Agilent Technologies

Maury Microwave

AMCAD Engineering
Advanced Modeling for Computer-Aided Design

Hybrid-Active Load Pull With PNA-X And Maury Microwave

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Your complete measurement & modeling solutions partner!

OUTLINE

– Background Info

– Vector-Receiver Load Pull

– Active and Hybrid-Active Load Pull

– X-Parameters and Active/Hybrid-Active Load Pull

– Pulsed-Bias Load Pull

– Conclusion

BACKGROUND INFO

```
# GHz    S       MA      R    50.00
!  FREQ       S11M          S11A     S21M         S21A      S12M        S12A      S22M        S22A
0.040000 1.157518E-01   -3.710 5.922372E+00   -5.243 6.274591E-04  -21.162 1.911442E-01  168.563
0.121200 1.266560E-01  -15.896 5.750123E+00  -15.489 1.689511E-04  138.045 2.034910E-01  164.212
0.202400 1.290937E-01  -41.697 5.694812E+00  -26.094 1.534801E-04  154.615 1.996204E-01  148.486
0.283600 1.067625E-01  -58.433 5.575610E+00  -35.371 2.154534E-04   68.351 1.841301E-01  136.932
0.364800 8.738539E-02  -68.825 5.682967E+00  -43.513 2.096765E-04   65.455 1.694200E-01  125.748
0.446000 8.056434E-02  -73.308 5.930343E+00  -53.585 5.399332E-04    5.607 1.544818E-01  116.827
0.527200 7.555955E-02  -80.844 6.136280E+00  -64.610 1.042182E-04  142.124 1.402974E-01  108.840
0.608400 7.497411E-02  -86.870 6.263798E+00  -77.026 3.081686E-04   71.327 1.230561E-01  102.798
0.689600 7.295863E-02  -93.382 6.136727E+00  -90.779 1.510877E-04  116.547 1.172368E-01  103.797
0.770800 7.386764E-02  -99.298 6.036165E+00 -101.499 3.284408E-04  129.861 1.095949E-01   92.296
0.852000 7.318650E-02 -105.194 5.848570E+00 -112.455 8.395422E-05   87.645 9.591621E-02   87.389
0.933200 7.235688E-02 -112.088 5.702302E+00 -121.464 1.231399E-04 -172.694 8.493296E-02   88.087
1.014400 7.233581E-02 -120.186 5.733521E+00 -129.912 1.999466E-04   52.778 7.911136E-02   89.575
1.095600 7.225432E-02 -127.552 5.892607E+00 -139.328 4.801104E-05   60.708 7.587810E-02   89.600
1.176800 7.313726E-02 -135.538 6.100566E+00 -149.979 3.209557E-04   16.738 6.707616E-02   97.937
1.258000 7.385175E-02 -143.046 6.240838E+00 -161.795 2.506652E-04   51.531 7.620265E-02  111.163
```

For a small-signal application, the S-Parameters can be measured by a Vector Network Analyzer (VNA), and the complex conjugates of S11 and S22 used to create input and output matching networks for maximum gain and power

Note: this only works for small-signal, DO NOT USE FOR POWER APPLICATIONS!

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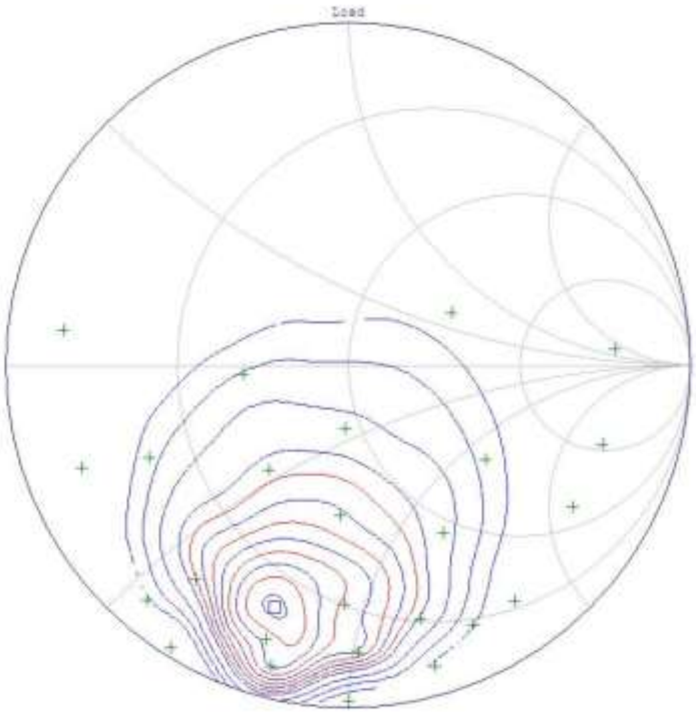
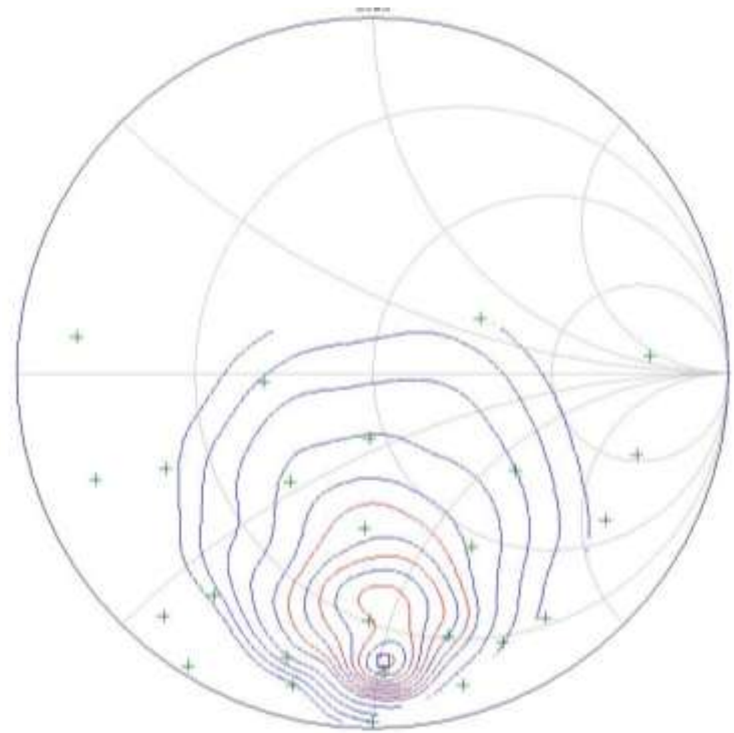
BACKGROUND INFO

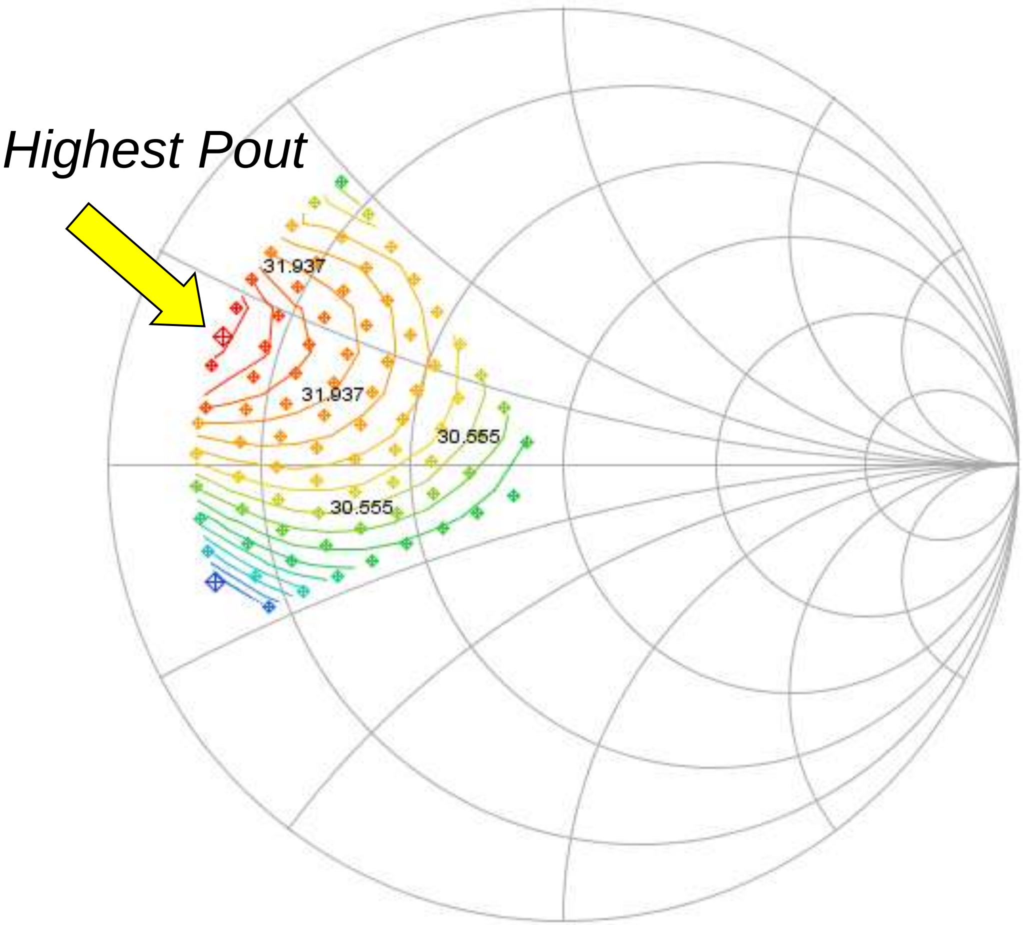




If small-signal s-parameters are used to determine the complex conjugate of S11 and S22 for a matching network, the output power, gain, efficiency… will not be at its maximum..

The above Smith Charts show the same impedance matching at different input power levels (small signal and large signal); note the large signal output power is down 3dB from its maximum (3dB = 50%!)

BACKGROUND INFO

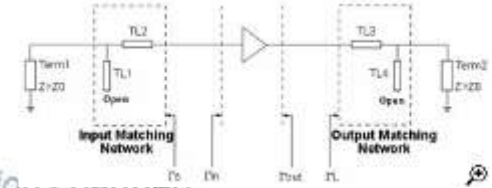


1) Vary impedance presented to DUT (active device, transistor)

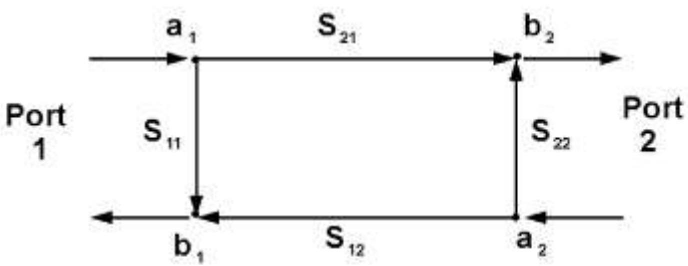
2) Measure Pout, Gain, Efficiency…

3) Determine best matching impedance

4) Design matching network (EEsof ADS)



BACKGROUND INFO

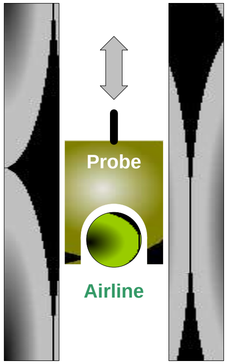


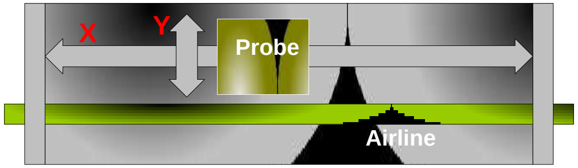
$$\Gamma_{x,n}(f_n) = \frac{a_{x,n}(f_n)}{b_{x,n}(f_n)}$$

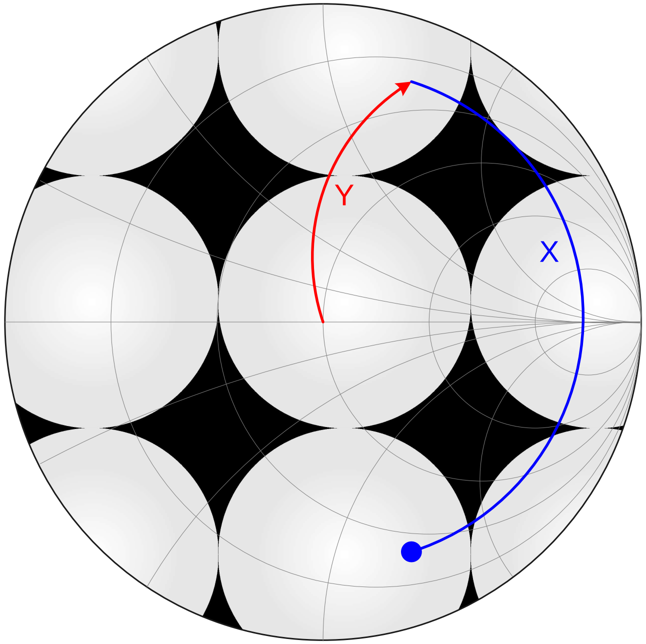
VSWR α Gamma α 1/Ω
10:1 VSWR = Γ=0.82 = 5Ω
20:1 VSWR = Γ=0.9 = 2.5Ω

