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CIRCUITS AND SYSTEMS

# A Peak-Search Algorithm for Combined PAE and ACPR Load-Pull

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# Baylor WMCS Program

- Wireless and Microwave Circuits and Systems
- Wireless and Microwave Education and Research in a Caring, Christian Environment
- Launched in 2008.
- For more information, go to http://www.wmcslab.org.

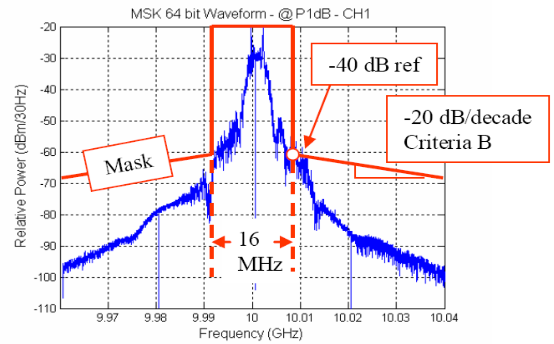
# Load-Pull and Radar Power Amplifiers

- Radar power amplifiers are being forced to operate in tighter spectrum allocations, while maintaining high efficiency.
- The National Broadband Plan
  - Mandates the release of 500 MHz of newly available spectrum for wireless applications in the next 10 years.
  - Much of this spectrum will be re-allocated from radar.
- Radar systems may have to eventually operate in a dynamic spectrum access (DSA) environment.
  - Changing spectral constraints
  - Reconfigurability

# Spectral Constraints

- Radar criteria imposed in the Radar Spectrum Evaluation Criteria (RSEC), which are determined by the National Telecommunications and Information Administration (NTIA).
- Spectral spreading is caused by nonlinearity in the nonlinear power amplifier → intermodulation
- Spectral mask outlines the required confines of the signal:

*Reprinted from J. de Graaf, H. Faust, J. Alatishe, and S. Talapatra, "Generation of Spectrally Confined Transmitted Radar Waveforms," Proc. IEEE Conf. on Radar, 2006, pp. 76-83



# Sources of Spreading

- Third-order nonlinearity ("intermodulation distortion") in the amplifier transistor between in-band components
- Assume a third-order nonlinear system:

$$v_{out}(t) = a + bv_{in}(t) + cv_{in}{}^{2}(t) + dv_{in}{}^{3}(t)$$

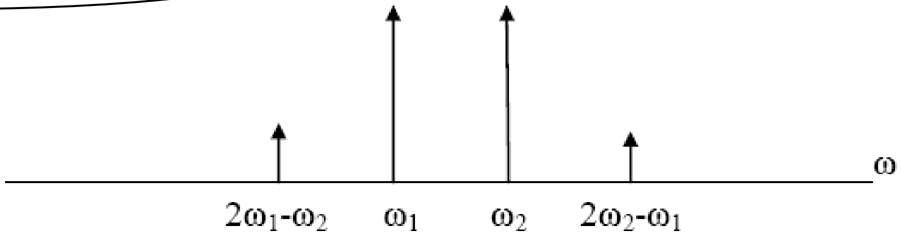
- Stimulate with a two-tone input signal:

$$v_{in}(t) = A\cos\omega_1 t + B\cos\omega_2 t$$

$$v_{out}(t) = a + b(A\cos\omega_1 t + B\cos\omega_2 t) + c(A^2\cos^2\omega_1 t + B^2\cos^2\omega_2 t + 2AB\cos\omega_1 t\cos\omega_2 t)^2 +$$

$$d(A^3\cos^3\omega_1 t + A^2B\cos^2\omega_1 t\cos\omega_2 t + AB^2\cos\omega_1 t\cos^2\omega_2 t + B^3\cos^3\omega_2 t)$$

