Power amplifier design using measured load pull data

One of the most popular empirical approaches for designing power amplifiers is through the use of load pull/source pull measurements, which is conventionally limited to the graphical display of key performance data. This paper describes a technique for creating an accurate behavioural model within the software that avoids the need for manual entry of load pull data.

Load pull data provides accurate performance information from the actual device, which the designer can use to make informed decisions about the power amplifier design. The conventional use of measured load pull data to design power amplifiers is usually limited to the graphical display of important quantities such as gain, third order intercept and efficiency using software available with load pull measurement system. This graphical display is used to pick a target impedance value for the matching circuit that represents the best design compromise.

Once the optimum impedance value is determined, design software can be used to design input and output matching networks. Using the measured load pull data in design software generally involves manual entry of complex impedance values. This empirical design approach is largely inefficient and error prone, but more significantly, limits the ability to simulate the amplifier behaviour under varying load conditions.

This paper will describe a way to directly use measured load pull data in design software to create an accurate behavioural model. The model is able to determine the impedance as seen from the output port and adjust its performance based on the measured load pull data.

This approach will help bridge the gap between a strictly empirical design approach and a more analytical approach. The designer will be able to accurately predict and optimize the response of the power amplifier under complex signal conditions.

Behavioural models

If one looks at the performance of a circuit-level device, such as an amplifier, the gain of the amplifier will depend on the equivalent circuit. The characteristics of the low-level circuit models will vary the

Figure 1: Measured data points from load pull, the triangular mesh and output power contours on the Smith chart
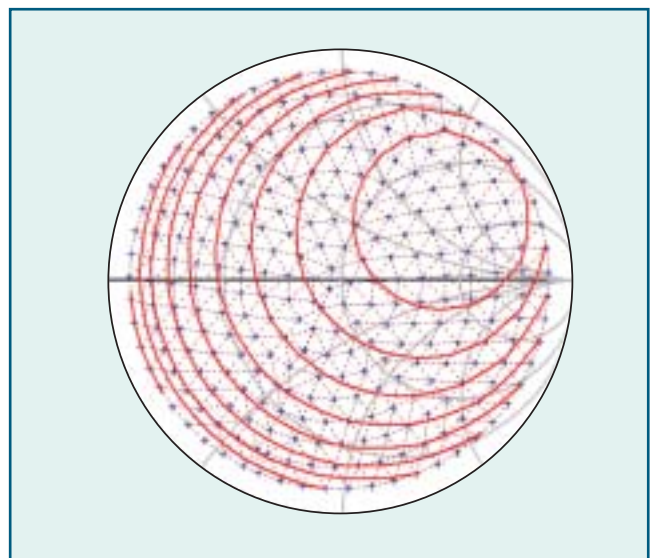
gain as a function of frequency, power, bias, temperature, and other independent variables. When the exact circuit-level description of a device is not known it is often valuable to represent it by a generalized behavioural model. Unlike a circuit-level device, the gain for a behavioural model will behave the way that one defines its parameters. A behavioural model is based on analytic equations, with parameters to allow important attributes such as the gain, match, noise and compression characteristics to be specified. A good behavioural model will give the flexibility to define parameters as simple numbers (independent of other parameters) or as equations (dependent on other parameters). The more information that is provided for the parameter, the more realistic will be its behaviour. For example, if gain is specified as a fixed number such as 10dB, it will have a value of 10dB regardless of frequency or power level or any other independent variable. If gain is expressed as an equation with frequency dependency, then the behaviour is more accurate as a function of frequency, but it

does not change the power dependency. Other parameters, such as gain compression or TOI will shape the gain performance so that it becomes a function of power.

Measured load pull data of the active device can be used to determine parameter values for the behavioural model, such as gain, TOI. A benefit of this approach is that even if the load at the output of the behavioural model changes, the model detects the impedance and adjusts the parameter accordingly. The end result is a model that "behaves" in a way that closely matches the actual measured device.

