

Design of Experiments (DOE) Tutorial

Design of Experiments (DOE) techniques enables designers to determine simultaneously the individual and interactive effects of many factors that could affect the output results in any design. DOE also provides a full insight of interaction between design elements; therefore, it helps turn any standard design into a robust one. Simply put, DOE helps to pin point the sensitive parts and sensitive areas in designs that cause problems in Yield. Designers are then able to fix these problems and produce robust and higher yield designs prior going into production.

Here is a simple and practical example that walks you through the basic ideas behind DOE. This example is meant to illustrate the concept in a very easy way to understand DOE and enables you to go on and expand your knowledge on DOE further.

DOE Example:

Let us assume that we have designed an amplifier and we need to design an experiment to investigate the sensitivity of this amplifier to process variation. In other words, we would like to find out if there are any elements in the design that largely affect the output response due to their high sensitivities to the output measure.

In ADS, the DOE tool comes with full supporting plots that enable designers to determine simultaneously the individual and interactive effects of many factors that could affect the output results in any design. Pareto plots, main effects and Interactions plots can be automatically displayed from the Data Display tool for study and investigation. However, in this example DOE is illustrated using a manual calculations approach in order to allow you to observe how the analysis and results are calculated, and what these results mean.

Let us start with our amplifier example:

In this example, let us chose three elements where we want to see their effects on the Gain of the amplifier. These elements are: W (the width of the microstrip lines), a resistor (R), and a Capacitor (C).

Since we chose three elements, we must construct 8 experiments (2^3) for a Full factorial experiment. We assign a -1 and +1 values to each of the elements. For example the nominal value of the Resistor is described with a "0". A "-1" represents a -5% variation from its nominal value and a "+1" represents a +5% variation from its nominal value. Therefore if our resistor's nominal value is 20 ohms, a "-1" represents a 19 ohms value, and a "+1" represents a 21 ohms value.

Step 1

Start by choosing variables that affect the response

Choose three variables with their +1 and -1 :

Width of lines (W)

$$W = W_{\text{nominal}} \pm .5 \text{ um}$$

Resistors (R)

$$R = R_{\text{nominal}} \pm 5\%$$

Capacitors (C)

$$C = C_{\text{nominal}} \pm 5\%$$

Example: For W

-1 corresponds to 9.5 μm

+1 corresponds to 10.5 μm

0 corresponds to nominal value, 10 μm

Step 2

Next, we run the simulation eight times to get the gain (our output measure) for all the combination of +1's and -1's of the three elements and this is what we get:

W	R	C	Gain
-1	-1	-1	12.85
1	-1	-1	13.01
-1	1	-1	14.52
1	1	-1	14.71
-1	-1	1	12.93
1	-1	1	13.09
-1	1	1	14.61
1	1	1	14.81

Step 3

From the results above, let us extract the main effects of Capacitor, C on the Gain. We calculate the average Gain when C is “-1” and when C is “+1” and determine the total gain variation due to the Capacitor. The table below shows that this gain variation (due to C) is .044 dB.

Main Effect of Capacitors, C on Gain

W	R	C	Gain
-1	-1	-1	12.85
1	-1	-1	13.01
-1	1	-1	14.52
1	1	-1	14.71
-1	-1	1	12.93
1	-1	1	13.09
-1	1	1	14.61
1	1	1	14.81

Average gain for C=-1
13.7725 dB (yellow)

Average gain for C=1
13.86 dB (blue)

Slope= .044

Next we do the same thing for the Resistor. Notice that the gain variation due to the Resistor is .85 dB, which is much higher than that of the Capacitor. (See table below). This already tells us that the resistor is a trouble component and causes higher variation in the gain.