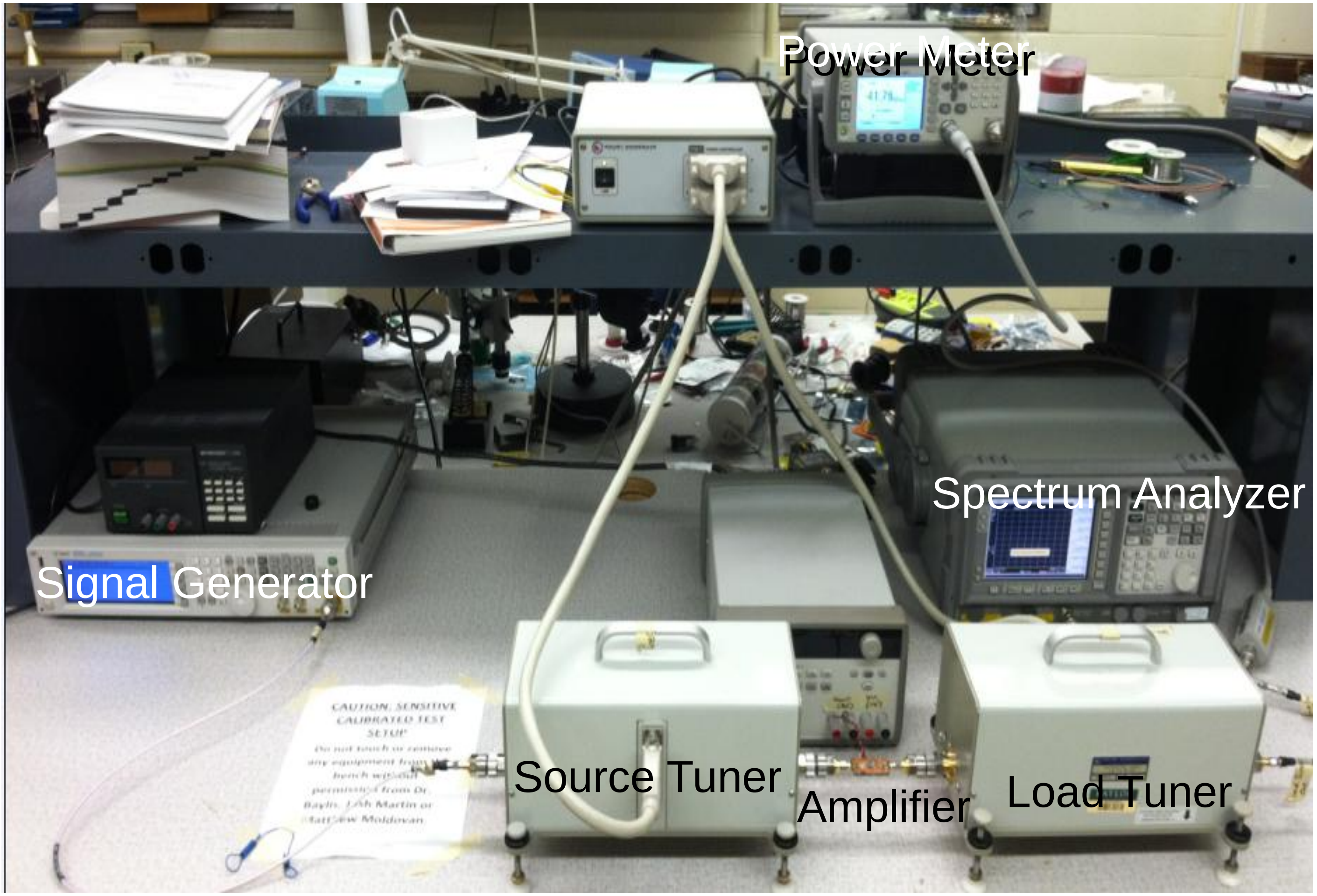
Third-Order Intermodulation Terms



# The Need:  Fast Pareto Search

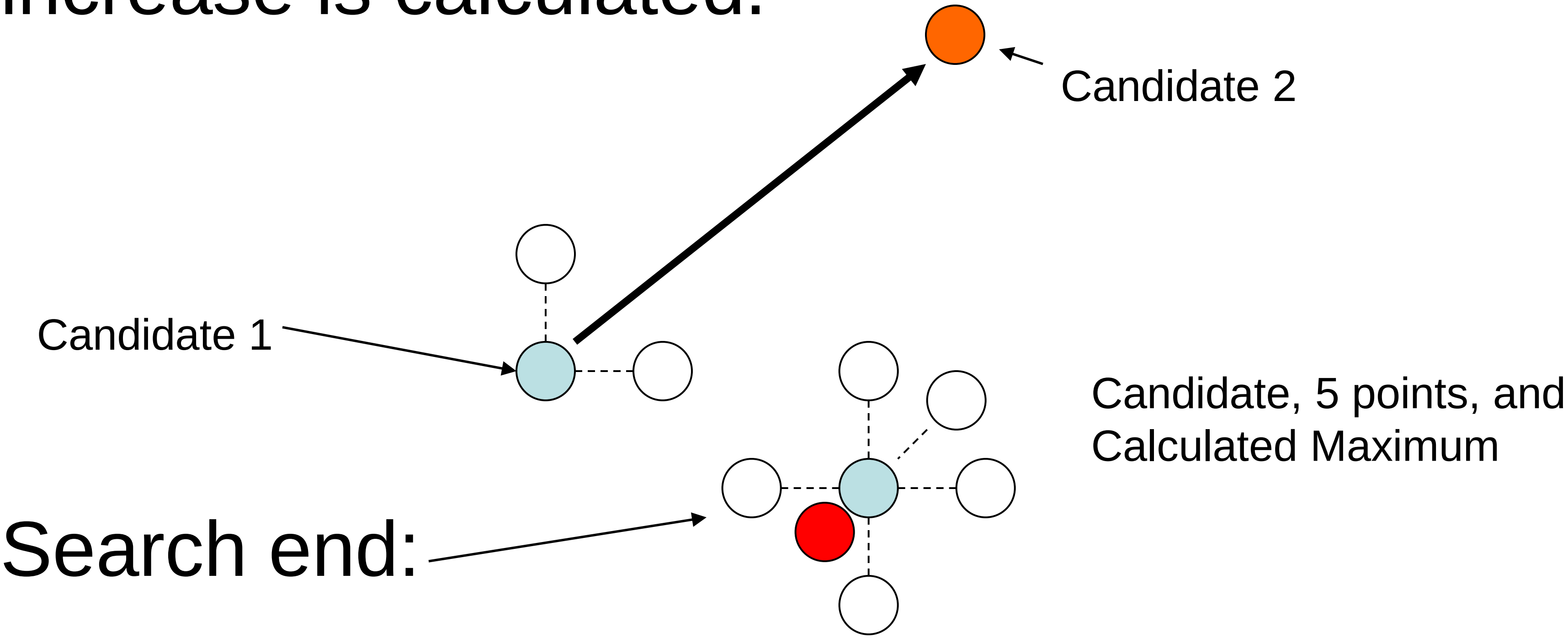
- Pareto search:  an optimization for two governing criteria (i.e. PAE and ACPR)
- The Pareto front is the “tradeoff curve” that connects the PAE and ACPR optimum points.
- Goal:  Maximize PAE while maintaining ACPR to meet spectral mask requirements.
- Applications:
  - Real-time radar reconfigurability
  - DSA cognitive radio platform
  - Faster bench-top measurements

# Baylor Optimization Test Platform



# Search Process

- During the search, neighboring points are measured and the direction of maximum increase is calculated.