Challenges involved in scattered data interpolation

A load pull system consists of varying load terminations seen by the device while measuring performance parameters of the device under test. The load pull data collected from a load pull system is usually irregularly spaced random or scattered data.

The first step to generate a behavioural model from measured load pull data is to
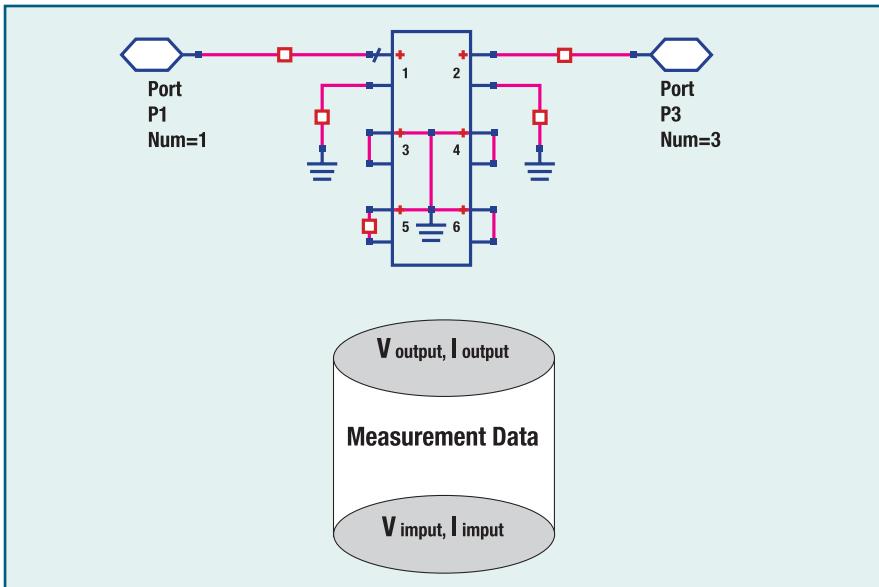
Figure 2: The SSD based load pull behavioural model uses voltage and current relationships between ports to calculate port impedance then pulls the correct wave vectors from a lookup table

import load pull scattered data into the design software. Due to the scattered nature of this data, conventional interpolation techniques cannot be applied directly to generate source pull and load pull contours. Interpolation of scattered data is a very common problem in other areas of science and engineering such as geology, metrology, physics etc. For example, temperature contour maps or rainfall within a state is a scattered data problem.

The problem of generating load pull contours from measured data is a similar problem and can be viewed as the problem of fitting a smooth surface through the non-uniform or sparse data samples. The solution requires scattered data interpolation to determine the value at any arbitrary position within the periphery of

the measured region. Over time a number of techniques have been suggested to solve this problem and a wide variety of literature has been published. Many common approaches to solve this problem suffer from problems related to implementation complexity, smoothness, computer time and the allowable data distribution.

Scattered data interpolation

One of the classic techniques used for scattered data interpolation is based on triangulation. Triangulation of the scattered data points generates an optimal triangular mesh between measured data points and approximates a three dimensional surface made up of triangular patches. Once the triangulation is per-