Main Effect of Resistors, R on Gain

W	R	C	Gain
-1	-1	-1	12.85
1	-1	-1	13.01
-1	1	-1	14.52
1	1	-1	14.71
-1	-1	1	12.93
1	-1	1	13.09
-1	1	1	14.61
1	1	1	14.81

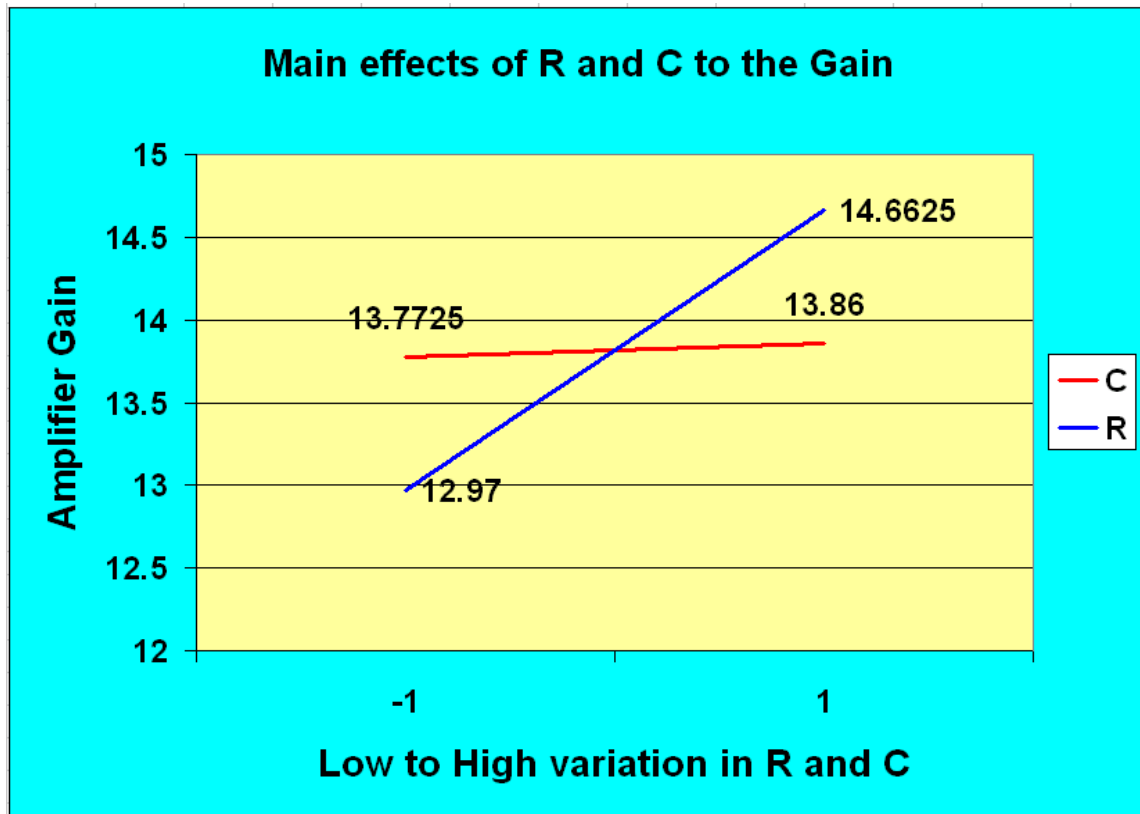
Average gain for R=-1
12.97 dB (blue)

Average gain for R=1
14.6625 dB (green)

Slope = .85

The main effects can be plotted for easier view of the components' sensitivities to Gain. Below is the main effects plot of the Capacitor and the resistor (calculated above) on the Gain variation.

Plotting Main Effects of C and R



Step 4

DOE is also very useful in getting information on the interactions between the elements in a design and how these interactions affect the variation in the output measure (Gain, in our example)

The table below calculates the interaction effect between W and R. The interaction is very small and negligible (.0088 dB).