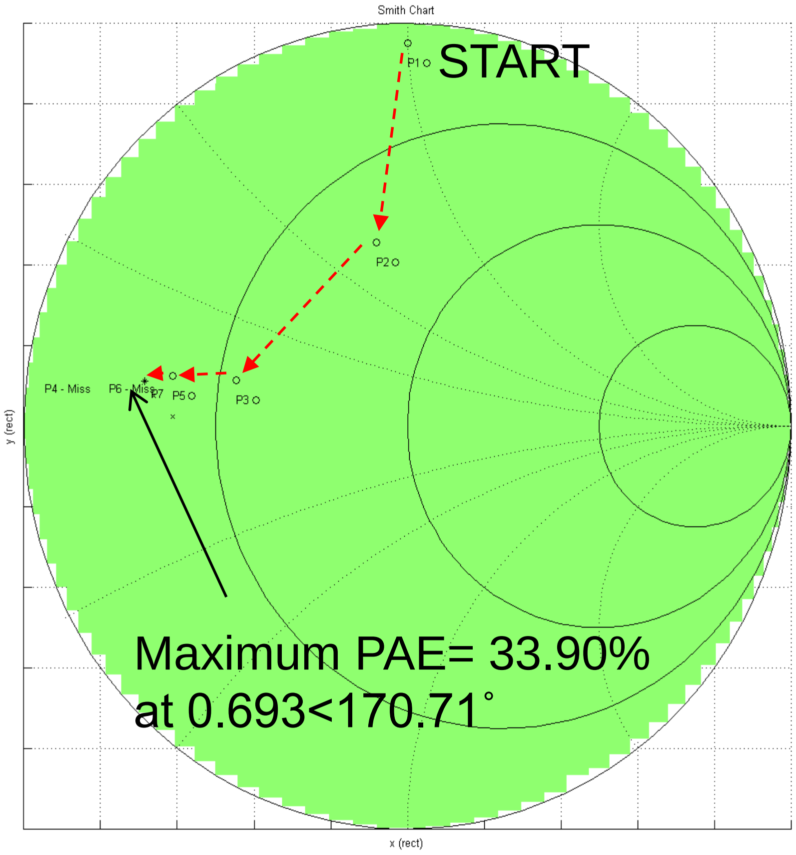
- Search end:

# Intelligent Search for PAE/ACPR

- Steepest ascent algorithm
- Maximum PAE found first.
- ACPR point found from another steepest ascent search starting at the maximum PAE location. A small step size is used.
- The ACPR search will be along the Pareto tradeoff line and can be stopped when ACPR is low enough.

# Agilent ADS/Modelithics Model Simulation Results

PAE Intelligent Algorithm

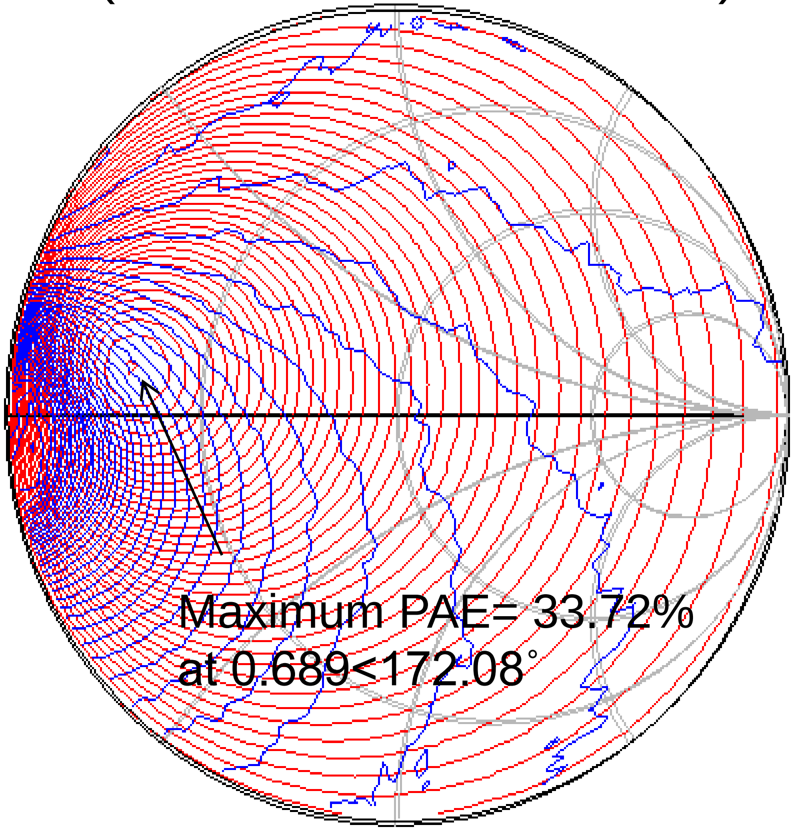


START

Maximum PAE= 33.90%
at 0.693<170.71°

18 measurements

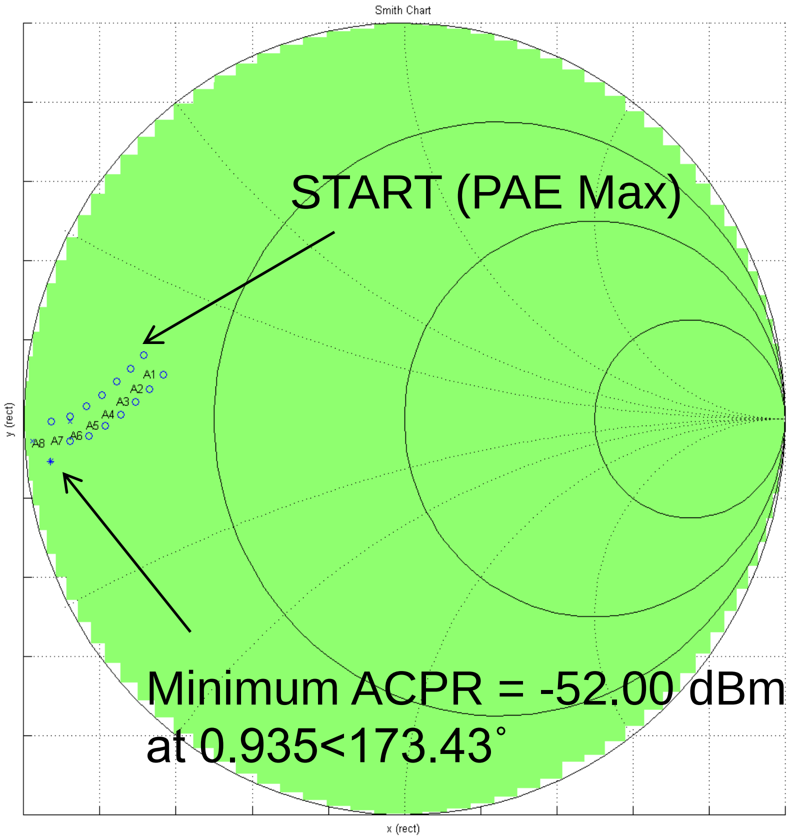
Standard Load-Pull:
(Red = PAE, Blue = ACPR)



