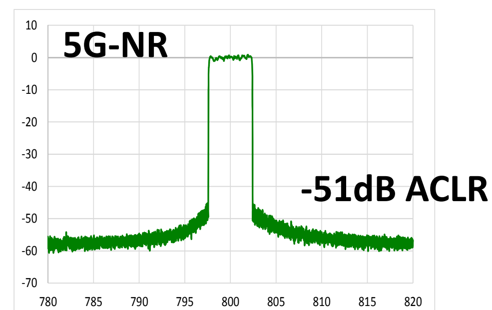


- **Use of switching circuitry greatly improves measured efficiency**
- **Modulation accuracy is maintained**
- **Modulation generality is not compromised**
- ***<u>Reported efficiency is fully linearized</u>***

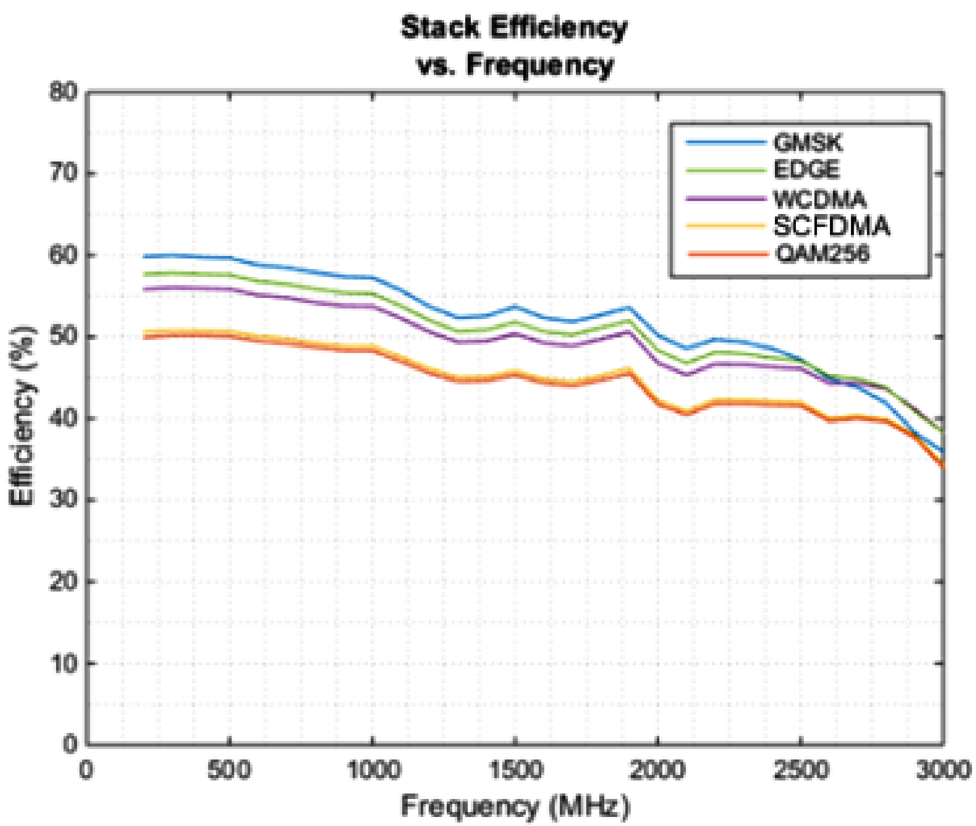
Keysight measurement







Modulated Efficiency across Frequency



IEEE 5G

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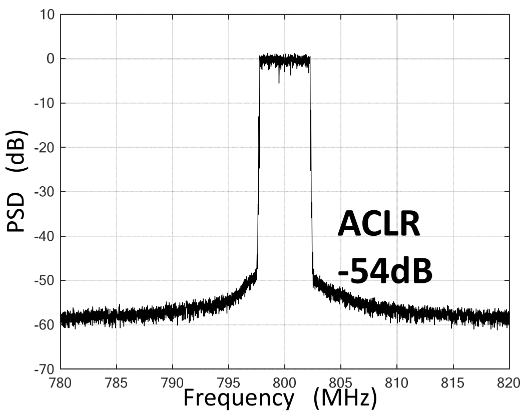
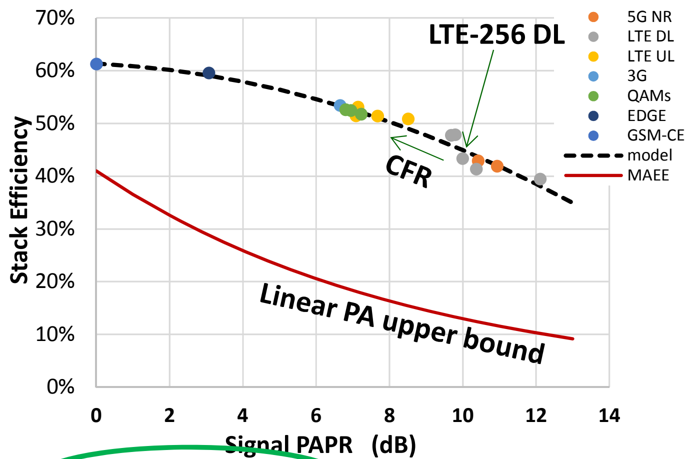
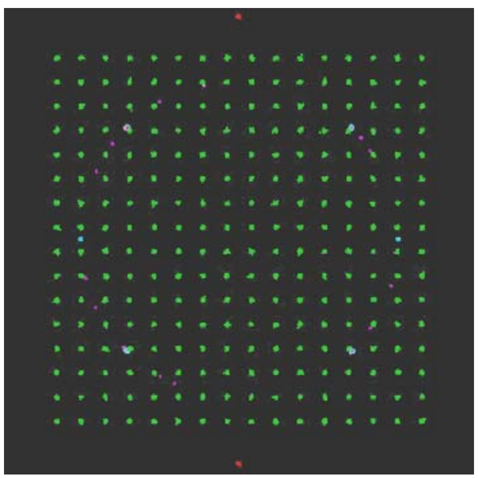
LTE using 256-QAM: Downlink