Interaction Effect of (W and R) on Gain

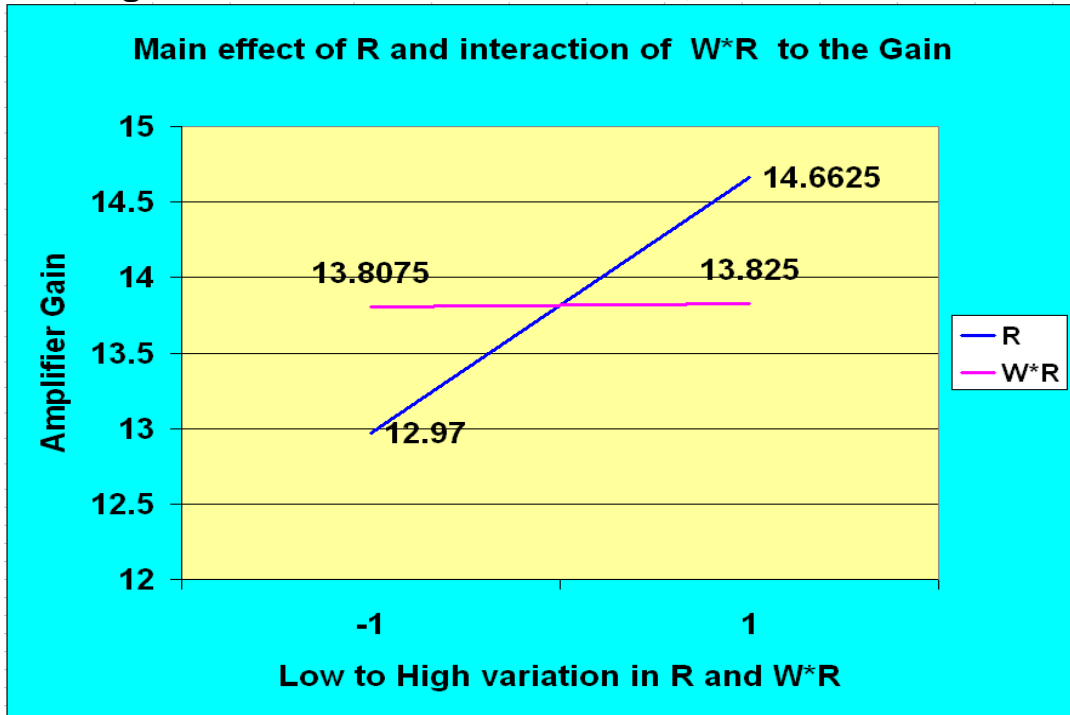
W	R	C	Gain
-1	-1	-1	12.85
1	-1	-1	13.01
-1	1	-1	14.52
1	1	-1	14.71
-1	-1	1	12.93
1	-1	1	13.09
-1	1	1	14.61
1	1	1	14.81

Average gain for $W \cdot R = -1$
13.8075 dB (blue)

Average gain for $W \cdot R = 1$
13.825 dB (pink)

Slope = .0088

Plotting Interaction Effects of W and R, Vs Main Effect due to R



Step 5

Doing the same procedure for all elements and their interactions, we obtain the following results.

Obtaining the Rest of the Coefficients

<u>Term</u>	<u>Coefficient</u>
Constant (nominal gain)	13.8
W	.09
R	.85
C	.044
W*R	.0088
W*C	.0013
R*C	.0050
W*R*C	0.0025