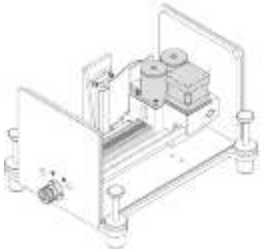
Γ = a/b

Mechanical Tuner
Gamma comes from probe (slug) inserted into airline









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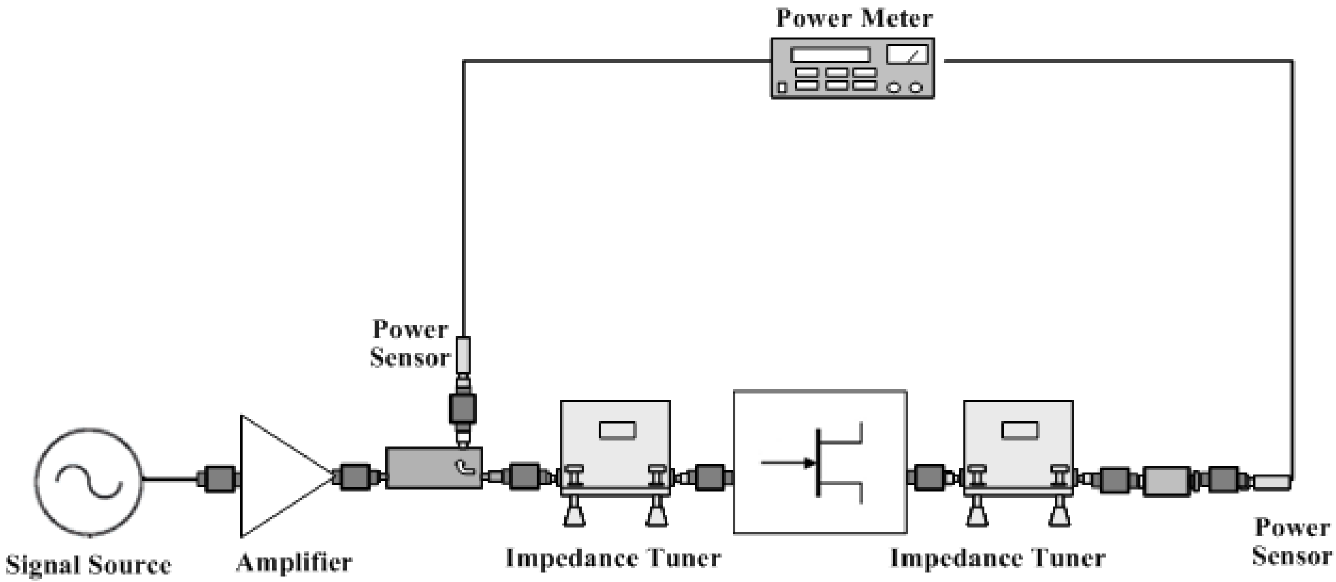
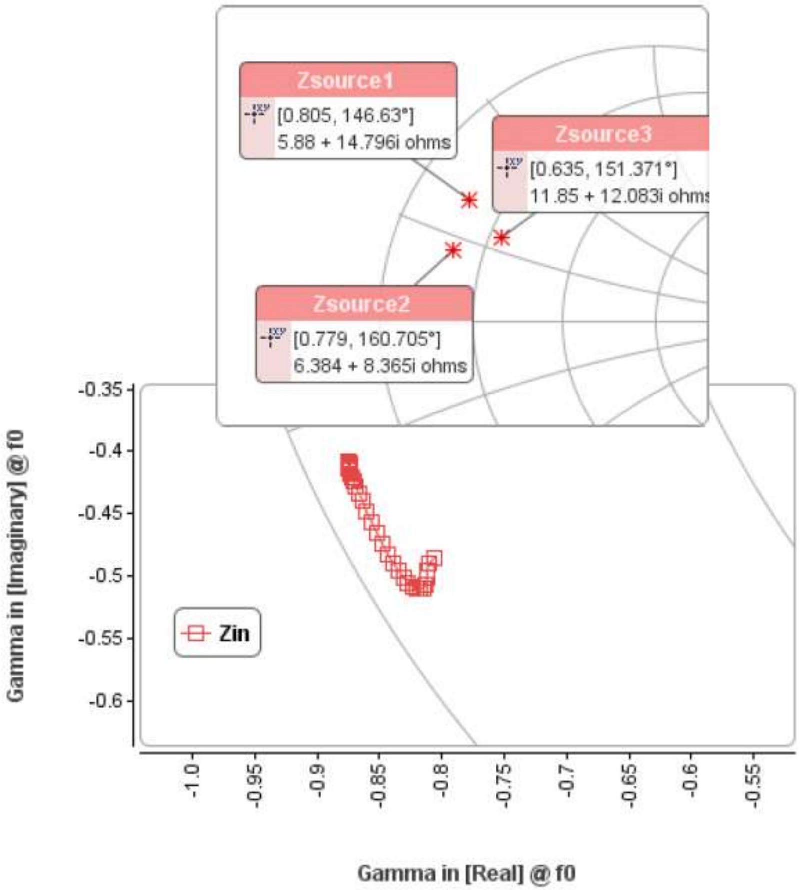


In **<u>Traditional Load Pull</u>**, delivered output power is calculated from Power Meter de-embedded through S-Parameter block and Impedance Tuner

<u>Available</u> input power is calculated from gain lookup table created during power calibration or from input Power Meter and then de-embedded through S-Parameter block and Impedance Tuner

BACKGROUND INFO

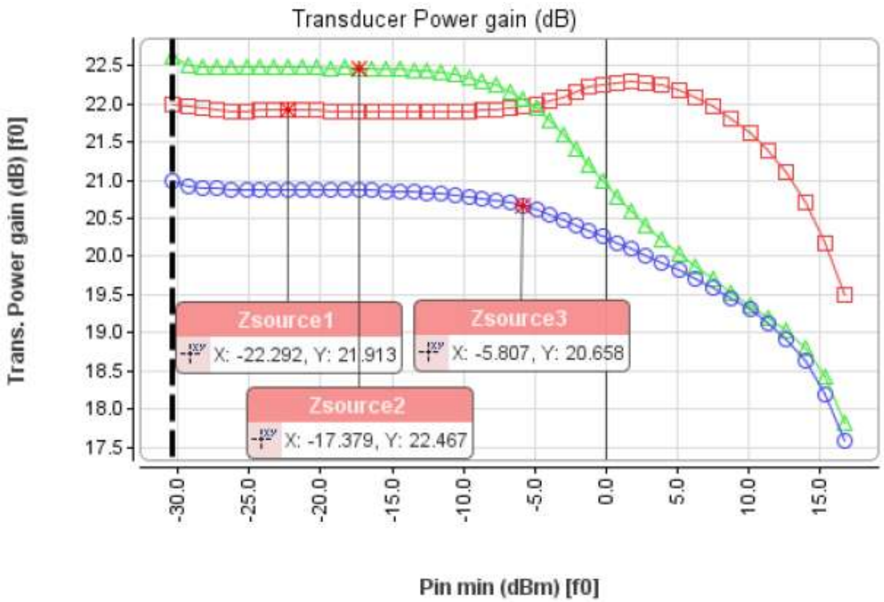


Large signal input impedance, Zin, changes as function of:

- Drive power
- Zload

Traditional load pull matches source impedance at single power, not taking into account varying Zin during power sweep

BACKGROUND INFO



Gain values look low because only Pin,available is used… reflected power due to mismatch is not taken into account

Traditional load pull only reports Transducer Gain

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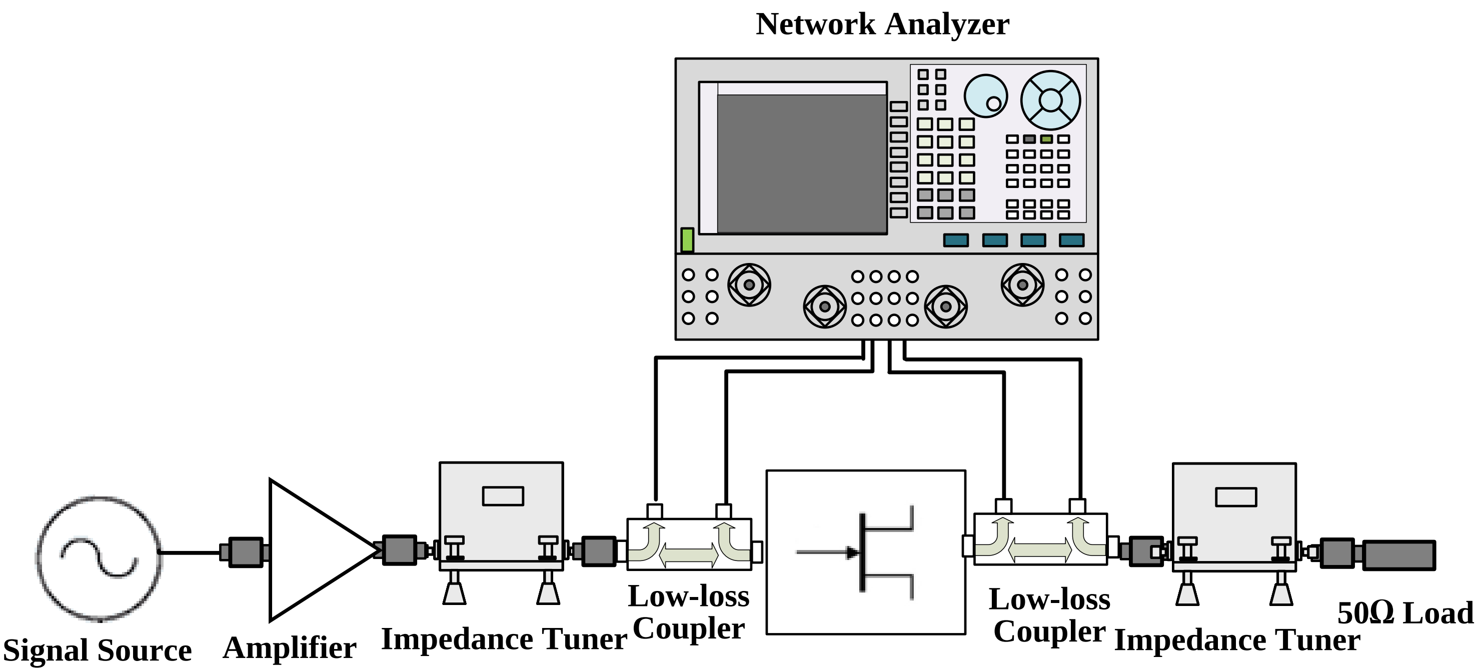
VECTOR-RECEIVER LOAD PULL



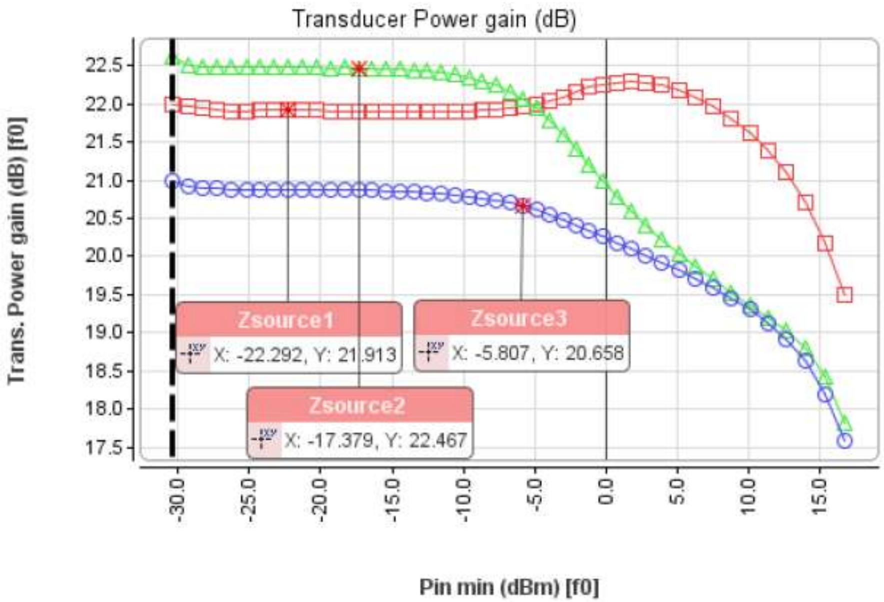
$$P_{out} = \frac{1}{2}\ |b_2|^2 - |a_2|^2 \ = \frac{1}{2}|b_2|^2 * \ 1 - |\Gamma_{load}|^2$$

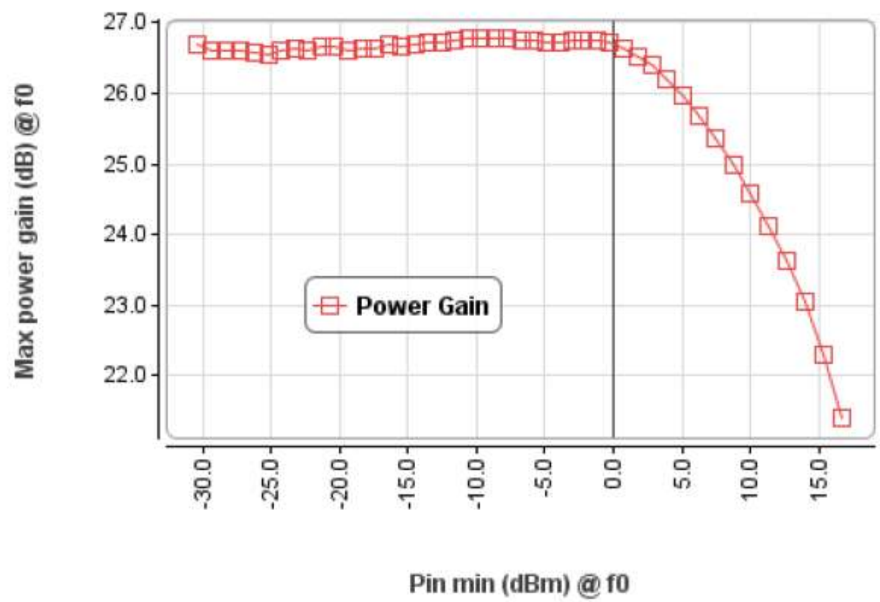
$$G_p = \frac{P_{out}}{P_{in,del}} = \frac{|b_2|^2 * \ 1 - |\Gamma_{load}|^2}{|a_1|^2 * \ 1 - |\Gamma_{in}|^2}$$

$$P_{in,del} = \frac{1}{2}\ |a_1|^2 - |b_1|^2 \ = \frac{1}{2}|a_1|^2 * \ 1 - |\Gamma_{in}|^2$$

$$PAE = \frac{P_{out} - P_{in,del}}{P_{DC}}$$

VECTOR-RECEIVER LOAD PULL



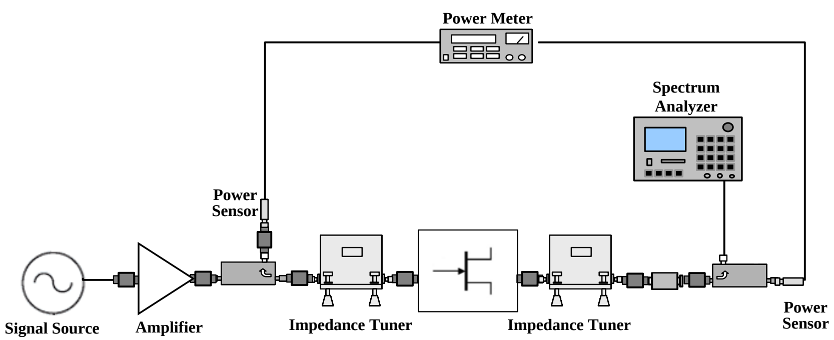


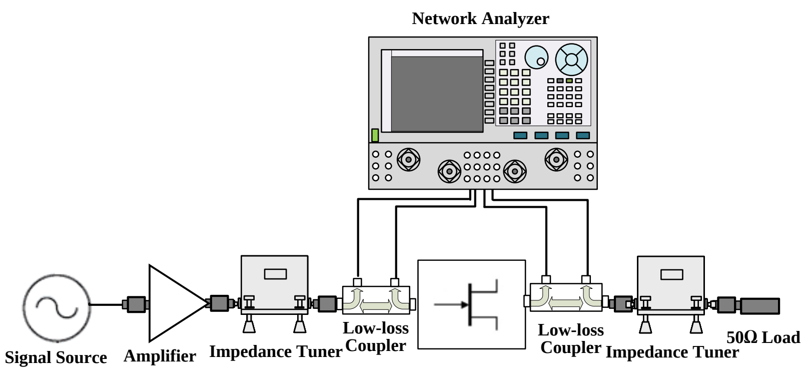
Gain values look low because only Pin,available is used… reflected power due to mismatch is not taken into account