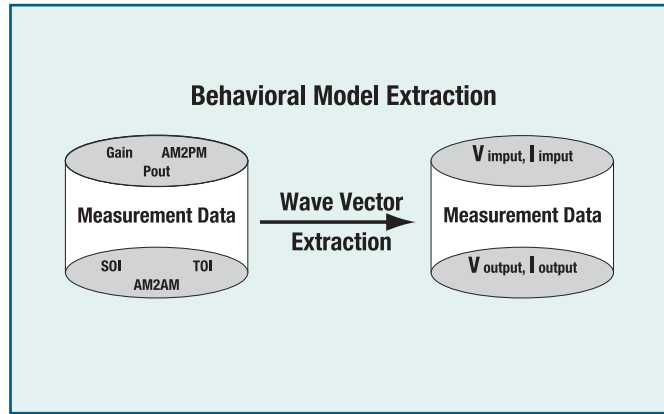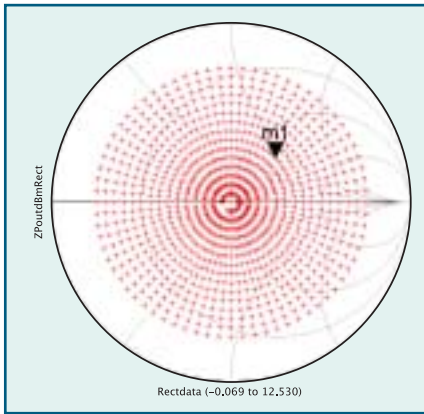**Figure 3: Load pull behavioural model generation**
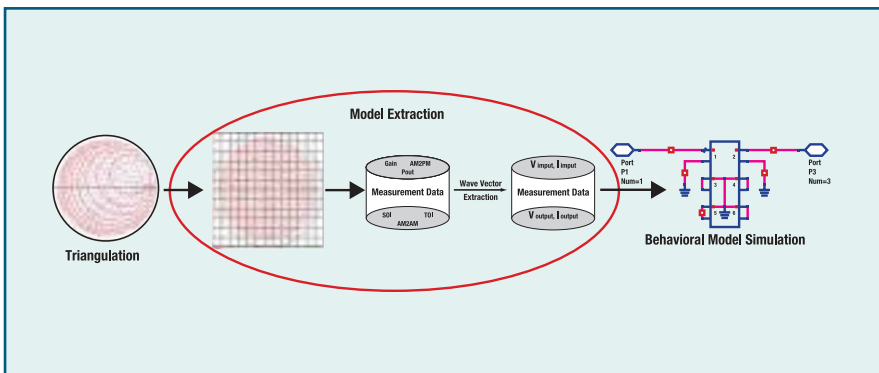
Behavioral Model Extraction

Figure 5 (left): Load pull wave vector extraction

formed, the load pull contours can easily be plotted by traversing these triangular patches and performing piecewise linear interpolation within each triangle of interest. Although the triangulation approach is computationally expensive and smoothness of the contours generated by this approach might suffer due to piecewise linear interpolation within triangles, this technique is especially attractive for the generation of load pull contours from measured data. An advantage of the triangulation method is that it does not make any assumption regarding the shape of the contours. As the shape of the contours can vary drastically from one measured parameter to another, e.g. the contour for power gain can be quite different from the output power contours, it is easier to generate contours of varying shapes for multiple measurement parameters without repeating the triangulation process for every measurement variable. In our approach, triangulation process is also used as an intermediate step to create a load pull behavioural model from measured data. If required for plotting purposes, the smoothness of the contours thus generated can be improved by further

post processing the data and approximating the individual contours by B-Spline, Bezier curve or polynomial curve fitting.

The triangular mesh is generated by creating a three dimensional convex hull using an incremental algorithm between the measured data points. The incremental algorithm uses a seed triangle to start the convex hull process. New vertices are added in a sequential order and every time a new vertex is added, it is determined if this new vertex lies within or outside the current convex hull. If the new vertex added lies outside the current hull, the hull is modified by adding the new faces of the cone formed by connecting the vertex with the current convex hull and deleting the internal faces which are found. The process is repeated till all vertex points are exhausted.

Contour maps are plotted from this triangulated data at user-defined power levels. To plot a contour for a given power level, the participating triangular patches are identified and traversed sequentially. Linear interpolation using barycentric coordinates is performed within the triangle of interest.

The contour maps thus generated are

converted to the data set directly, and can be plotted on the Smith chart or on the rectangular grid. Figure 1 shows the plots of measured data points, the triangular mesh and output power contours on the Smith Chart.

Scattered data interpolation discussed in the previous section allows us to plot load pull contours and helps us to determine optimum impedance for power amplifier design. The contour maps plotted from triangulated data are not sufficient to create a measurement based load pull behavioural model and therefore requires further processing.

Model creation
The behavioural model of a device should allow fast load pull simulation for a given input power and varying port reflection coefficients. The expected behaviour of such a measurement based model is to automatically detect the port impedance in the simulation environment and assign transfer function coefficients from measured parameters such as gain, TOI, SOI and AM2PM etc.