We calculated these three coefficients above

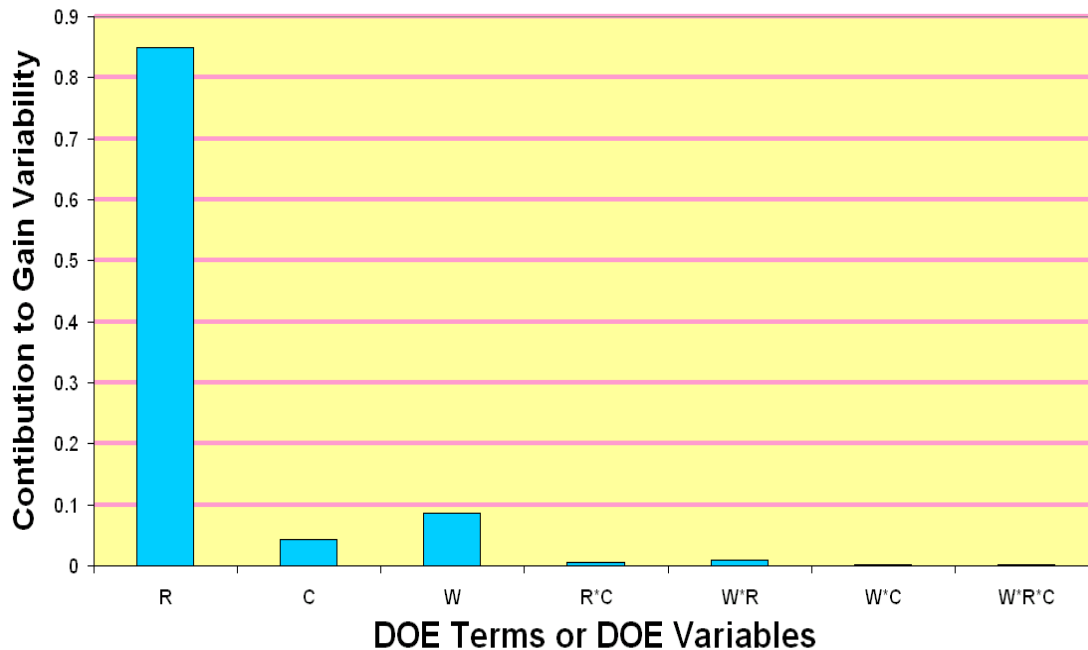
Construct a linear equation to represent the experiment results:

$$\text{Gain} = 13.8 + .09W + .85R + .044C + .0088WR + \dots \text{ Etc.}$$

Step 6

Pareto Charts are very useful in DOE. The above results can be plotted on a Pareto type chart in order to make it much easier to visualize the main and interaction effects of all components to the Gain variation.

Display All Effects on a Pareto Chart



It is very clear from the results above that the Resistor R has the most contribution to the Gain variability and sensitivity. The effects plot (shown earlier) for the resistor tell us how much is this variability due to the resistor and that was .85 dB.

The designer will then focus his / her efforts in reducing that variation due to the resistor. One way to do that in Board or MIC designs is to buy a screened part that has +/- 1% tolerance instead of a +/- 5% tolerance. In MMIC design, the designer would want to either use a different resistive layer of lower sensitivity, or make the resistor as wide as possible since this would reduce its sensitivity.

What we have shown was a very simple example with three elements in order to illustrate the concept of DOE.

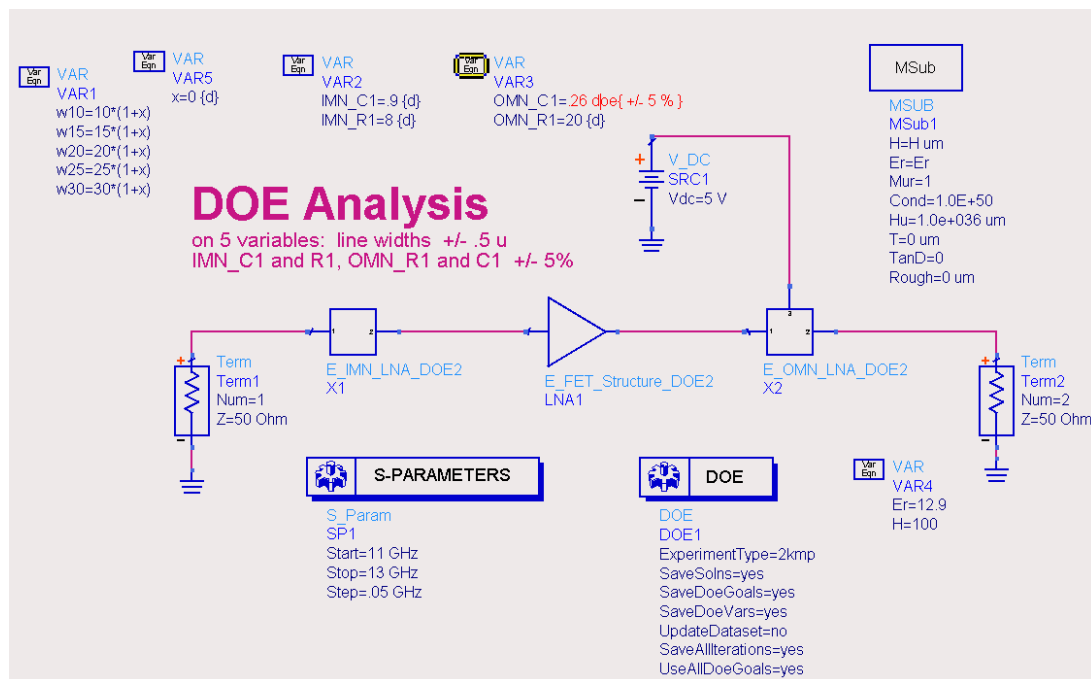
The following section expands on this introductory material and shows few examples from the "Design of Experiments" tool in ADS.