Knowing Zin allows us to calculate Power Gain, taking into account mismatch thereby showing true gain potential of device

VECTOR-RECEIVER LOAD PULL

	Traditional LP	Vector Receiver LP
Pre-Characterization	Required	Recommended (not required)
Number of Points	More points = greater accuracy (even with interpolation)	Minimum points required (no impact on accuracy)
Tuner De-embedding	Critical! (Accuracy relies on de-embedding)	No tuner de-embedding





VECTOR-RECEIVER LOAD PULL

	Traditional LP	Vector Receiver LP
Verification Procedure	ΔG_t complex conjugate matched verification	**Zin vs. Zload comparison** ΔG_t complex conjugate matched verification

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VECTOR-RECEIVER LOAD PULL

Measurement Parameter	Traditional Load Pull	Vector-Receiver Load Pull
Input Reflection Coefficient (Z_{in})	✗	✓
Available Input Power ($P_{in,avail}$)	✓	✓
Delivered Input Power ($P_{in,del}$)	✗	✓
Output Power (P_{out})	✓	✓
Power Gain (G_p)	✗	✓
Transducer Gain (G_t)	✓	✓
Power Added Efficiency (PAE)	✗	✓
Efficiency (Eff)	✓	✓
AM/PM	✗	✓
Calibrated Harmonic Power	Spectrum analyzer required	✓
Multi-tone Measurements	Spectrum analyzer required	✓
Modulated Measurements	Spectrum analyzer required	✗
Power Sweep Speed (for 25 power levels)	~20 seconds	~1 second

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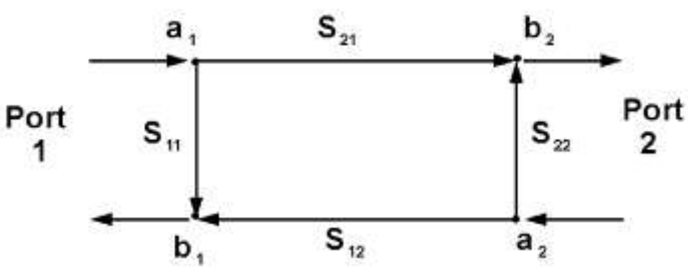
ACTIVE & HYBRID-ACTIVE LOAD PULL



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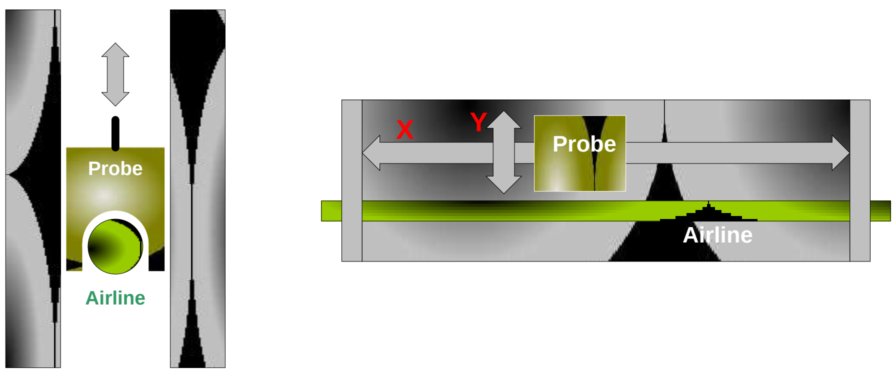
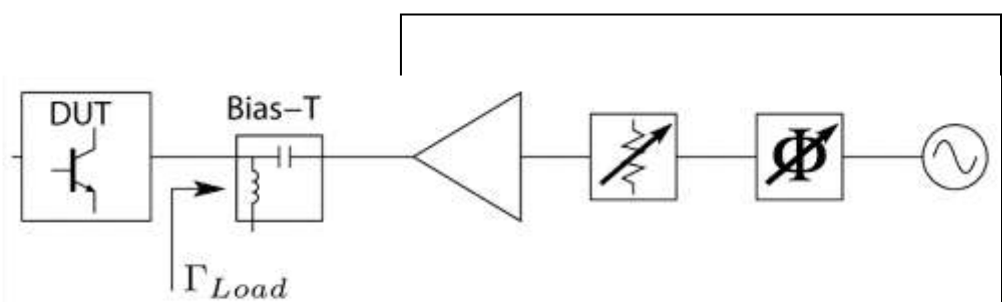
Γ = a/b



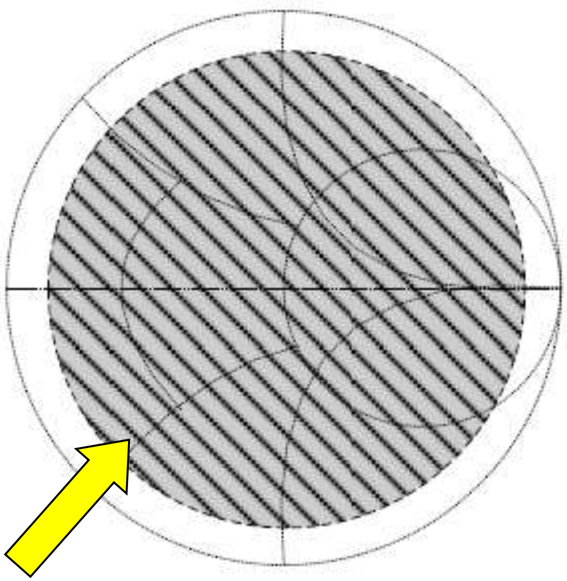
Mechanical Tuner
Gamma comes from probe (slug) inserted into airline
Γ<1



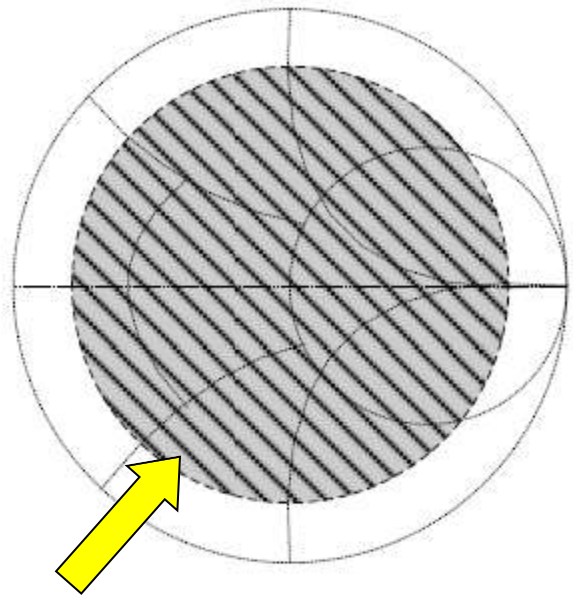
Active Tuner
Gamma comes from signal generator and amplifier
Γ=1 or Γ>1

ACTIVE & HYBRID-ACTIVE LOAD PULL

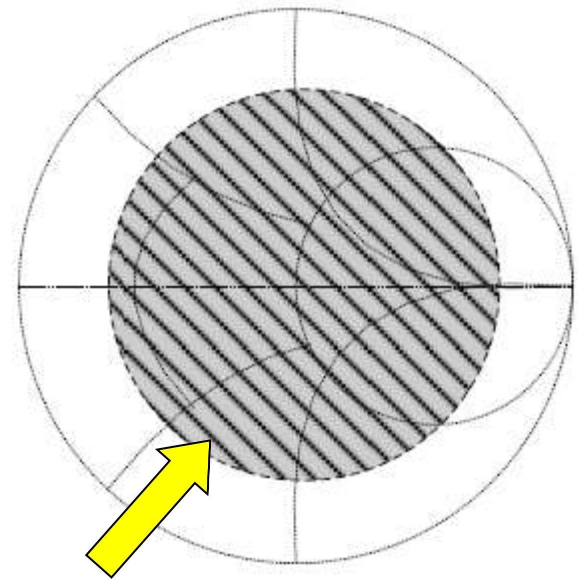
Maximum Tuning Range *(exaggerated for effect)*



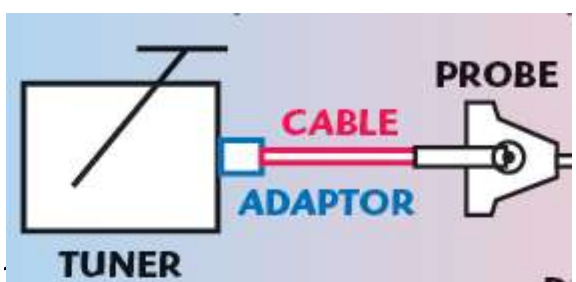
Tuner



Tuner + Cable



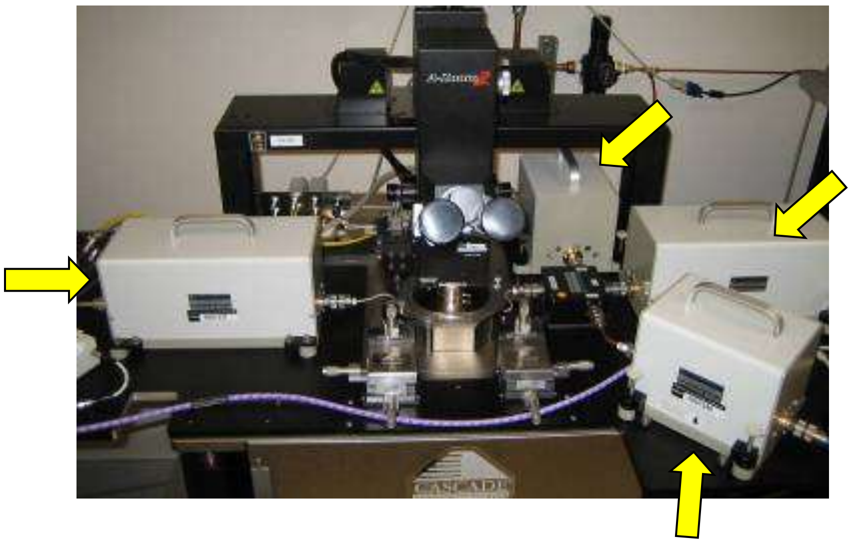
Tuner + Cable + Probe



Losses of cables, probes, test fixtures reduces tuning range and <u>*cannot*</u> be overcome using traditional load pull methods

ACTIVE & HYBRID-ACTIVE LOAD PULL

External Tuners

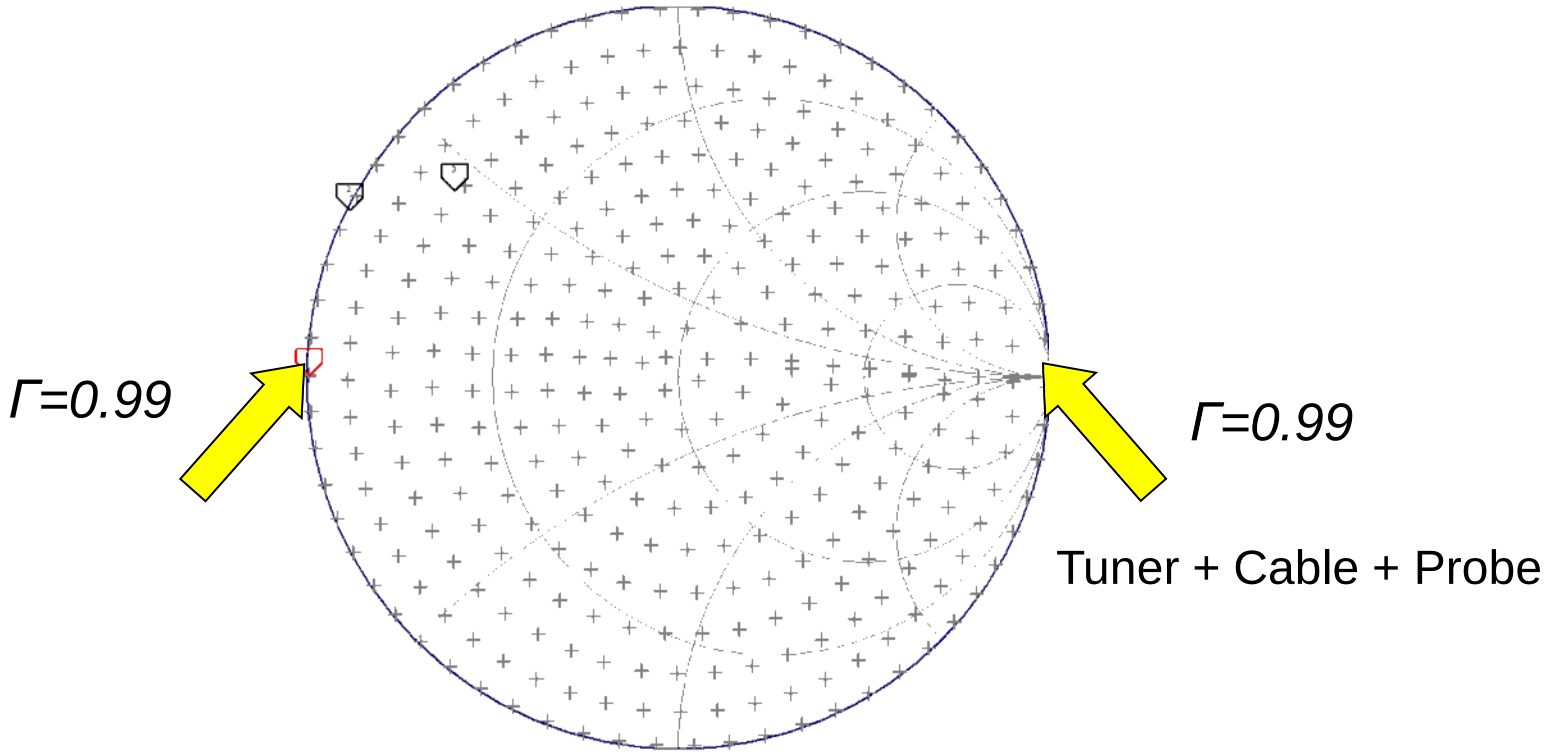


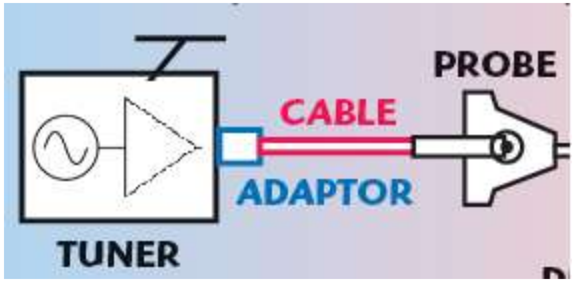
For Harmonic Load Pull, Traditional Load Pull systems require one mechanical tuner per frequency per DUT side

