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

<table>
<thead>
<tr>
<th>Key 5G Parameters</th>
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<tbody>
<tr>
<td>Latency in the air link</td>
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<tr>
<td>Latency end-to-end (device to core)</td>
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<tr>
<td>Connection density</td>
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<tr>
<td>Area capacity density</td>
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<tr>
<td>System spectral efficiency</td>
</tr>
<tr>
<td>Peak throughput (downlink) per connection</td>
</tr>
<tr>
<td>Energy efficiency</td>
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</tbody>
</table>
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

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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*

$\eta_{\text{MAX}} \leq \eta_0 \cdot \frac{P_{\text{APR,MAX}}}{10^{\frac{P_{\text{APR,MAX}}}{20}}}$

<table>
<thead>
<tr>
<th>Theory</th>
<th>$V_k/V_s$</th>
<th>$\eta_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaAs HBT</td>
<td>0.17</td>
<td>0.35</td>
</tr>
<tr>
<td>CMOS</td>
<td>0.29</td>
<td>0.27</td>
</tr>
</tbody>
</table>
Power Flow in Transmitters

Conservation relation

\[ P_{\text{DC}} + P_{\text{IN}} = P_{\text{OUT}} + P_D \]

Conservation of Power actually models Conservation of Energy

Output power is specified
- Normalize to \( P_{\text{OUT}} \)

Power dissipation \( (P_D) \) is not wanted

Design to minimize \( P_D \)

\[ \eta \equiv \frac{P_{\text{OUT}}}{P_{\text{DC}} + P_{\text{IN}}} \approx 1 - \frac{P_D}{P_{\text{DC}}} \quad \text{for small } P_{\text{IN}} \]

Minimize \( P_D \) for best efficiency

27% Efficiency

70% Efficiency

\( P_{\text{IN}} \)

\( P_{\text{DC}} \)

\( P_{\text{OUT}} \)

\( P_D \)

\( \eta \)

\( \% \)

\( \text{Input Power} \)

\( \text{Power Dissipation} \)

\( \text{Power supply size} \)

\( \text{Heatsink size} \)

\( \text{TX power} \)

\( \text{Circuit Energy Efficiency} \)

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LTE Downlink Case (to scale)

Linear Transmitter Efficiency < 11% by the design of the LTE signal

Power In \( P_{DC} \)

Power Dissipation (bad)

Temperature rise (deg C)

Thermal Resistance (deg C/watt)

Heatsink

Ambient temperature

\[ P_D \]

11% Efficiency

Signal Power Out (good)

\[ P_{OUT} \]

\[ P_{IN} \]

\[ 11\% \text{ Efficiency} \]

• Improve transmitter efficiency
  ▪ reduce size (and cost) of the power supply
  ▪ reduce size (and cost) of the heatsink

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Active Antenna Array Challenge

25% all-in efficiency
Heatsink around 4 sides

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)

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

\[ V_{out} = I_D \cdot R_L \]

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

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

\[ \eta_{MAX} = \frac{R_L}{R_L + R_{ON}} \]

\[ \frac{R_L}{R_{ON}} = 100 \]
\[ \frac{R_L}{R_{ON}} = 30 \]
\[ \frac{R_L}{R_{ON}} = 10 \]
• DPS has a DC-DC converter and linear regulator (LAM) in series

• LAM stays efficient because the voltage drop across it remains very small

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Keys to Success: Magnitude Dynamic Range

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

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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

Peak power is 2.5 W
Repetition period: 0.051 s
Measured Efficiency vs. Signal PAPR

- Use of switching circuitry greatly improves measured efficiency
- Modulation accuracy is maintained
- Modulation generality is not compromised
- Reported efficiency is fully linearized

Keysight measurement

IEEE 5G

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Modulated Efficiency across Frequency

![Efficiency vs. Frequency Graph](image-url)
LTE using 256-QAM: Downlink

- 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

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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

\[ \Delta t \leq 100\text{ps} \]
Architecture Trade-offs

Traditional Linear Amplifier

Direct Polar SM³

Comparison is at the dashed outline

<table>
<thead>
<tr>
<th>Feature</th>
<th>Linear TX</th>
<th>Doherty TX</th>
<th>MIRACLE TX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tuning range (f_{\text{high}} : f_{\text{low}})</td>
<td>1.22 : 1</td>
<td>1.22 : 1</td>
<td>50 : 1</td>
</tr>
<tr>
<td>5G signal efficiency</td>
<td>9%</td>
<td>22%</td>
<td>43%</td>
</tr>
<tr>
<td>Data density (max)</td>
<td>6 bps/Hz</td>
<td>6 bps/Hz</td>
<td>&gt;14 bps/Hz</td>
</tr>
<tr>
<td>Power supply (W)</td>
<td>1x (normalized)</td>
<td>0.4x</td>
<td>0.2x</td>
</tr>
<tr>
<td>Heat absorber (m³)</td>
<td>8.4x</td>
<td>2.5x</td>
<td>1x (normalized)</td>
</tr>
<tr>
<td>Maximum frequency</td>
<td>(f_T / 3)</td>
<td>(f_T / 6)</td>
<td>(f_T / 10)</td>
</tr>
</tbody>
</table>
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

16384-QAM output signal measurement

140nm GaN DPS MMIC
Keys to Success: Switch Resistance Consistency

• Extremely reliable SM$^3$ 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
Q & A

Thanks for your time and attention!

Any questions?

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