Example: Ku-band LNA

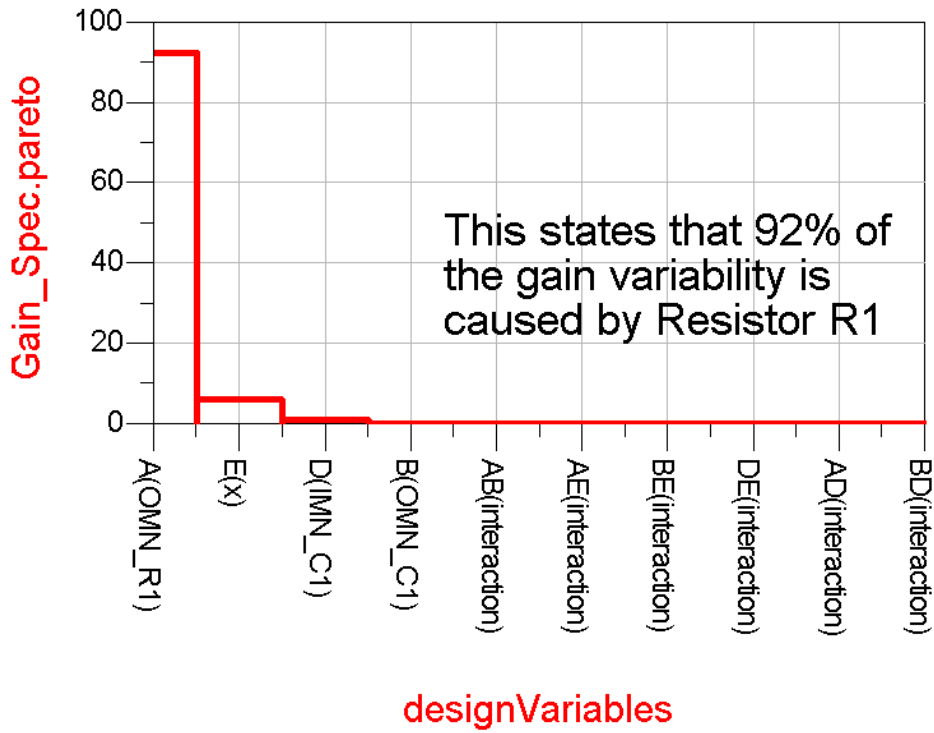
The following one stage LNA has three sub-networks.
We ran DOE analysis on five variables:

- Line widths: +/- .5 microns
- Input Matching Network: C1 and R1 (+/- 5%)
- Output Matching Network: C1 and R1 (+/- 5%)