To tune Fo, 2Fo and 3Fo at the same time requires <u>3 tuners</u> (using multiplexer or cascaded methods)

It is possible to build 3 tuners in 1 box, but it becomes 2-3x longer and 2-3x more expensive

ACTIVE & HYBRID-ACTIVE LOAD PULL

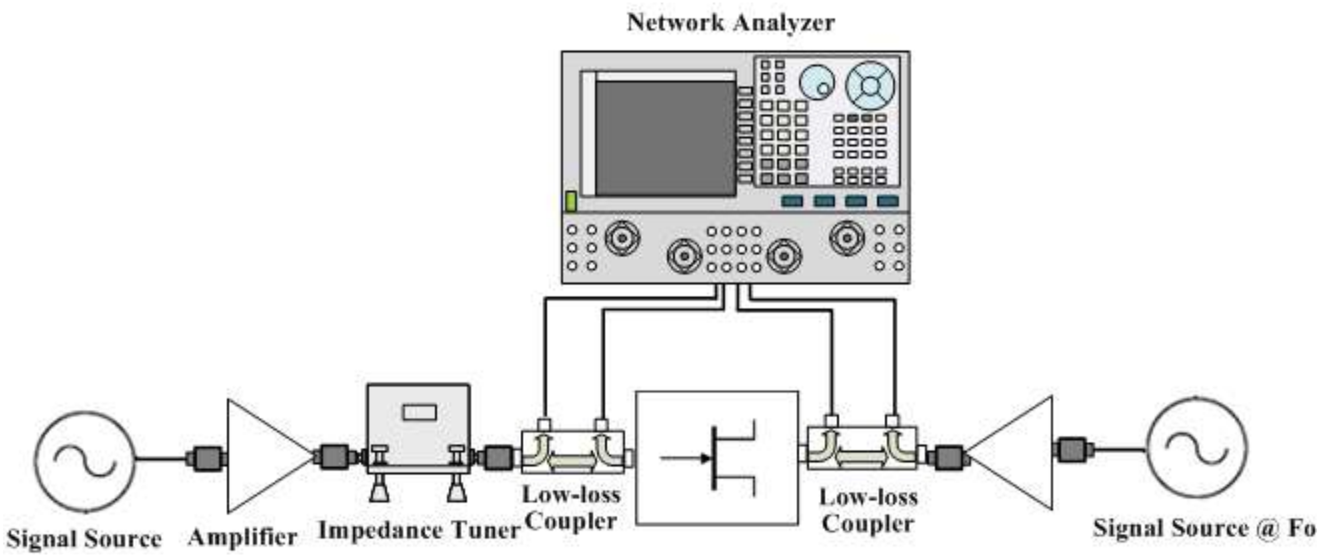




Gamma advantage of Active Load Pull → Losses of cables, probes, test fixtures reduces tuning range, *and can be overcome* using larger amplifiers