Most design software provides the capability to create user-defined custom

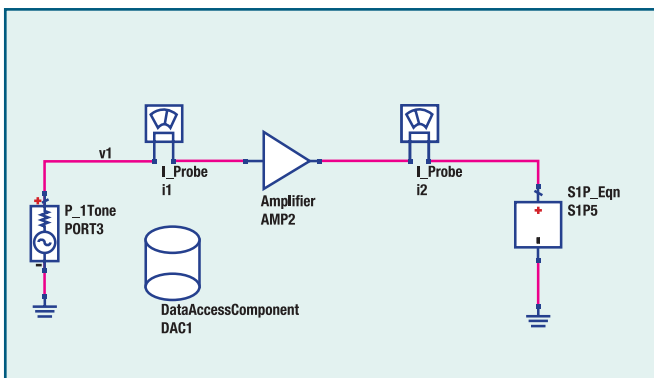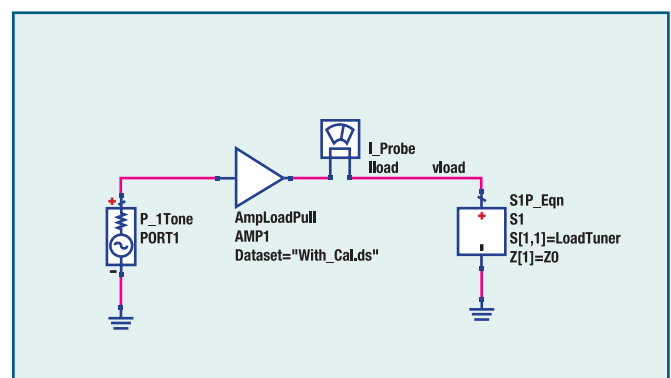**Figure 6: Wave vector extraction using load pull harmonic balance simulation**

Figure 7: Load pull behavioural model simulation

models, usually written in C/C++ or another custom language. The creation of these custom models is difficult and often requires through knowledge of the software and the underlying process. Macros available in design software provide a fast and relatively easy development of user defined custom models. The macros enable the user to create equation based, user defined, non-linear components, which are defined by specifying an algebraic relationship that relates the port voltages, currents, and their derivatives. A load pull behavioural model created using such a macro allows us to sense the port voltages and currents during simulation, determine the port impedance, and set the gain of the device based on the detected impedance.

The load pull behavioural model requires a port voltage and current relationship derived from measured load pull using a model extraction process.

The load pull model extraction from measurement data is a two-step process:

1. Convert triangulated scattered data to a grid (i.e. regular data).
2. Represent device behaviour as a function of port voltages and currents (wave vectors).

To simplify the model extraction process, it is assumed that the load pull measurement is carried out on a device covering the entire Smith chart region. Further it is assumed that the source tuner is set at a fixed impedance value and parameters such as power, gain, TOI are measured at random load termination points.

Data gridding

The first essential step to create a load pull behavioural model is to generate a new set of regular or uniform data points from the raw scattered data. It is always easier to use regular data in a simulation environment as it allows the use of standard lookup tables and conventional interpolation techniques during simulation. The process of generating regular data points from scattered data is referred to as gridding. A rectangular grid or a polar grid data can be generated using triangulated non-uniform data points. It is easier to cover the entire Smith chart region and avoid the region of instability (that is the region outside the unit Smith chart) using polar coordinates rather than rectangular coordinates.

The gridding process starts by creating a set of polar grid points of varying complex reflection coefficient in regular intervals. The goal is to generate the load pull measurement parameters at these uniform grid points. The grid points are traversed in a sequential order and the triangle enclosing the polar grid point is identified. The point is said to lie within the triangle if its edges are traversed in a sequential order and the point always lies on one side for all the three edges i.e. right side or left side.