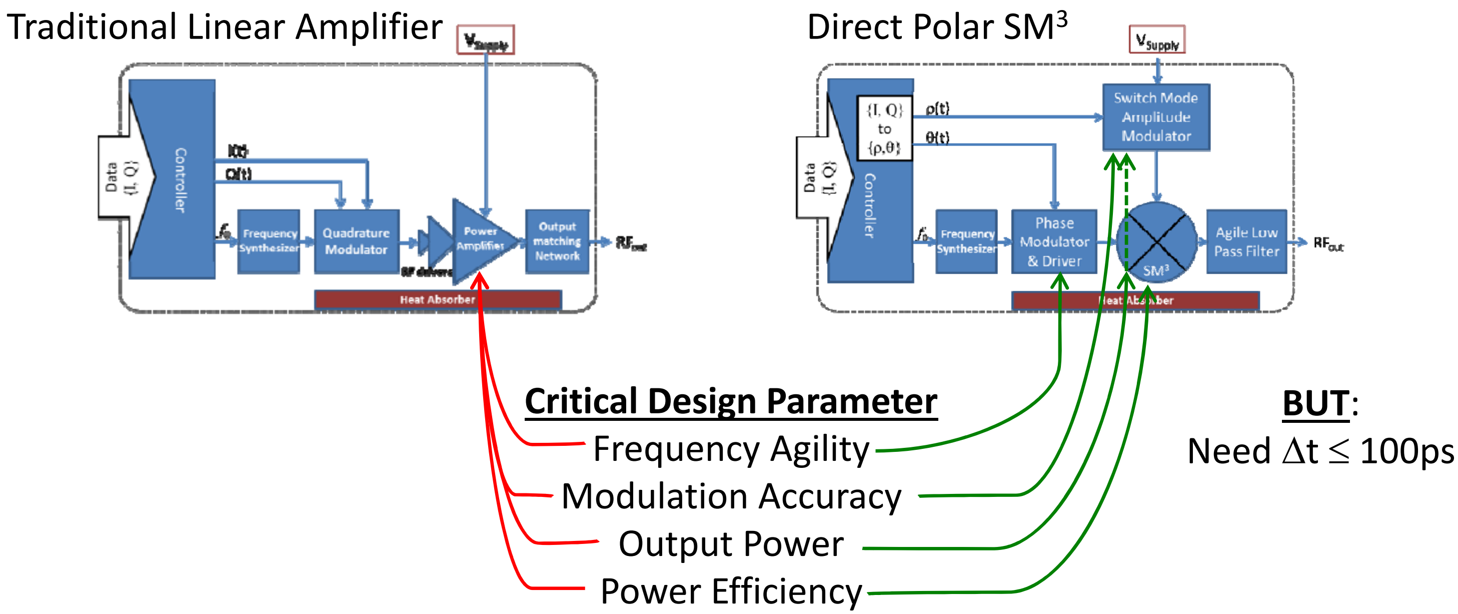




EVM	=	722.54	m%rms	at EVM Window End
EVM Pk	=	2.9073	%	at sym 2, subcar 149
Data EVM	=	735.46	m%rms	
- 3GPP-defined QPSK EVM	=	—		
- 3GPP-defined 16QAM EVM	=	—		
- 3GPP-defined 64QAM EVM	=	—		
- 3GPP-defined 256QAM EVM	=	741.21	m%rms	
RS EVM	=	721.98	m%rms	
Channel Power	=	-7.191	dBm	
RS Tx. Power (Avg)	=	-31.897	dBm	
OFDM Sym. Tx. Power	=	-7.117	dBm	
RS Rx. Power (Avg)	=	-31.897	dBm	
RSSI	=	-7.174	dBm	
RS Rx. Quality	=	-10.744	dB	
Freq Err	=	23.727	Hz	
SyncCorr	=	99.927	%	using P-SS
Common Tracking Error	=	108.52	m%rms	
SymClk Err	=	-1.0465	ppm	