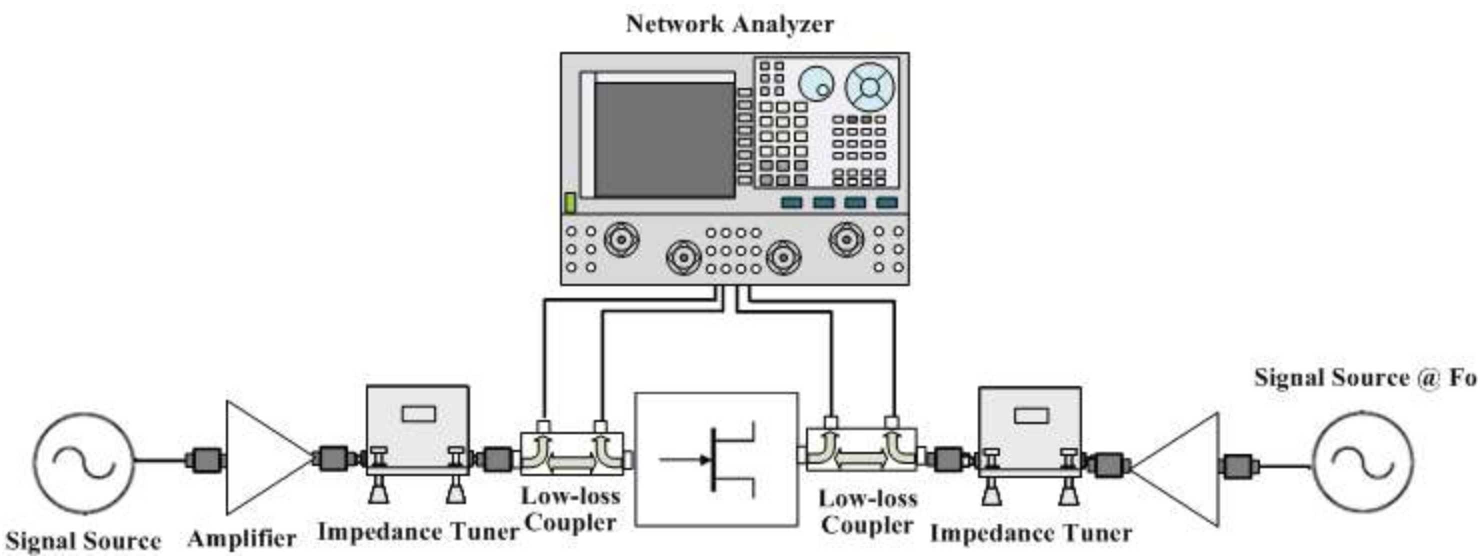
ACTIVE & HYBRID-ACTIVE LOAD PULL

Active Fo Load Pull



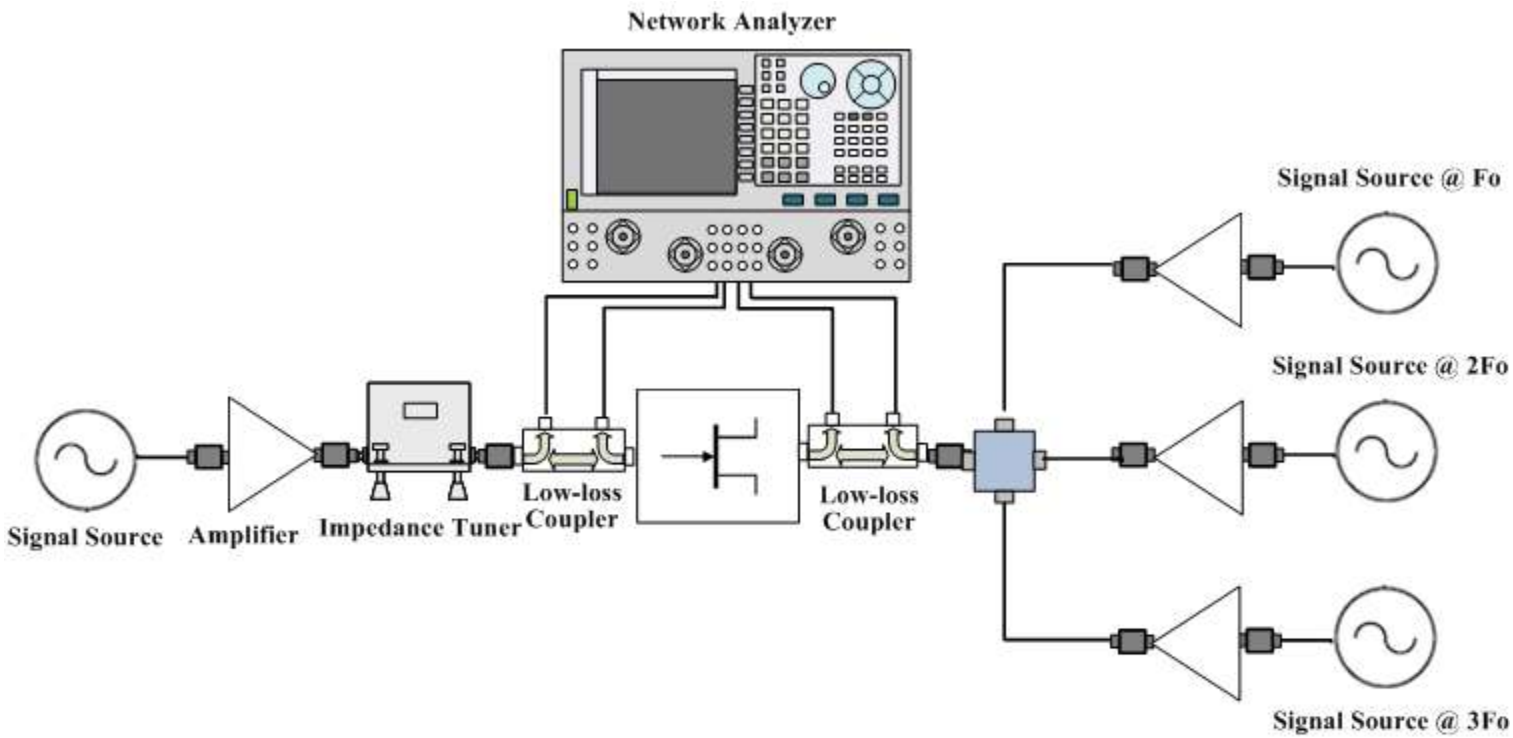
ACTIVE & HYBRID-ACTIVE LOAD PULL

Hybrid-Active Fo Load Pull



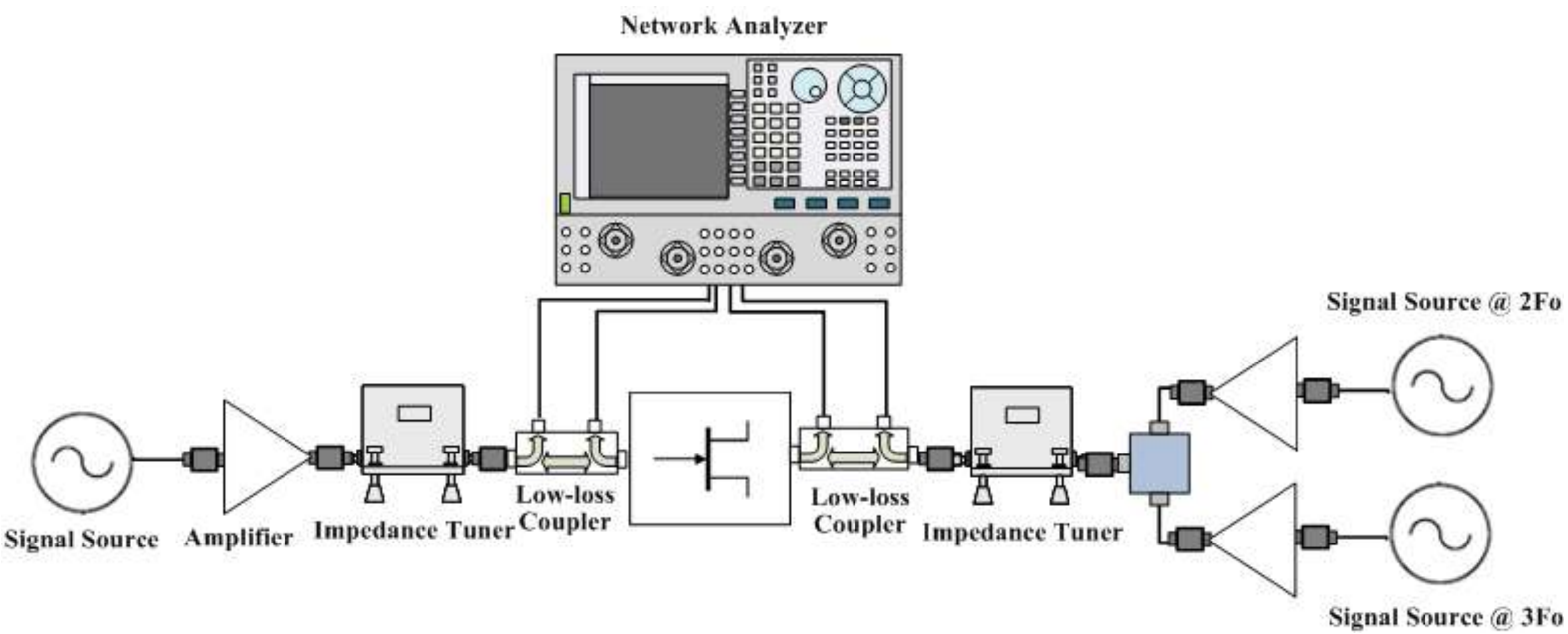
ACTIVE & HYBRID-ACTIVE LOAD PULL

Active Fo, 2Fo, 3Fo Load Pull



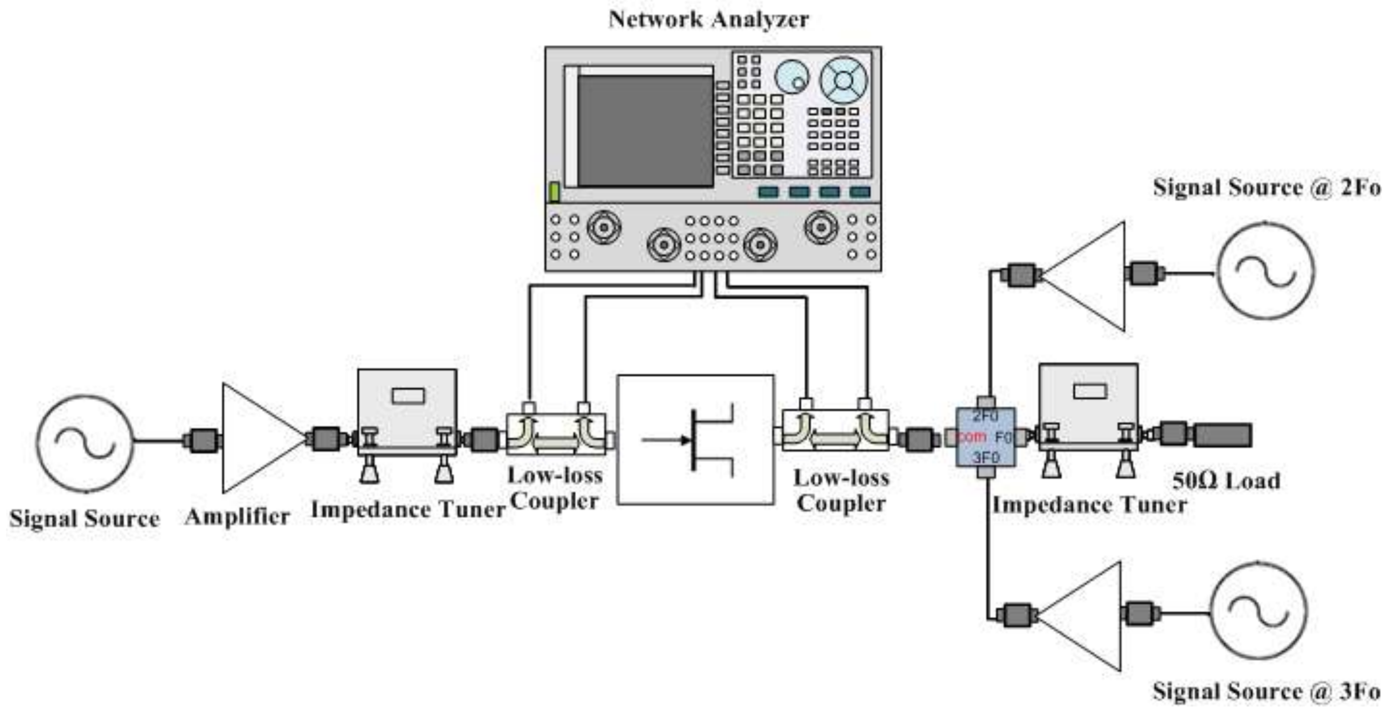
ACTIVE & HYBRID-ACTIVE LOAD PULL

Hybrid Active Fo, 2Fo, 3Fo Load Pull



ACTIVE & HYBRID-ACTIVE LOAD PULL

Hybrid Active Fo, 2Fo, 3Fo Load Pull



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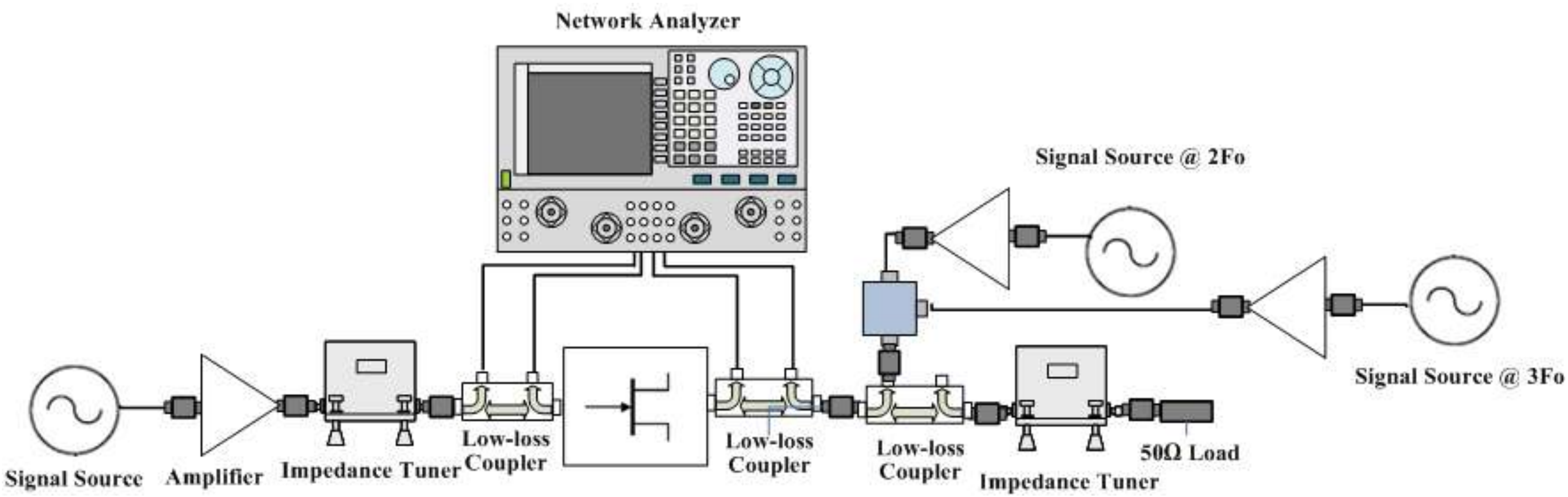
ACTIVE & HYBRID-ACTIVE LOAD PULL

Hybrid Active Fo, 2Fo, 3Fo Load Pull



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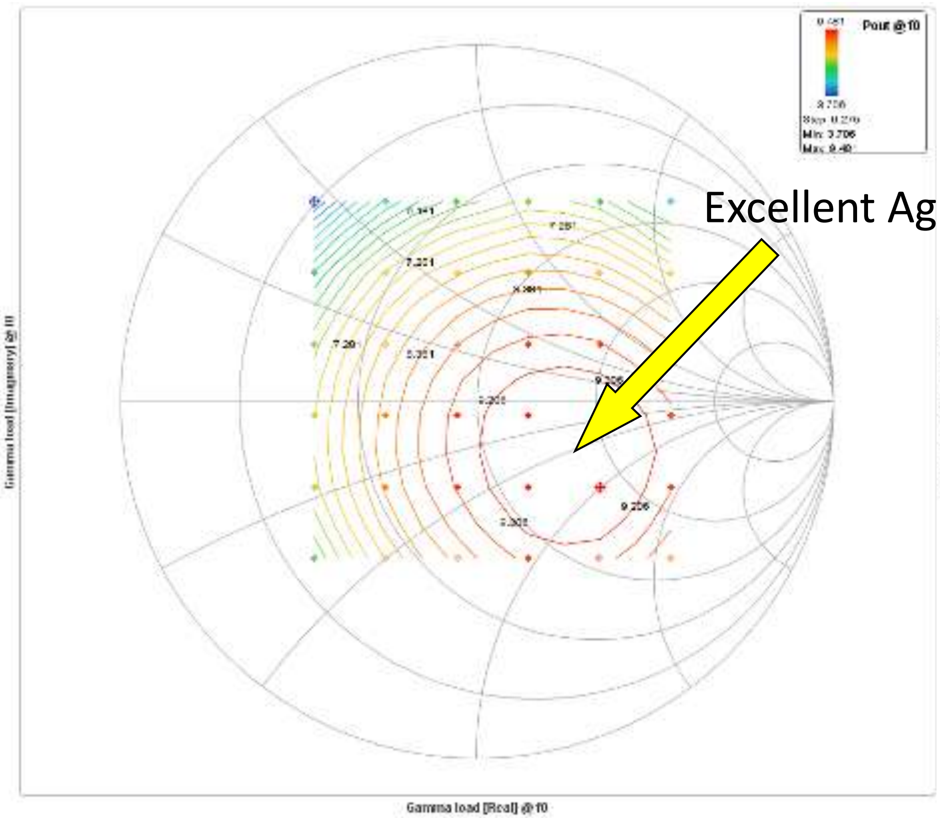
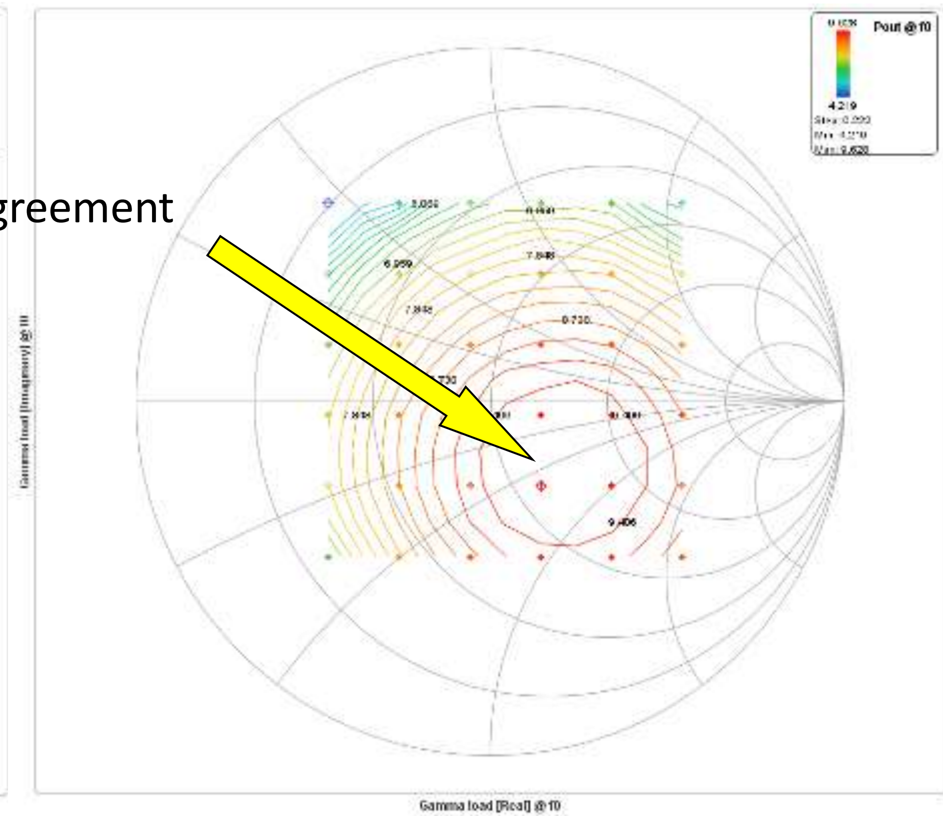
ACTIVE & HYBRID-ACTIVE LOAD PULL

Measured Data – Passive VS Active

Excellent Agreement



Traditional Load Pull



Active Load Pull

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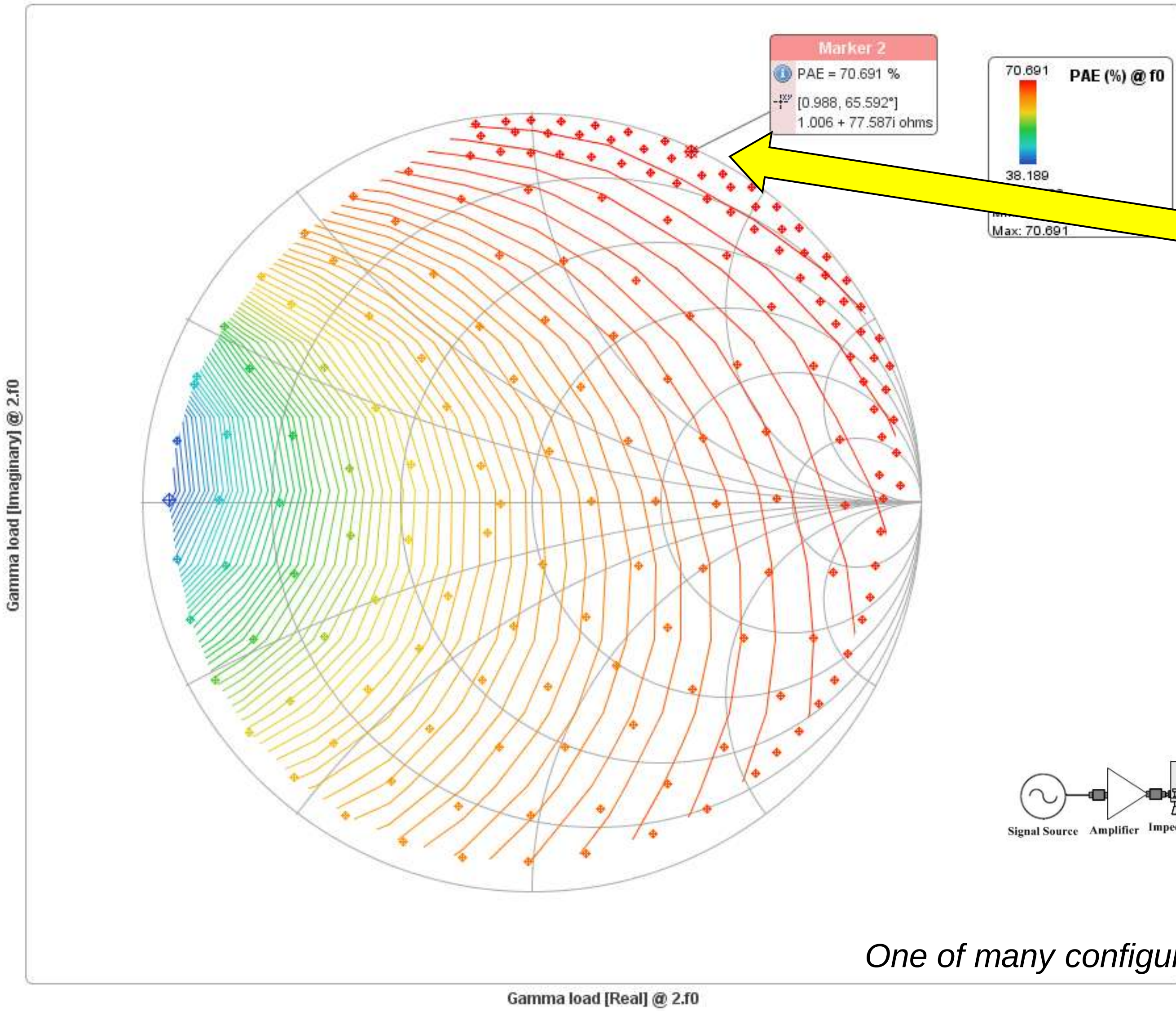
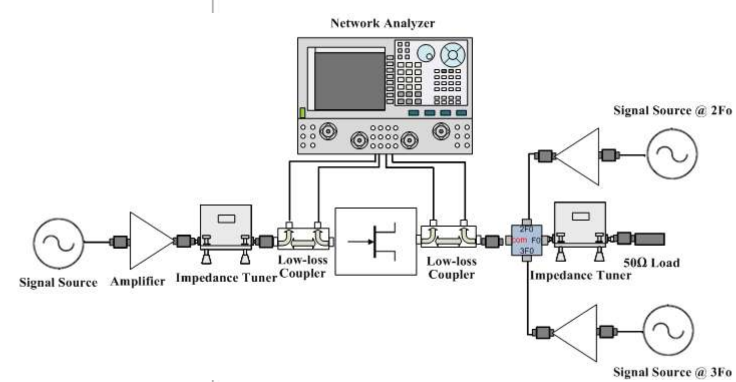
ACTIVE & HYBRID-ACTIVE LOAD PULL



Passive Fo

Active 2Fo, 3Fo

Γ_{2Fo}=0.988 @ DUT on-wafer!