Maximum PAE= 33.72%
at 0.689<172.08°

# Simulation Results

ACPR Intelligent Algorithm

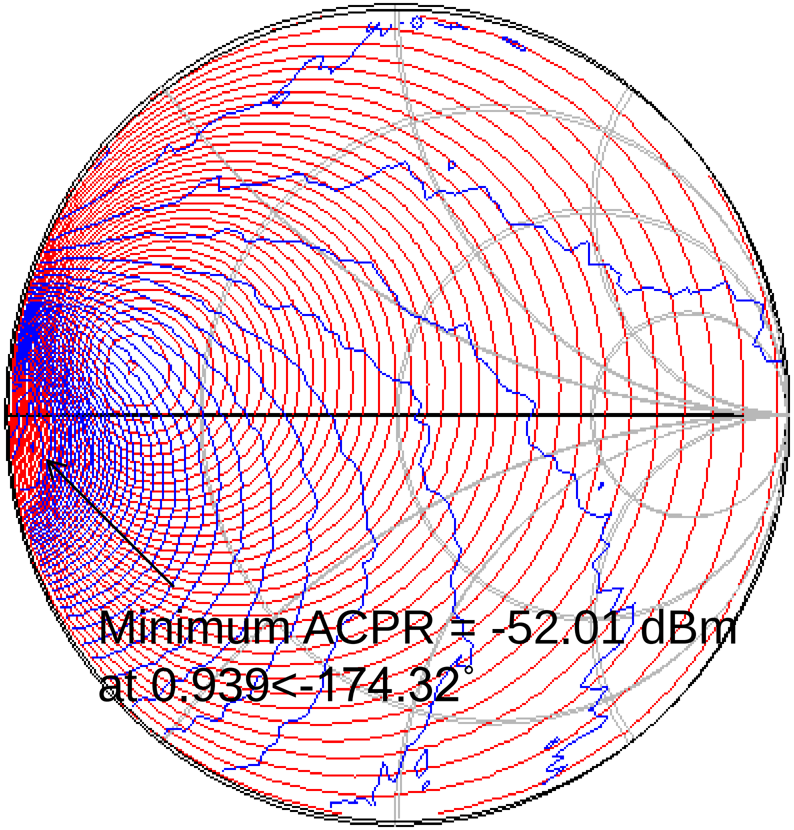


START (PAE Max)

Minimum ACPR = -52.00 dBm
at 0.935<173.43˚

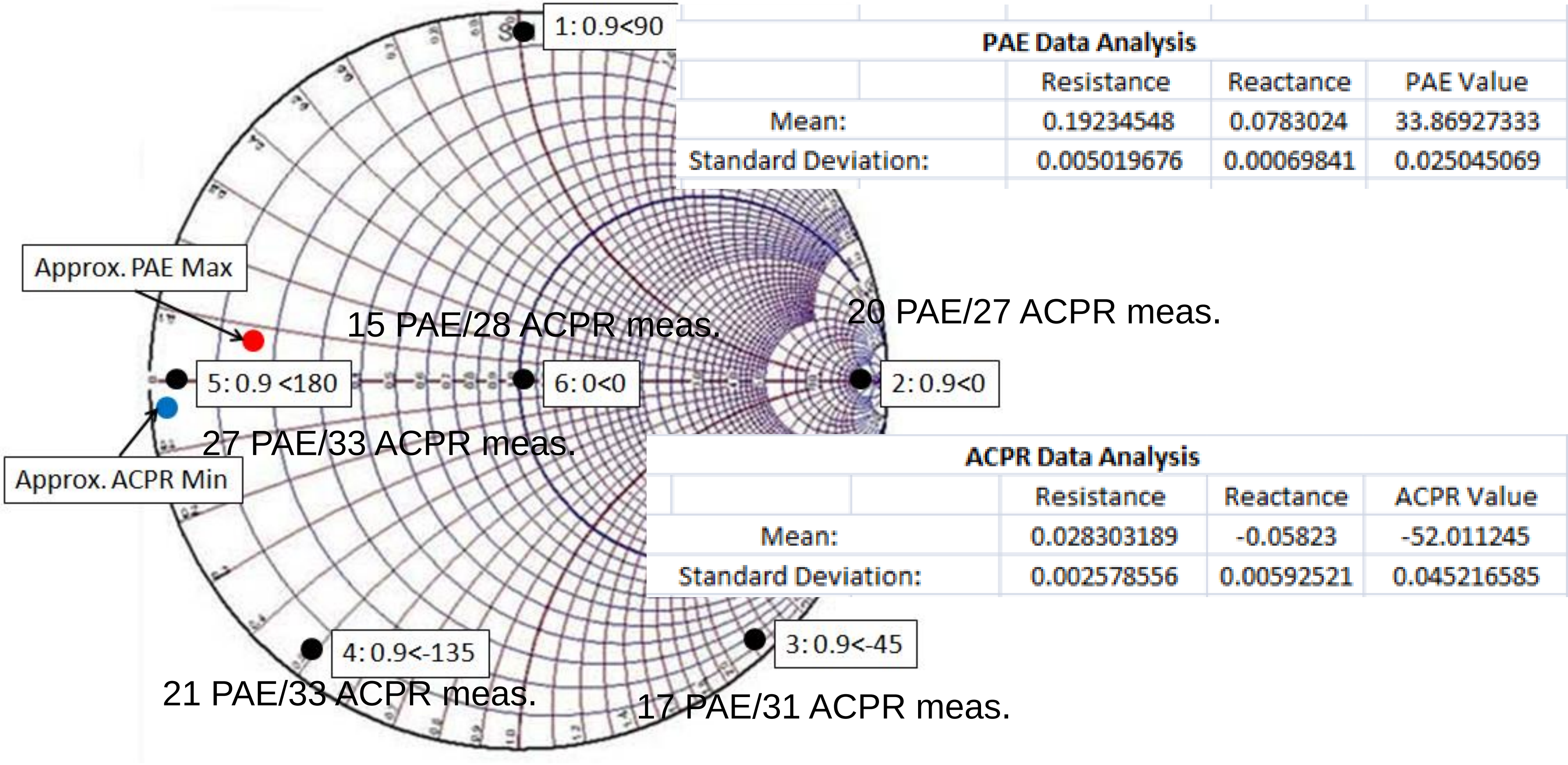
25 measurements

Standard Load-Pull:
(Red = PAE, Blue = ACPR)