Time Offset	=	4.4691	msec	
IQ Offset	=	-67.153	dB	
IQ Gain Imbalance	=	-0.006	dB	
IQ Quad. Error	=	37.459	mdeg	
IQ Timing Skew	=	75.035	psec	

- **0.72% EVM**
- **-54 dB ACLR**
- **43.3% Efficiency inclusive of linearizer**
  - Improves with CFR
- **2.5W Peak envelope power**
- **10.0 dB PAPR**
  - Innate signal used here

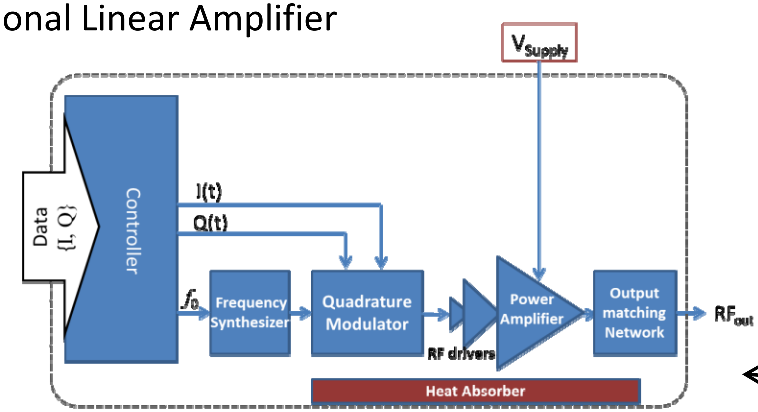
Spreading the Key Performance Points



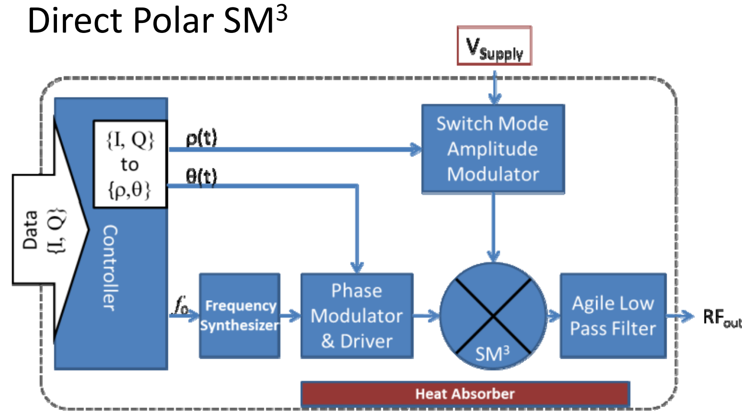
- **Traditional power amplifier must achieve all required parameters**
- **Spreading the precision driver points improves options for local and global optimization**