One of many configurations of hybrid/active load pull

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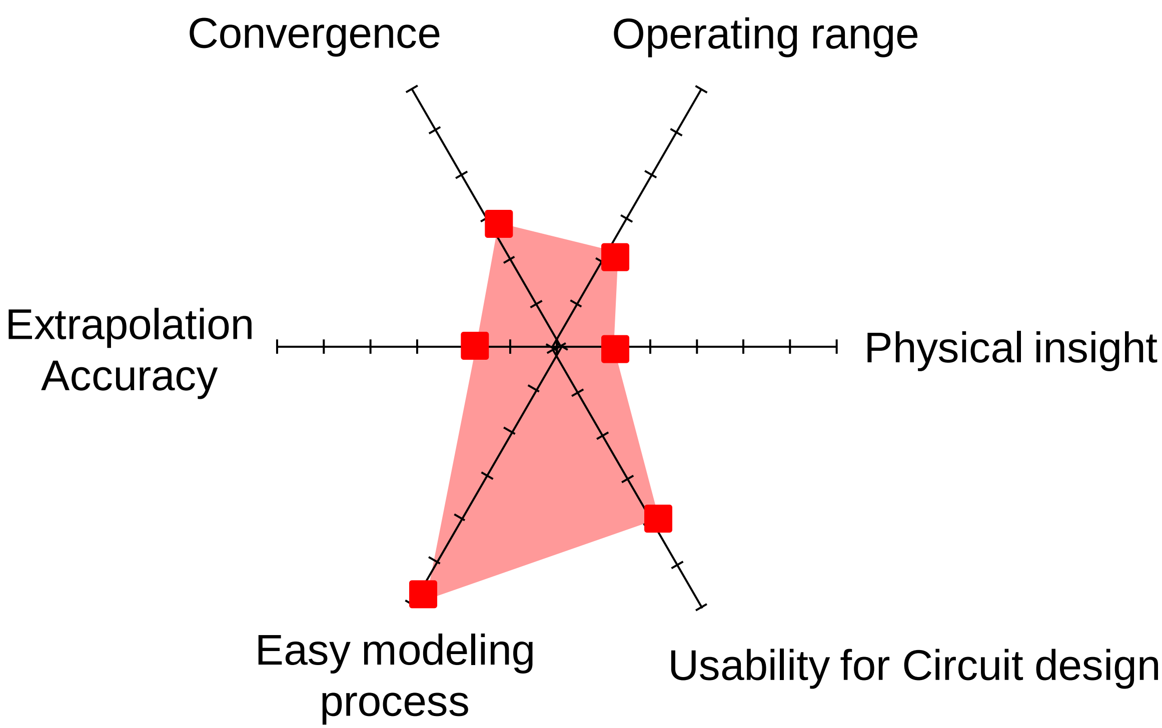
X-PARAMETERS & ACTIVE/HYBRID-ACTIVE LOAD PULL

X-Parameters

- Behavioral model (measurement based)
- Black-box model
- Response to stimuli
- Valid under operating conditions used to create model
- Easily developed



X-PARAMETERS & ACTIVE/HYBRID-ACTIVE LOAD PULL

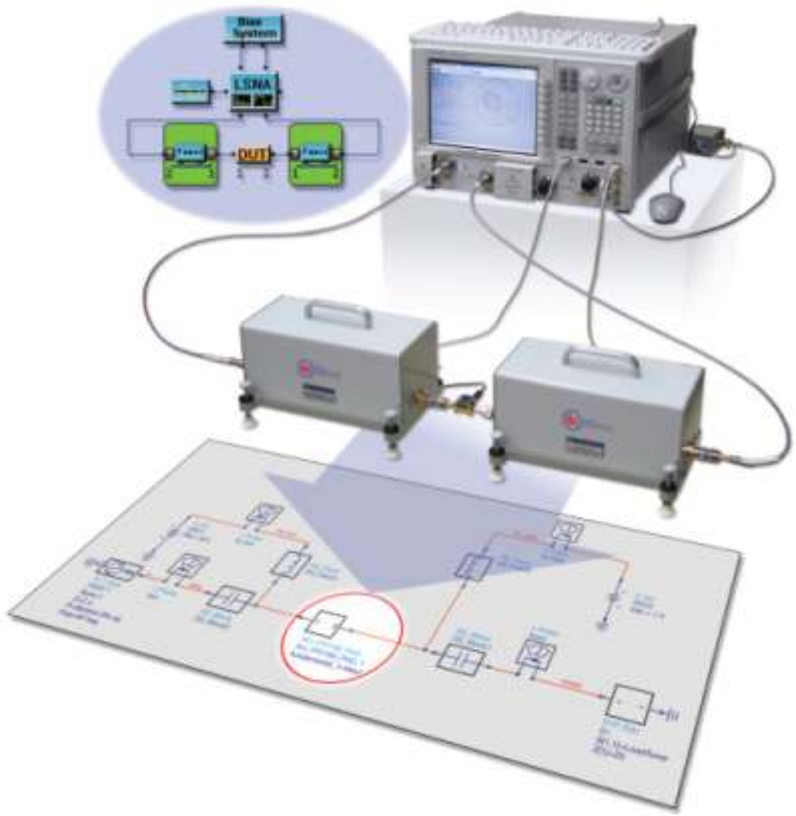
Prior Art
Separate Disciplines

- Load Pull
  - Determine Match for a Single Device (basic amplifier design)
  - Verify Large Signal Models (model validation tool)
- X-Parameters at 50 Ohms
  - Excellent data for 50 ohm matched devices, even in non-linear region
  - What about non-50 ohms?

X-PARAMETERS & ACTIVE/HYBRID-ACTIVE LOAD PULL

New Solution

Combine Load Pull and X-Parameters



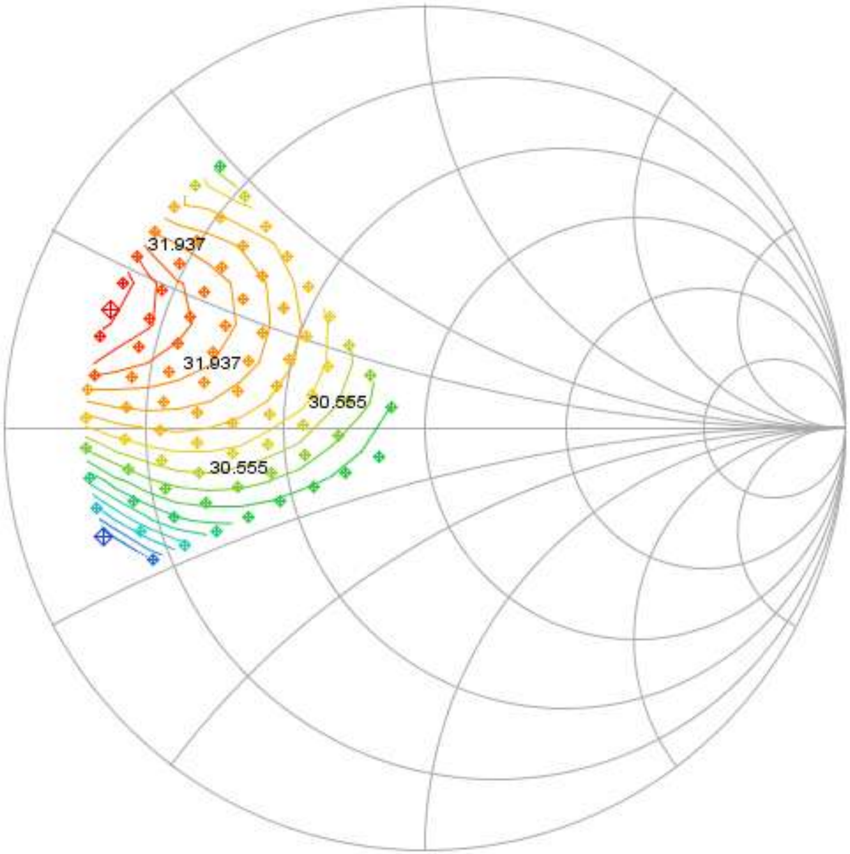
1) Calibrate PNA-X NVNA

2) Vary impedances/power /bias presented to DUT (active device, transistor) → no change!

3) Measure Pout, Gain, Efficiency… → no change!

4) Import X-Parameter model into ADS and simulate circuits

X-PARAMETERS & ACTIVE/HYBRID-ACTIVE LOAD PULL



X-Parameters with Passive Load Pull → useful for all devices (within frequency range of tuner)

X-Parameters with Active Load Pull → ideal for low power devices (no tuner needed)

X-Parameters with Hybrid-Active Load Pull → ideal for higher power devices with low impedance requirements

→ Ideal for harmonic load pull

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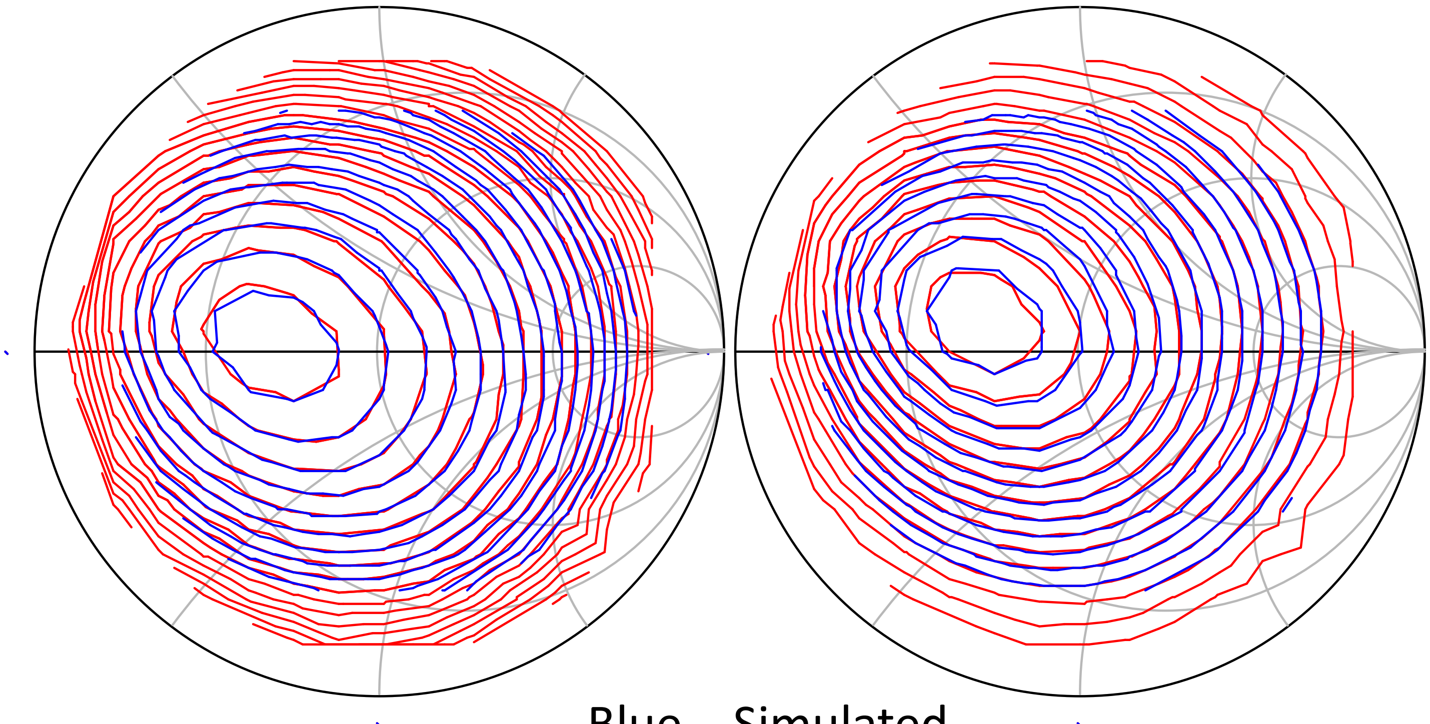
X-PARAMETERS & ACTIVE/HYBRID-ACTIVE LOAD PULL