Minimum ACPR = -52.01 dBm
at 0.939<-174.32˚

# Simulation: Multiple Starting Points



18 PAE/25 ACPR meas.

15 PAE/28 ACPR meas.

20 PAE/27 ACPR meas.

27 PAE/33 ACPR meas.

21 PAE/33 ACPR meas.

17 PAE/31 ACPR meas.

**PAE Data Analysis**

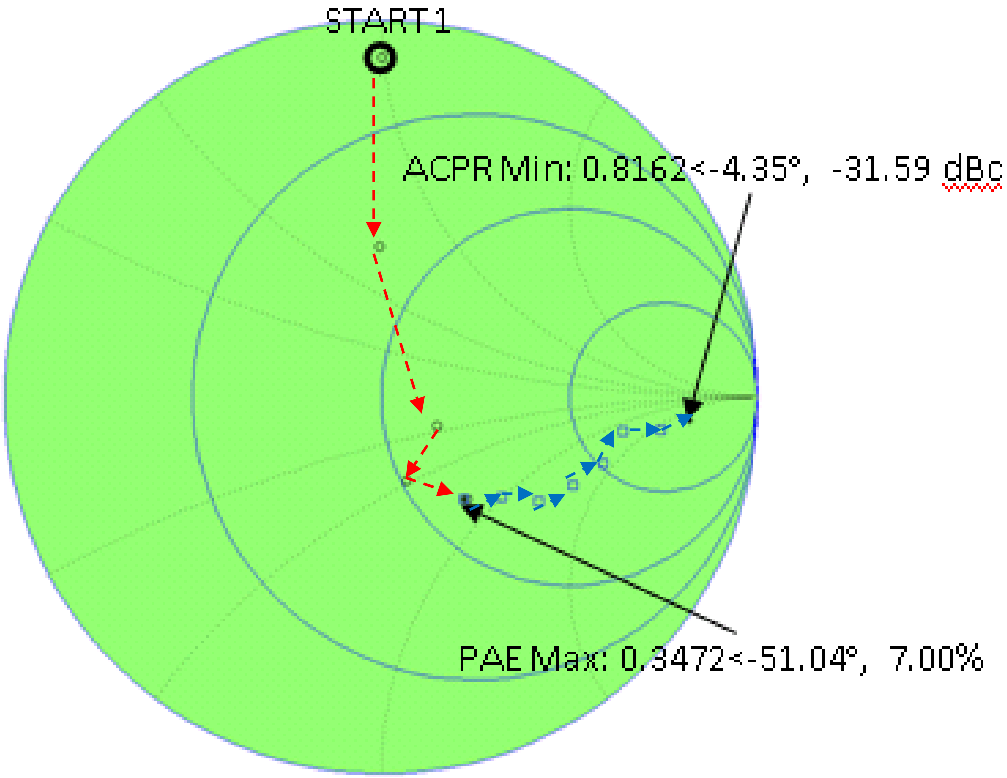
| | Resistance | Reactance | PAE Value |
|---|---|---|---|
| Mean: | 0.19234548 | 0.0783024 | 33.86927333 |
| Standard Deviation: | 0.005019676 | 0.00069841 | 0.025045069 |

**ACPR Data Analysis**

| | Resistance | Reactance | ACPR Value |
|---|---|---|---|
| Mean: | 0.028303189 | -0.05823 | -52.011245 |
| Standard Deviation: | 0.002578556 | 0.00592521 | 0.045216585 |