Once the triangle containing the grid point is identified, all the measured parameter values are calculated at that grid point using barycentric coordinates. The grid point location problem is again a complex and computationally expensive

Figure 8: Comparison of output power load pull contours from measured triangulated data and simulated behavioural model
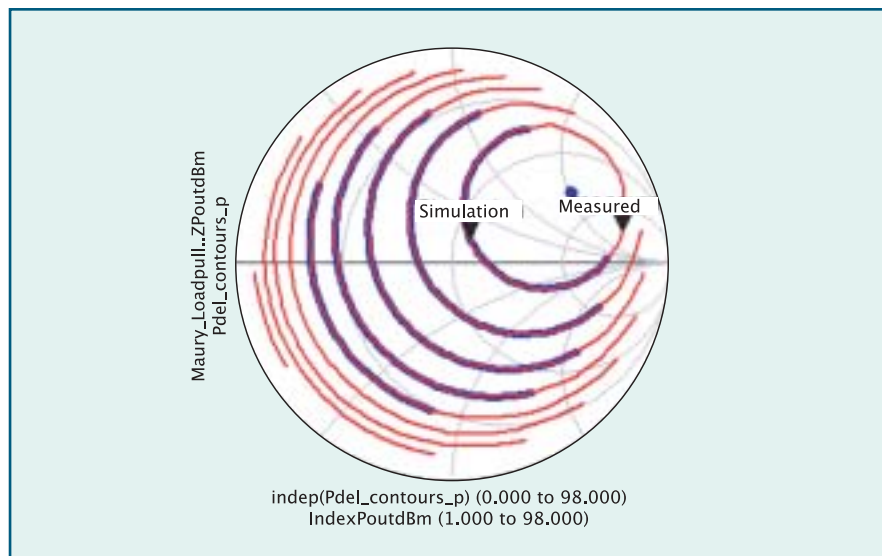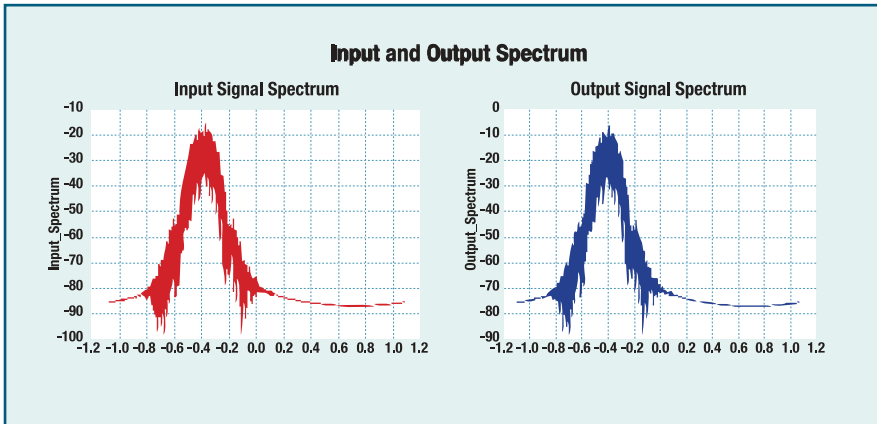
Figure 9: Input and output spectrum plots from measurement-based load pull behavioural model

problem. With careful implementation of its algorithm and by choosing the right database structure, the computation time can be significantly reduced. The new set of gridded data thus obtained (shown in figure 4) is then converted into a look up table format with the reflection coefficient as an independent variable and all other measured parameters as dependent variables. This look up table is used to calculate the port voltage and current relationship (wave vectors), which is required to create a measurement-based behavioural model.

Wave vectors
The second step in the model extraction process is to generate wave vectors as a function of load impedance from measured load pull data. The wave vectors are required by a load pull behavioural model to emulate the device behaviour during non-linear simulation. The accuracy of the load pull behavioural model generated using this approach is thus depends upon the accuracy with which load pull measurement data is converted into wave vectors.

During the model extraction process, each reflection coefficient point on the polar grid is chosen sequentially and wave vectors are calculated from the gridded data. To generate wave vectors from measured data, all key linear and non-linear load pull measurements need to be combined together and the resultant port voltages and currents need to be calculated.