Architecture Trade-offs

Traditional Linear Amplifier



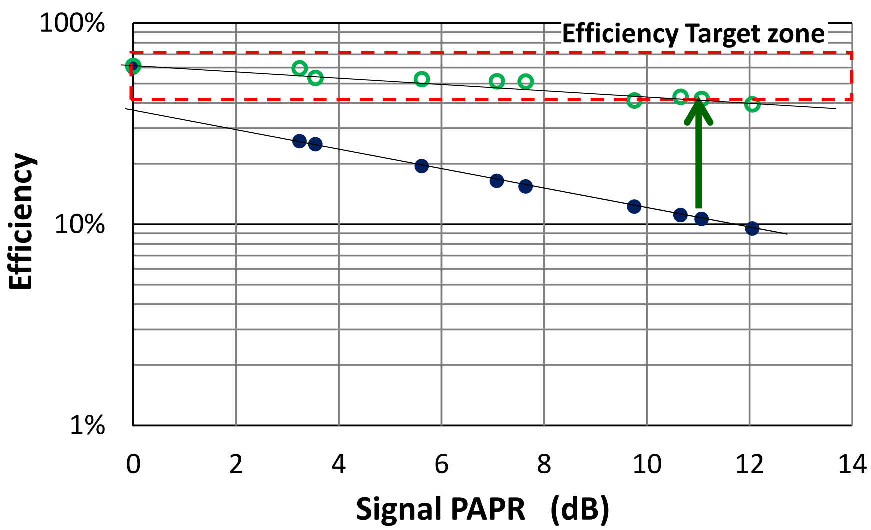
Direct Polar SM³

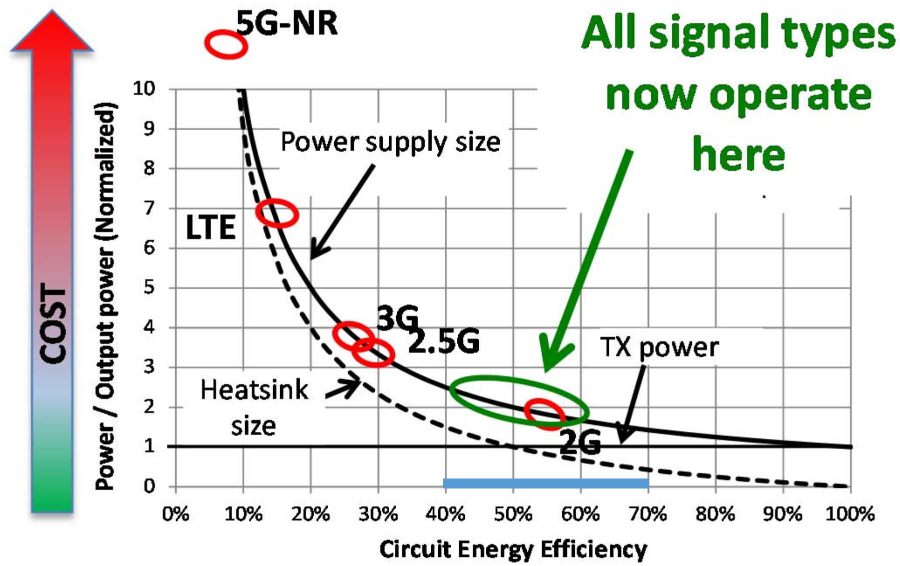


Comparison is at the dashed outline

Feature	Linear TX	Doherty TX	MIRACLE TX
Tuning range ($f_{high} : f_{low}$)	1.22 : 1	1.22 : 1	50 : 1
5G signal efficiency	9%	22%	43%
Data density (max)	6 bps/Hz	6 bps/Hz	>14 bps/Hz
Power supply (W)	1x (normalized)	0.4x	0.2x
Heat absorber (m^3)	8.4x	2.5x	1x (normalized)
Maximum frequency	f_T / 3	f_T / 6	f_T / 10

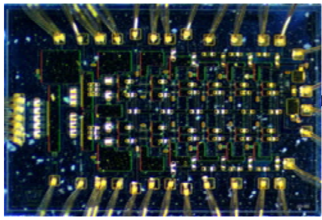
Net Business Impact



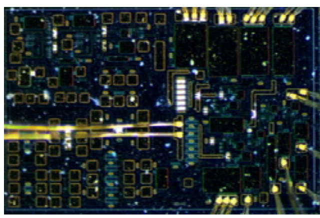


- **Sampling based transmitter; measured efficiency**
- **Costs fall for all of the present modulations**
  - Input power is reduced by 2x to 6x
  - Heatsink size drops by 3x to 7x
- **All signal types are in the industry-preferred efficiency range : 40 to 60 %**
- ***5G can now be profitable to build and operate***