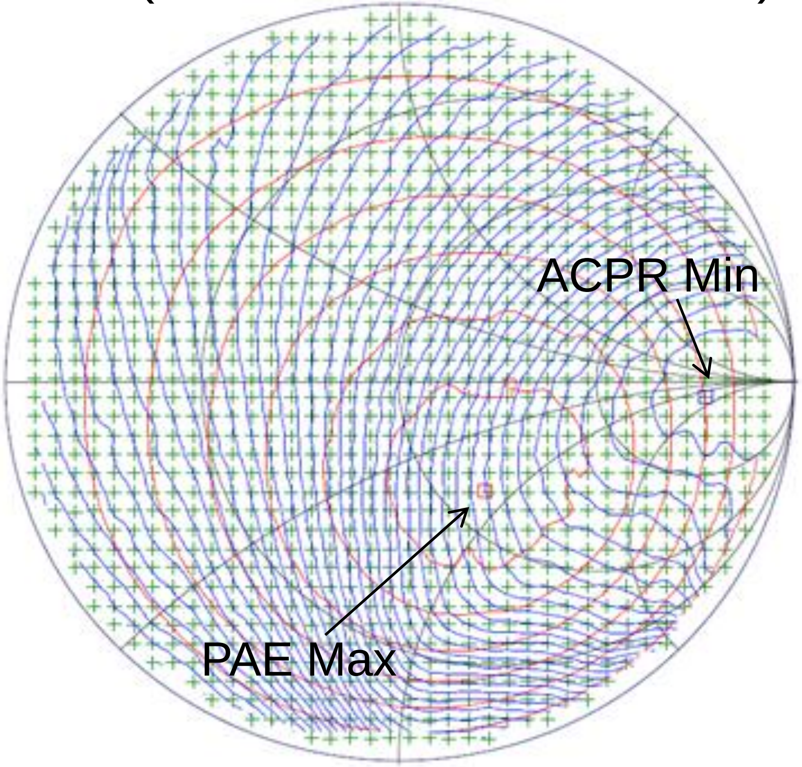
# Measurement Search

Intelligent Search



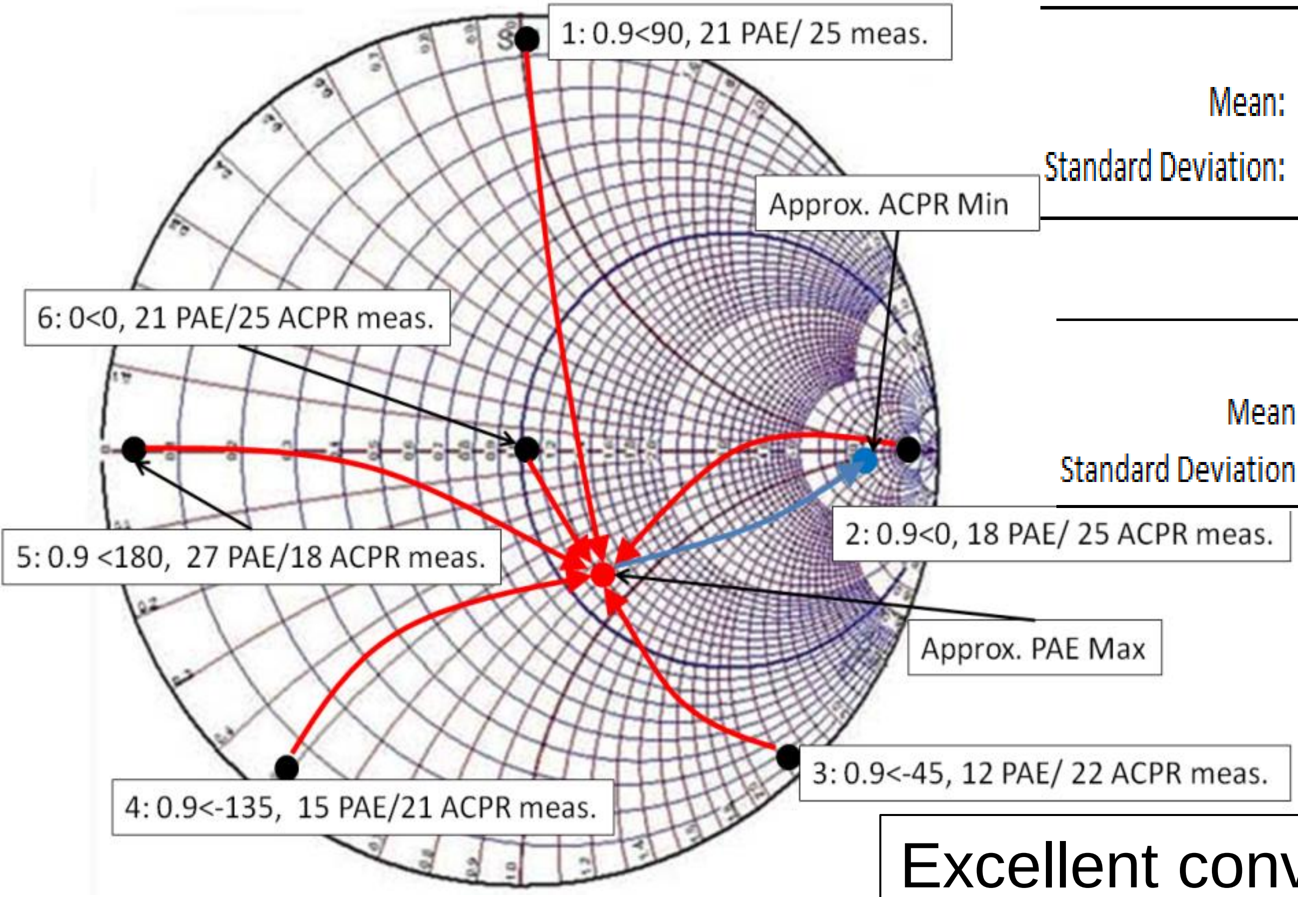
21 PAE/ 25 ACPR Measurements

Standard Load-Pull
(Red = PAE, Blue = ACPR)



1000 Measurements

# Measurement: Multiple Starting Points



**PAE Data Analysis**

| | Resistance | Reactance | PAE Value |
|---|---|---|---|
| Mean: | 1.361180063 | -0.7988641 | 6.971472167 |
| Standard Deviation: | 0.124145414 | 0.16150114 | 0.08574343 |

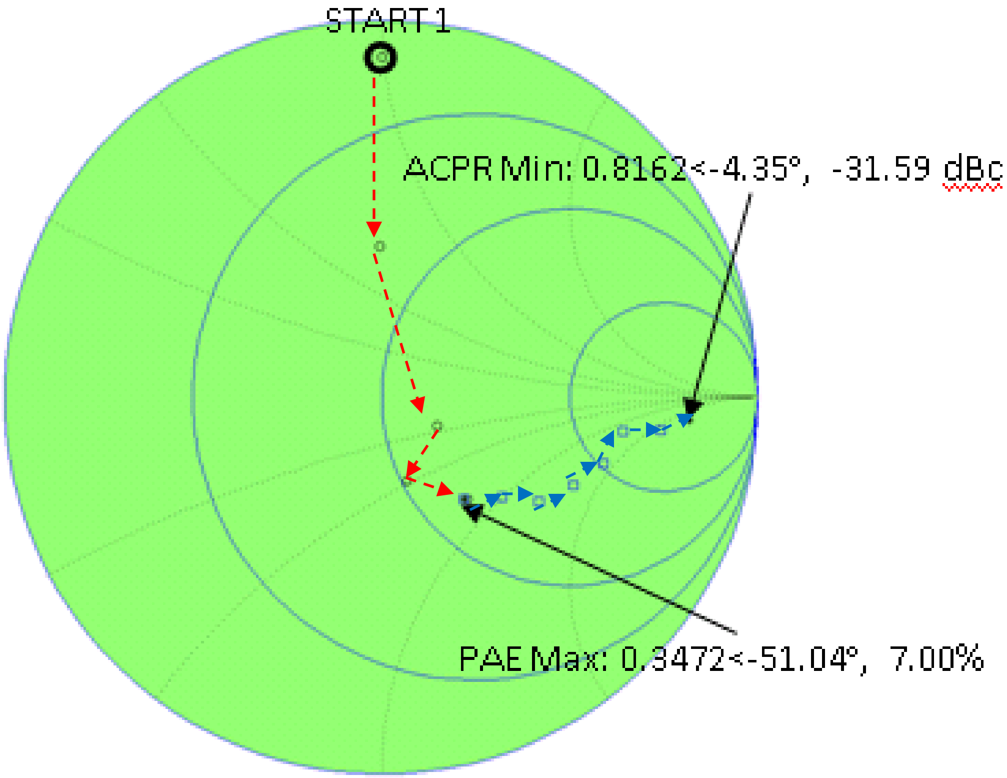
**ACPR Data Analysis**

| | Resistance | Reactance | ACPR Value |
|---|---|---|---|
| Mean: | 9.206037952 | -2.1641172 | -31.55460333 |
| Standard Deviation: | 2.915267993 | 2.32658164 | 0.078731224 |