Comparison of Measured and Simulated Data

Pout PAE



Blue – Simulated

Red - Measured

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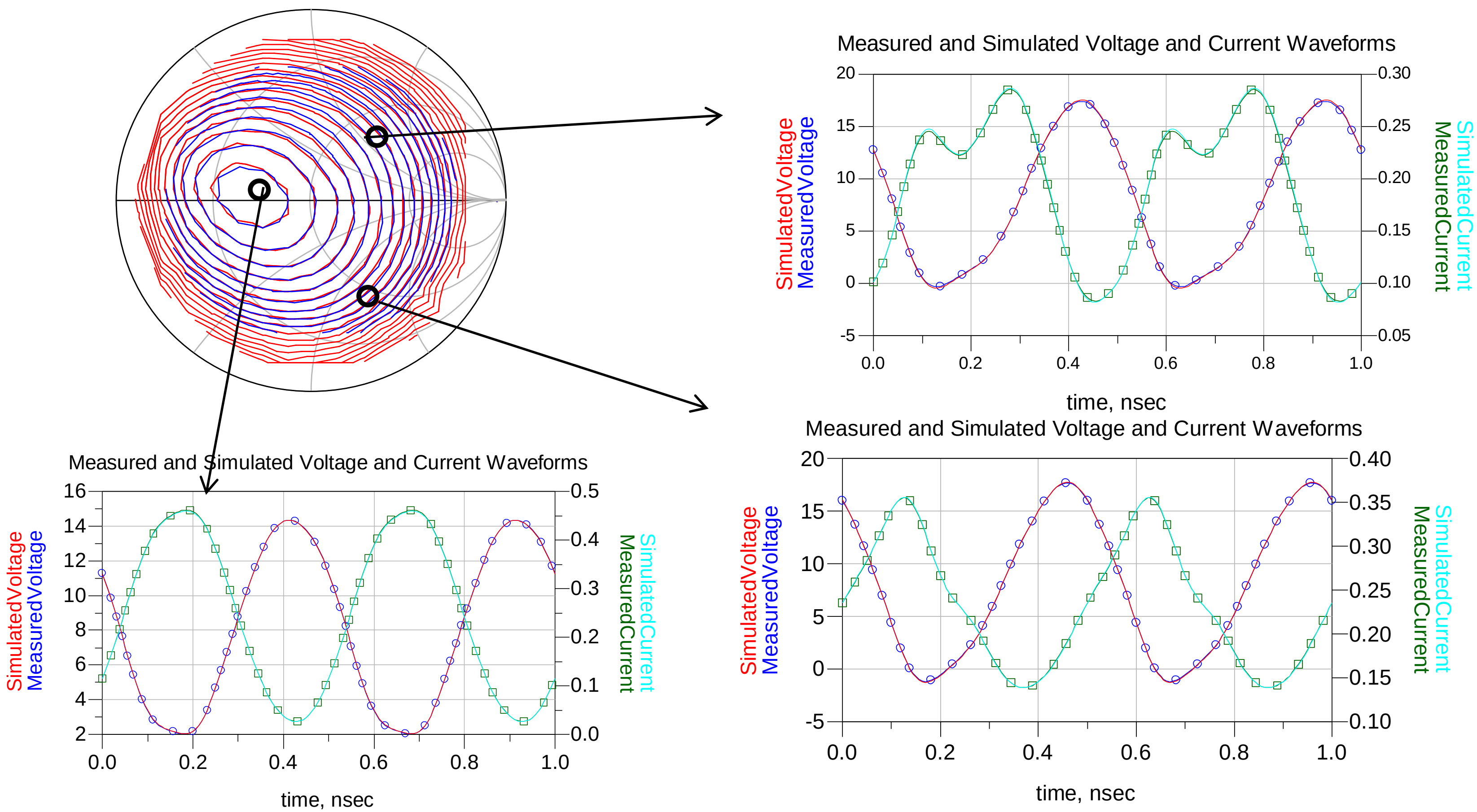
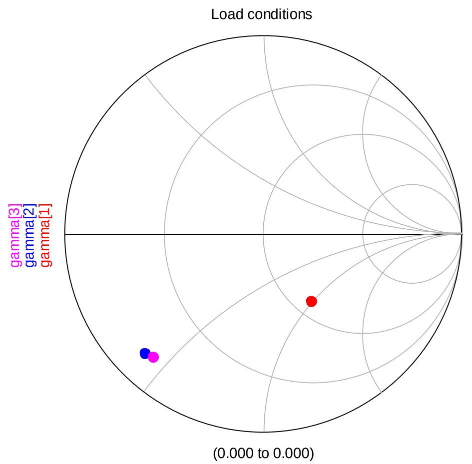
X-PARAMETERS & ACTIVE/HYBRID-ACTIVE LOAD PULL

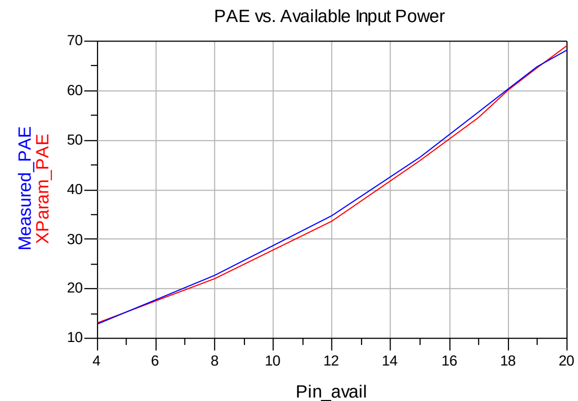
Comparison of Measured and Simulated Data

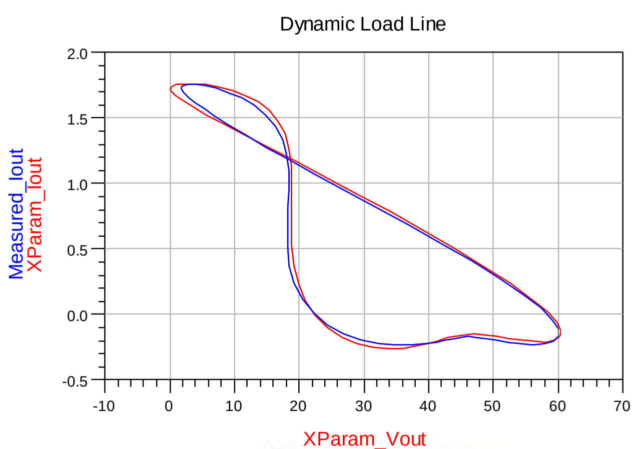


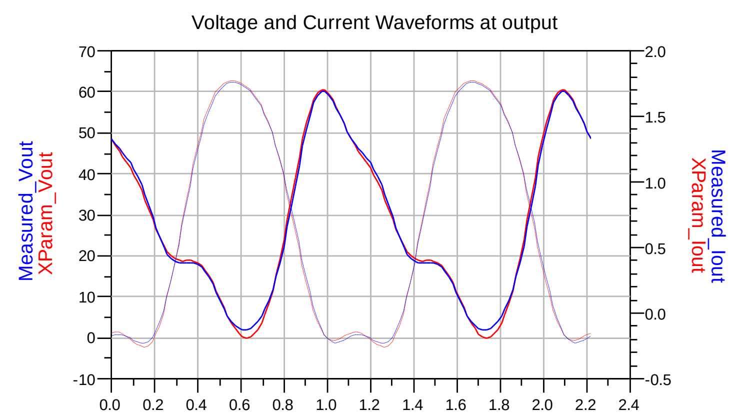
X-PARAMETERS & ACTIVE/HYBRID-ACTIVE LOAD PULL

Virtual 2Fo and 3Fo Load Tuning, Example 1









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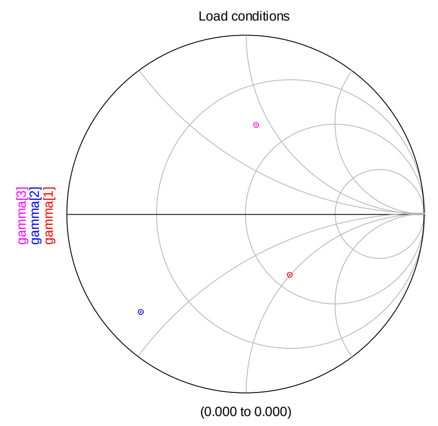
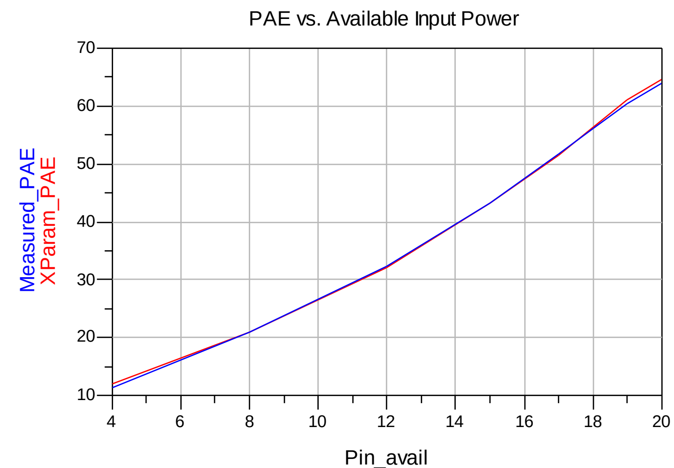
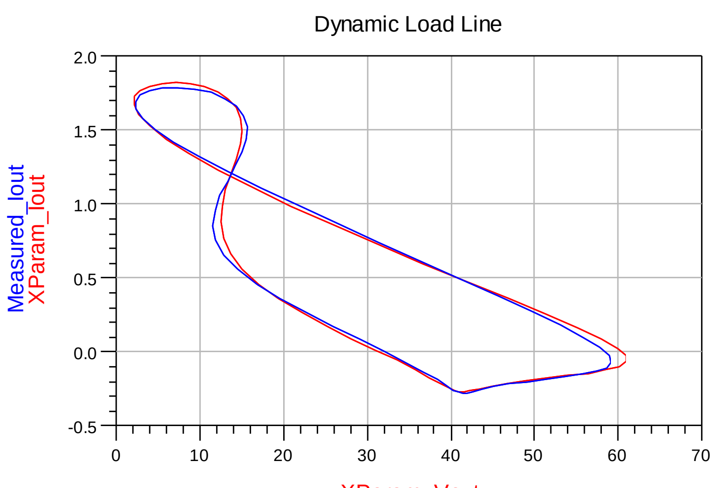
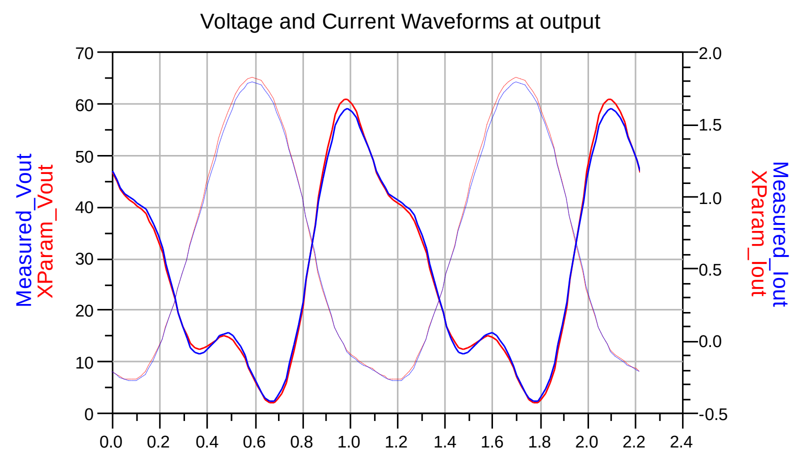
X-PARAMETERS & ACTIVE/HYBRID-ACTIVE LOAD PULL

Virtual 2Fo and 3Fo Load Tuning, Example 2









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X-PARAMETERS & ACTIVE/HYBRID-ACTIVE LOAD PULL

X-Parameters combined with load pull are most useful for:

Advanced Amplifier Design – such as Doherty amplifiers, where multiple amplifiers must be individually modeled and then designed into the same simulation

System Engineering – X-Parameter models can be taken of amplifiers, mixers… and modeling into an entire system to simulate overall system performance

OUTLINE

– Background Info

– Vector-Receiver Load Pull

– Active and Hybrid-Active Load Pull

– X-Parameters and Active/Hybrid-Active Load Pull

– Pulsed-Bias Load Pull

– Conclusion

PULSED-BIAS LOAD PULL

Prior Art
Separate Disciplines

- Load Pull
  - Performed under CW or Pulsed-CW operation conditions
  - DC bias (or customer-improvised gate- or drain-pulser)

- Pulsed IV and S-Parameters
  - Used to collect IV curves under pulsed bias conditions
  - Used primarily for modeling activities

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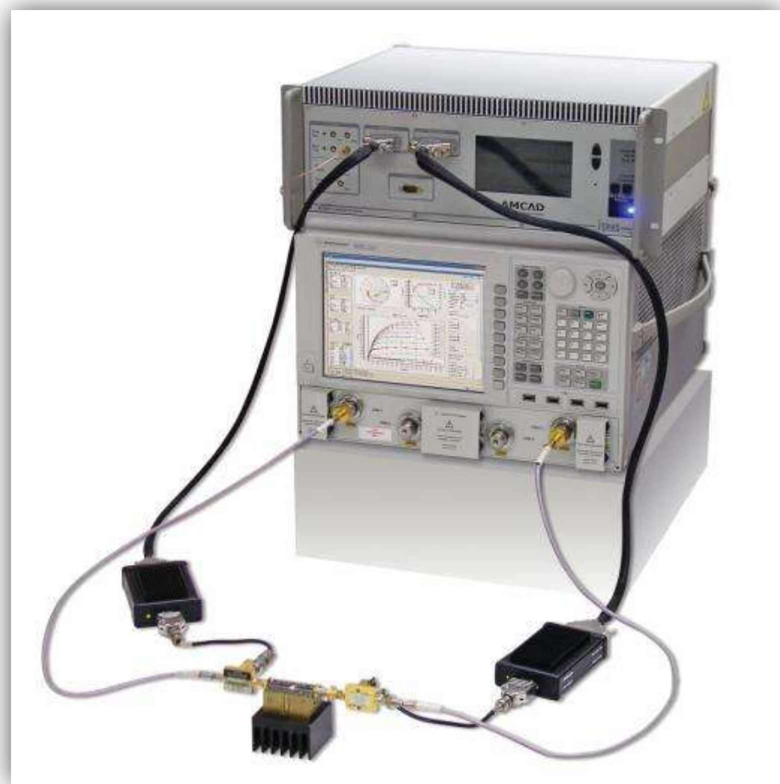
PULSED-BIAS LOAD PULL

New Solution

Combine Load Pull and Pulsed IV



PULSED-BIAS LOAD PULL

- Challenges
  - Synchronization between RF and bias
  - Sequencing between gate and drain pulsing and acquisition
  - Sequencing between bias and RF generation and measurement
- Solutions
  - Common trigger between PNA-X and BILT mainframe
  - Single software suite performs all sequencing and measurement of bias and load pull parameters