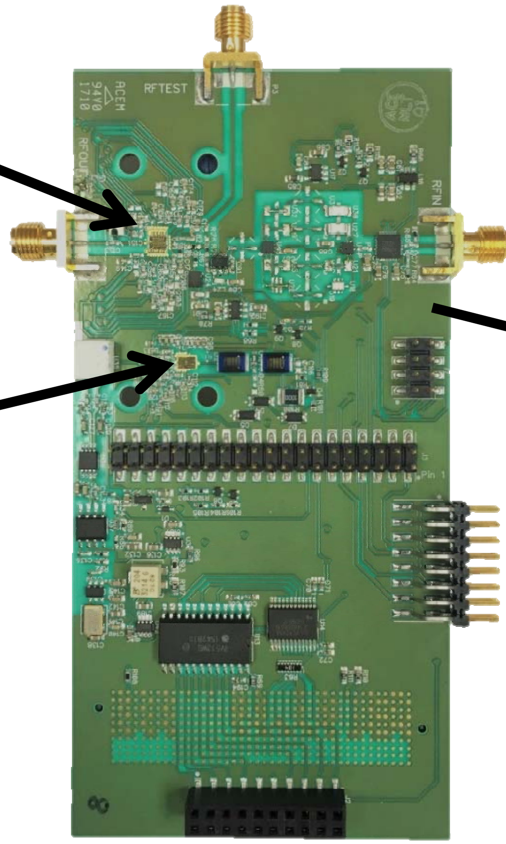
This is real – Hardware is *here* now



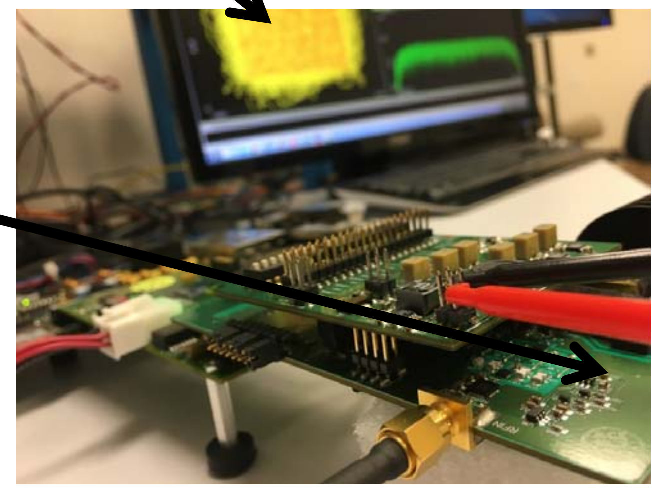
140nm GaN SM^3 MMIC



140nm GaN DPS MMIC

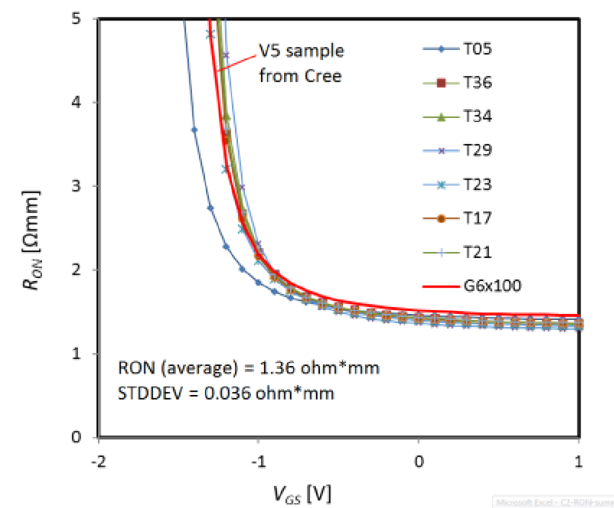


16384-QAM output signal measurement



Keys to Success: Switch Resistance Consistency

- **Extremely reliable SM³ device timing is critical**
  - R_{on} vs. V_{gs} uniformity
  - Proper foundry process is key
  - Switch based design also key
- **It exists – proof is in hand**
  - Multiple devices from multiple wafers with no change to calibration tables



Conclusions

- **Generating 5G-NR and LTE-256 signals with *simultaneous***
  - **43% / 47% fully-linearized TX energy efficiency**
  - **ACLR: -54 dB (LTE-256 signal) ; -52 dB (5G-NR signal)**
  - **0.7% EVM (LTE-256 signal)**
- **Use sampling theory, not linear network theory**
- **Modulation agnostic: fully backward compatible**
- **Also forward compatible:**
  - **Keysight lab validated 16,384-QAM with 0.4% EVM**

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Q & A

Thanks for your time and attention!

Any questions?

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