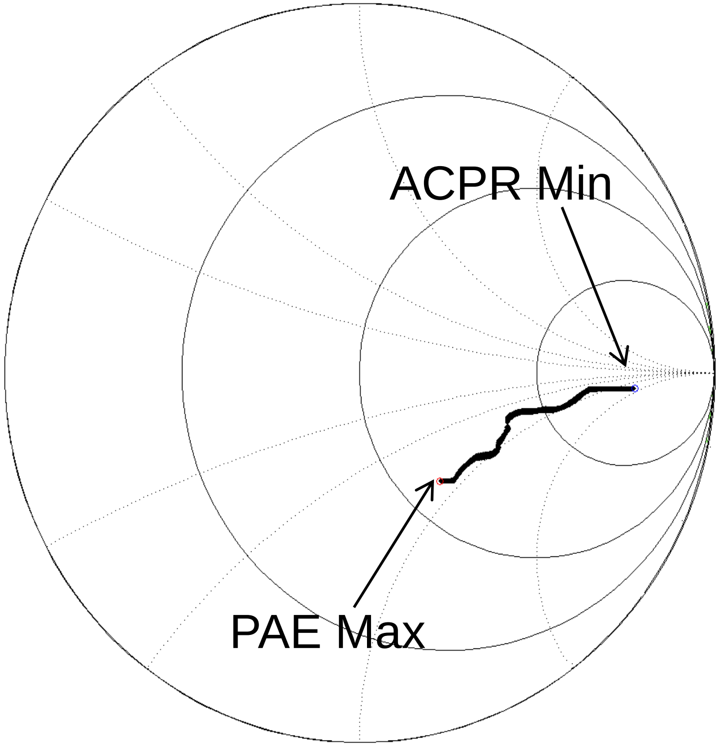
Excellent convergence agreement between all starting points

# Pareto Path Approximation

Intelligent Search



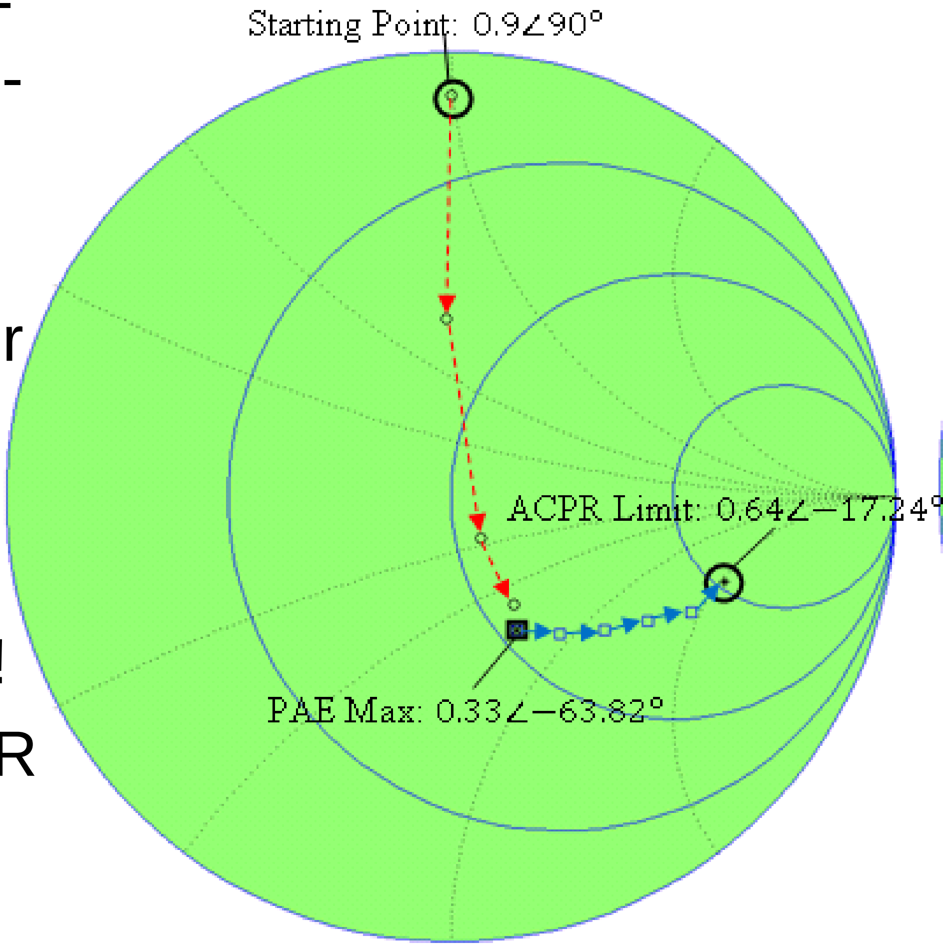
Pareto Line Plotted from Standard Load Pull