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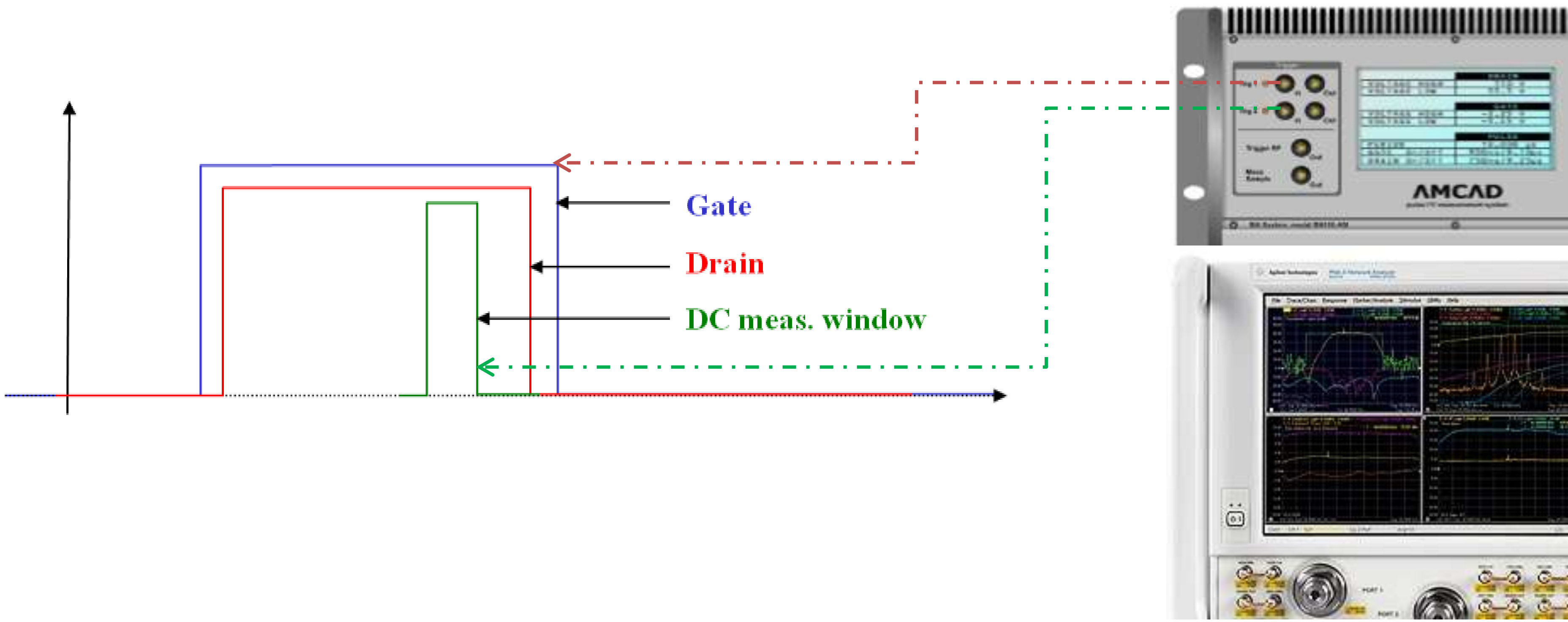
PULSED-BIAS LOAD PULL

Synchronization between gate and drain pulsing and acquisition



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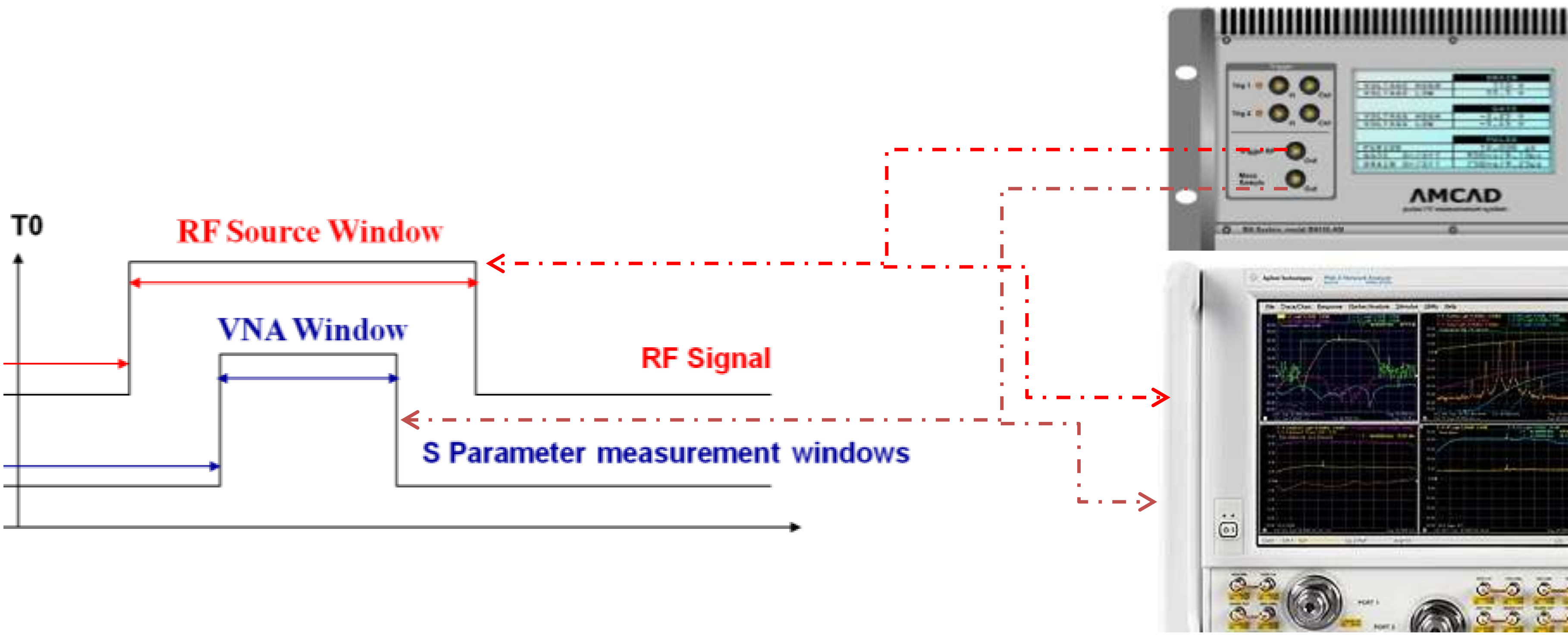
PULSED-BIAS LOAD PULL

Synchronization between RF generation and measurement



OUTLINE

– Background Info

– Vector-Receiver Load Pull

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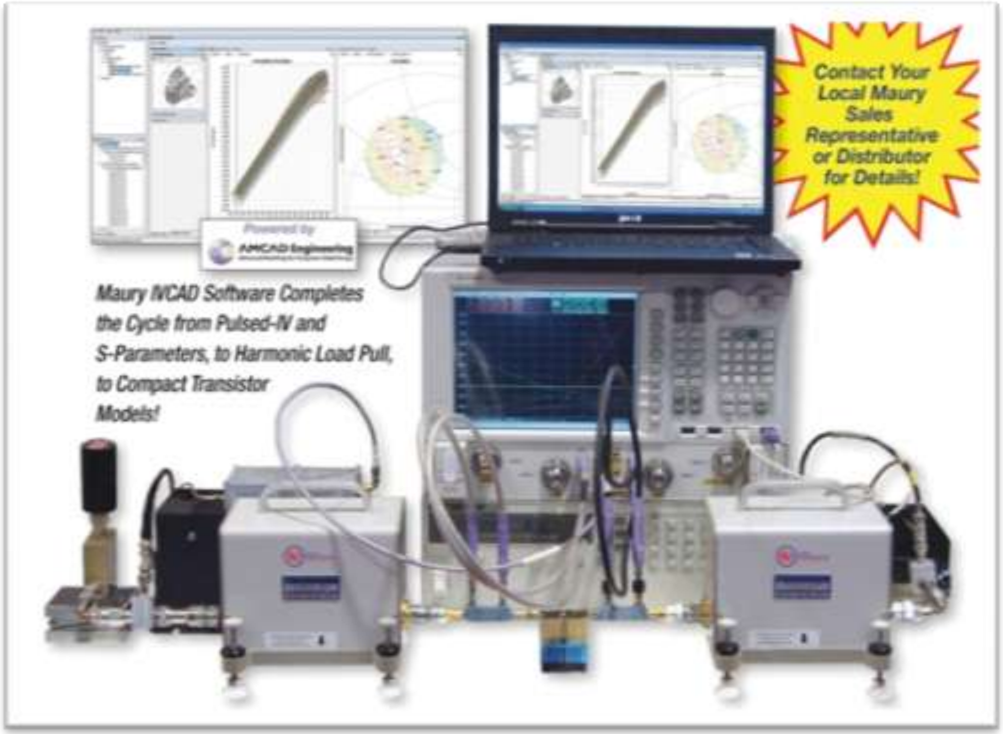
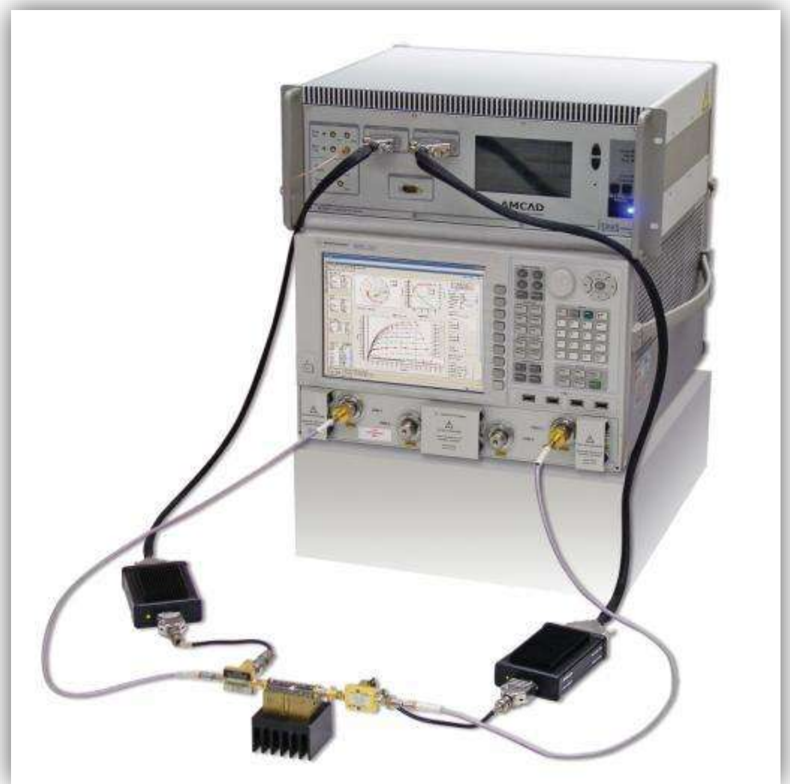
CONCLUSION

Agilent, Maury and AMCAD Joint Solutions





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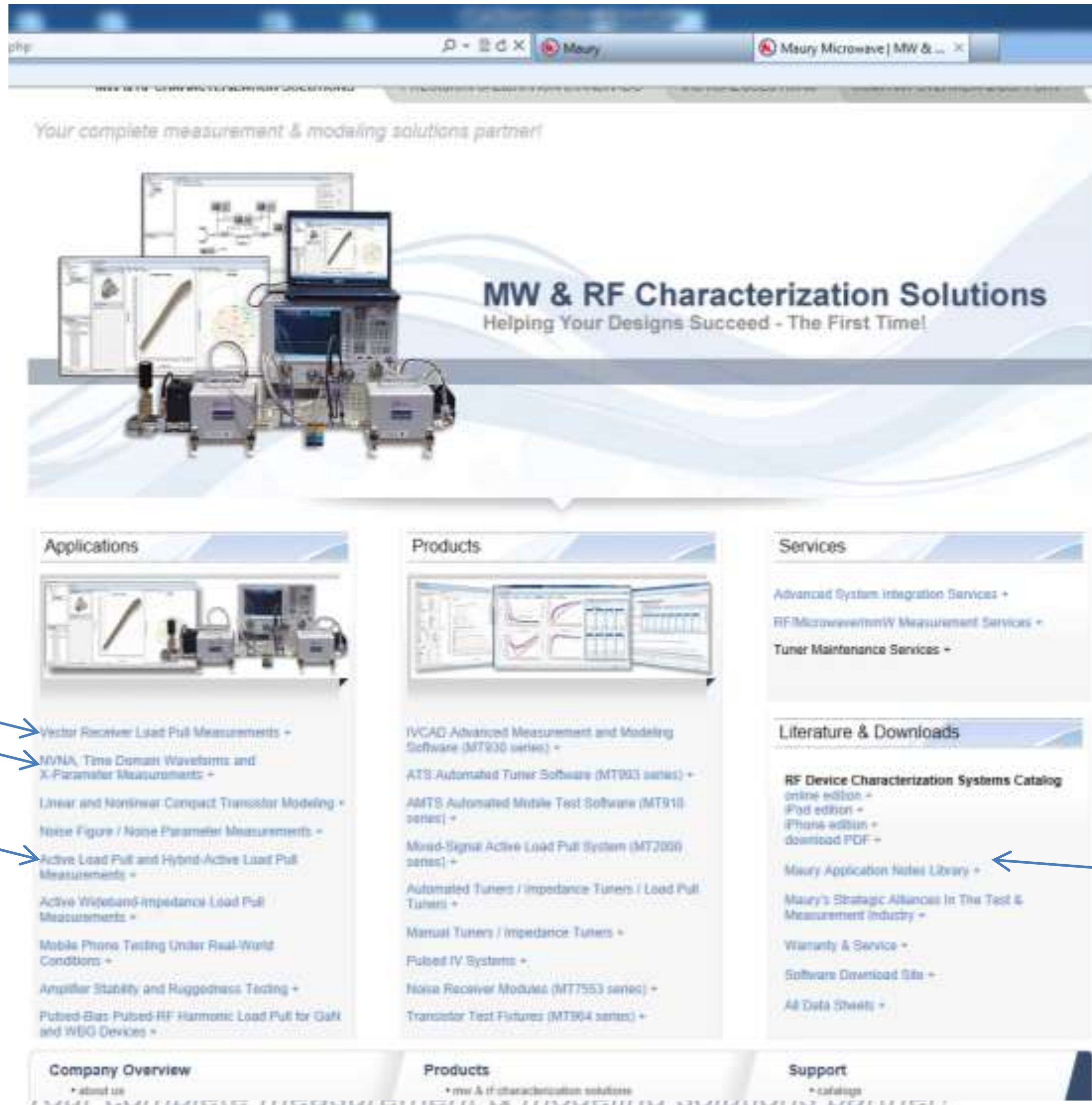
CONCLUSION



CONCLUSION

For any questions, please contact your local Agilent FE or

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