This tedious process of generating wave vectors from load pull measurements such as gain, IP3, SOI, AM2PM can be simplified by performing a load pull simulation on a RF system amplifier behavioural model in most design software. The mea-sured load pull data is assigned to this system amplifier model using a look up table approach.

The use of system amplifier model helps us to combine all key linear and non-linear load pull measurements and convert that into a set of input and output port voltage and current relationship for a given reflection coefficient. A fair representation of device linear and nonlinear behaviour is thus embedded into these wave vectors, which are function of port impedance.

Wave vectors are defined by the following equations:

$$b_1 = (v_1 - 50*i_1)/(v_1 + 50*i_1)$$

$$b_2 = (v_2 - 50*i_2)/(v_1 + 50*i_1)$$

Here v_1, i_1 and v_2, i_2 are voltage and current values at the input and output port at a specified termination impedance. Figure 6 shows the load pull simulation setup used for extracting wave vectors.

To generate the output power contours shown here, it is assumed that the input power to the device is held constant and that gain, IP3 are the only parameters used with the system amplifier model to create the device wave vectors. This is not a limitation of this approach, as other load pull measurements such as SOI and AM2PM can be carried out and used with RF system amplifier model to create wave vectors. These additional measurements, if available and assigned to the system amplifier model, will improve the accuracy of the extracted load pull behavioural model.

The gridded data stored in a look up table file format is measured for a termination impedance value different from

the characteristic impedance of 50Ω, thus a correction factor is required to compensate for the power loss due to impedance mismatch.

The correction factor used to compensate for this power loss is given by:

Correction factor (ML)=10log$_{10}$(1-γ^2)

Here γ is the termination reflection coefficient.

In the simulation environment, the voltage probe and current probe component are used at the input and output ports. The measurement equations defined on the schematic page calculate the wave vectors from measured port voltages and currents and store it as an output data set.

Once wave vectors are calculated, they are used with the load pull behavioural model for non-linear simulation. During simulation of the load pull behavioural model in a circuit, output termination is determined automatically based on port voltages and currents, and corresponding wave vectors are pulled from the wave vector data set.

Simulation of behavioural model

The performance of the load pull behavioural model is verified by performing a harmonic balance simulation for various values of load termination and comparing it against the load pull contours generated from the measured data (Figure 7). For verification purpose, a harmonic load tuner and a fixed source impedance are used. The harmonic load tuner is swept by varying the value of complex impedance within the area of the Smith chart at the

fundamental frequency. The simulated output power contours are plotted and compared against measured data.

As the output port impedance is different from 50Ω, the power in dBm is calculated using the measurement expression:

$$P_{out}(dBm) = 10log_{10}(0.5 * V_{out} * conj(I_{out}t)) + 30$$

Here V_{out} and I_{out} are the output port frequency dependent voltage and current. Figure 8 shows contour plots of measured data and the simulated behavioural model. It is observed that the simulated output power contours are in good agreement with the measured data

The load pull behavioural model generated for a fixed input power point is simulated for a reverse link GSM modulated signal source under linear conditions. Input and output spectrum plots (Figure-9) show good correlation and thus prove the usability of the measurement based load pull behavioural model under complex signal environment.

Accuracy of load pull behavioural model

The accuracy of the behavioural model created using this approach depends upon the set of measurement parameters used with the system amplifier model to generate wave vectors. Parameters such as 1dB gain compression and AM2PM will enhance the accuracy of load pull behavioural model, but are not always available.

The main limitations of this approach are as follows:

■ The load pull behavioural model uses power dependent data and hence cannot be used for linear simulators.
■ This approach cannot be used to generate power added efficiency contours.

Conclusion

This paper presents a simple approach for generating a behavioural model from measured load pull data. The behavioural model generated can be used to design and optimize matching circuits for power amplifier design, predict nonlinear performance of the complete amplifier under varying load conditions. The behavioural model can also be used as a system component and can be simulated under modulated signal environment.

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