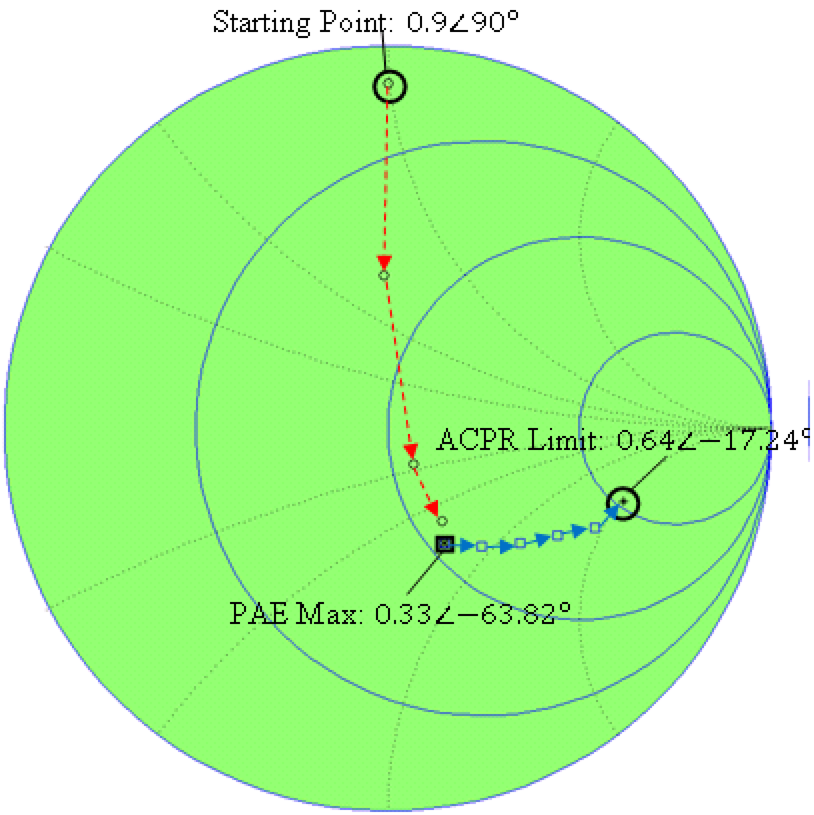
The steepest ascent reasonably estimates the Pareto front.

# ACPR Tolerance Measurement Search

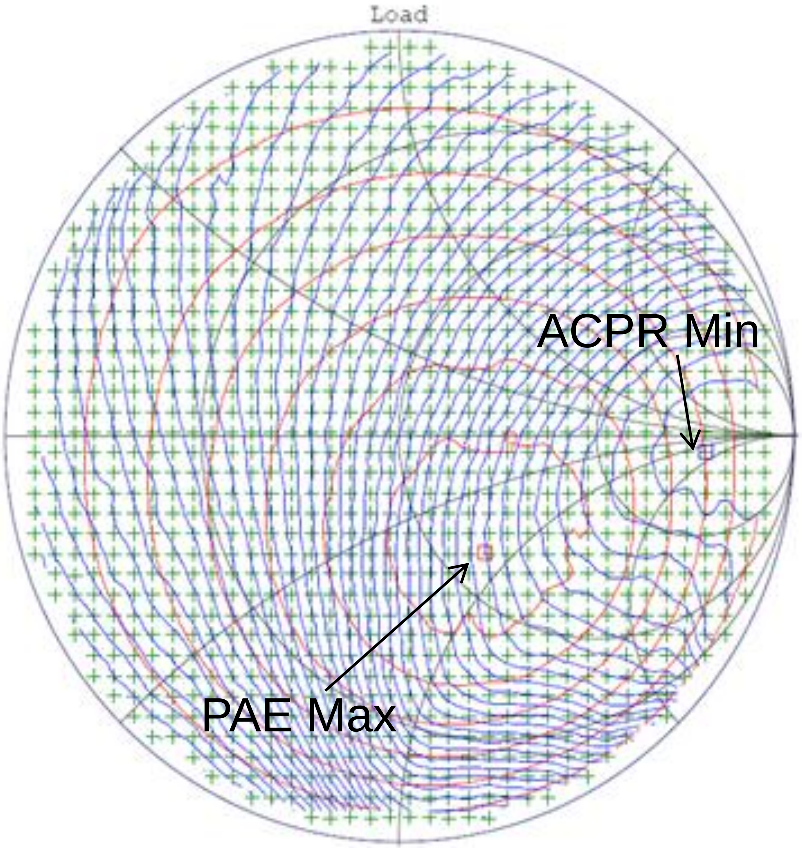
- Goal: Obtain the best power-added efficiency for ACPR < -29.4 dBc.
- Intelligent search process:
  - Steepest ascent search for PAE maximum (red).
  - Small-distance steepest-descent toward ACPR minimum (blue) → Pareto!
  - Stop once inside the ACPR tolerance.
- 21+16 = 37 measurements



# ACPR Tolerance Measurement Search



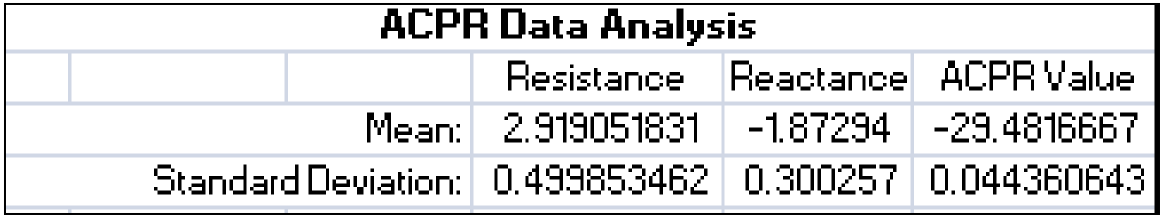
21 PAE/16 ACPR meas.



1000 meas.

# ACPR Tolerance Measurement: Multiple Starting Points

- End-point statistics:



**ACPR Data Analysis**

| | Resistance | Reactance | ACPR Value |
|---|---|---|---|
| Mean: | 2.919051831 | -1.87294 | -29.4816667 |
| Standard Deviation: | 0.499853462 | 0.300257 | 0.044360643 |

- All starting points converge to approximately the same point on the Smith chart.

# Conclusions

- For radar power amplifiers, the highest possible power efficiency should be obtained while meeting linearity requirements.
- A load-pull search optimizing PAE under ACPR requirements has been developed.
- Excellent correspondence has been obtained in both measurement and simulation with traditionally acquired load-pull queries.
- The work is broadly applicable to both real-time reconfigurable systems and bench-top laboratory measurements.

# Acknowledgments

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- Modelithics, for donation of the model libraries through the Modelithics University Program

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