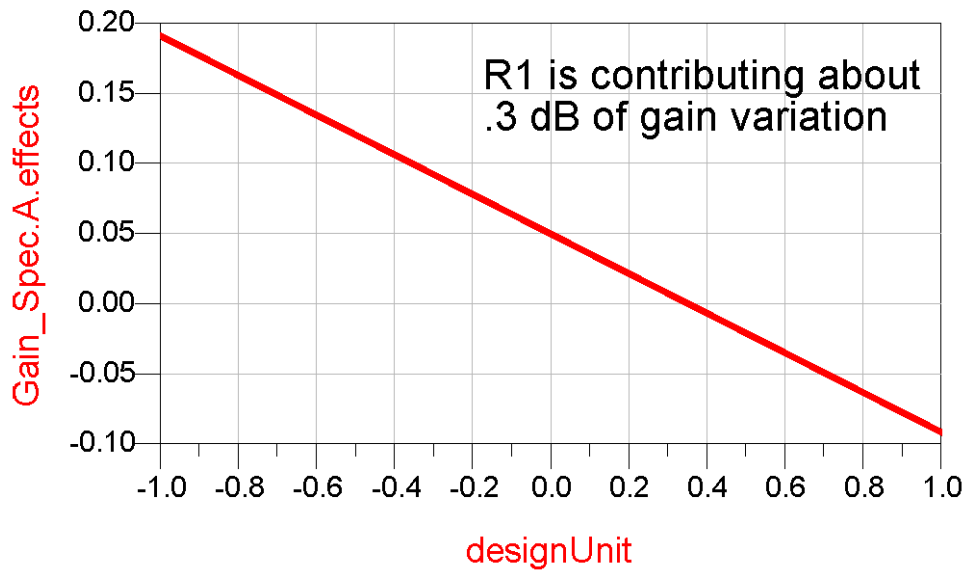
A five elements full factorial DOE requires 32 experiments ($2^5 = 32$).
These 32 simulations cover all possible combinations of +1 and -1 on each component. Let us see some of the output results:



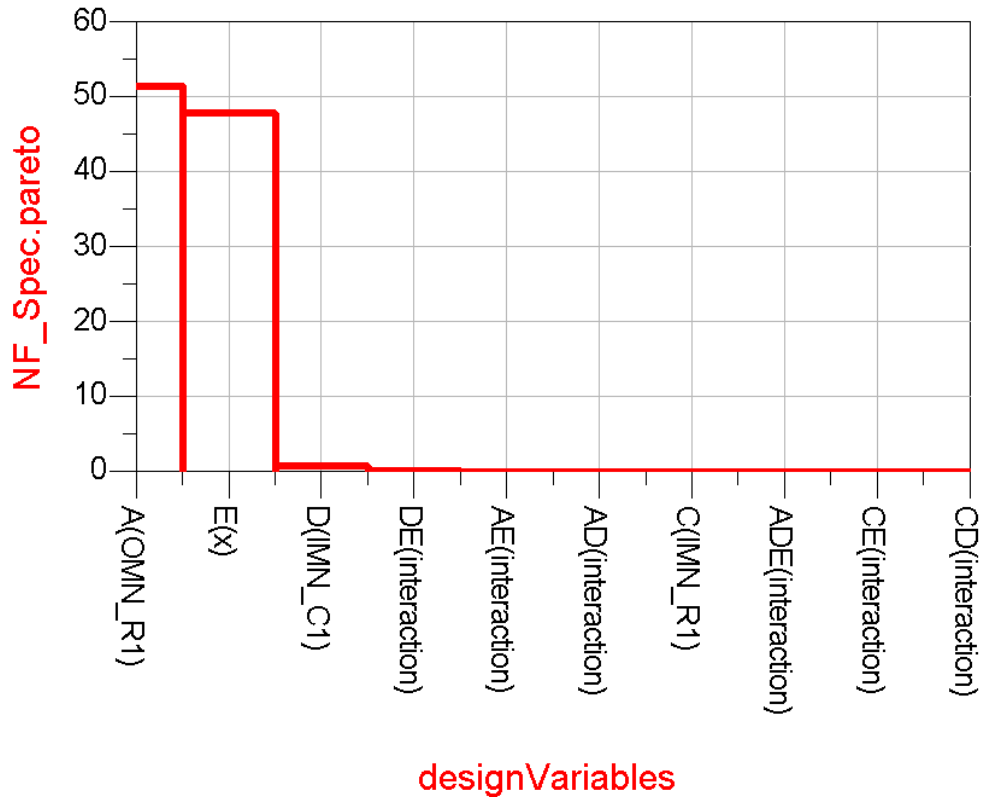
Pareto Plot for the Gain



Main Effect Plot for R1 on Gain



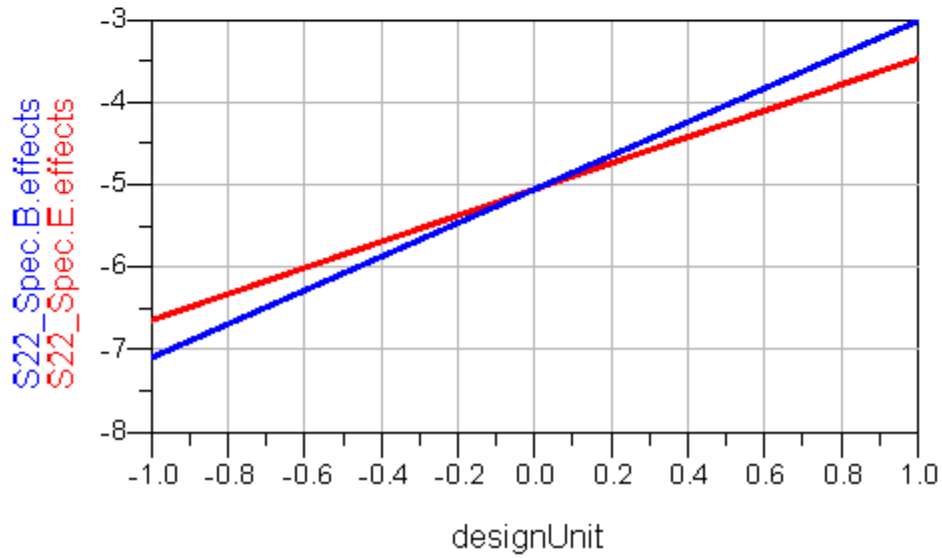
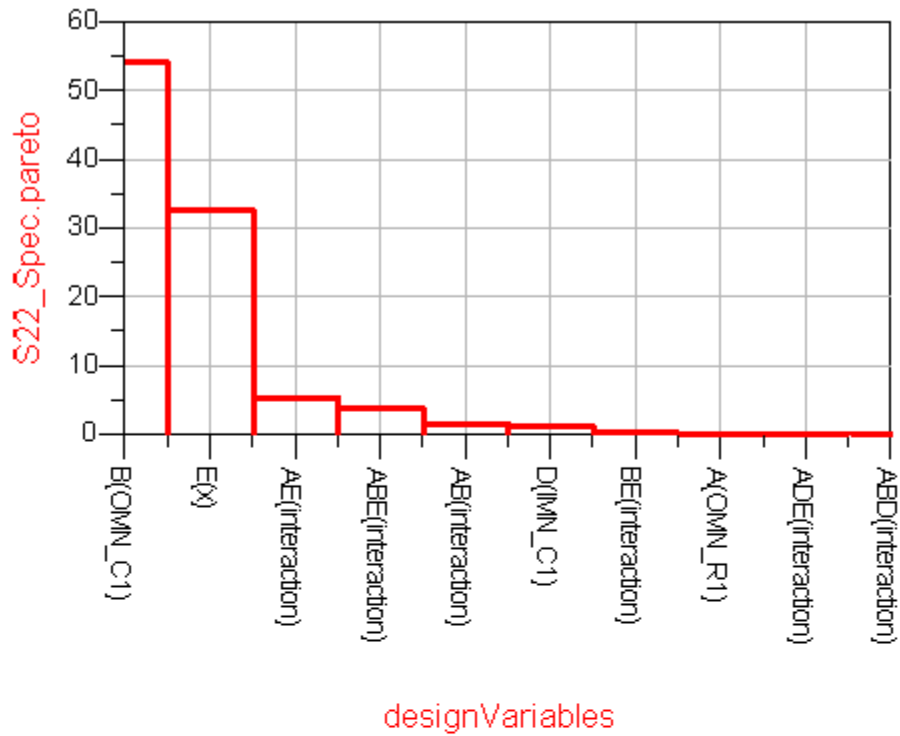
Pareto Plot for Noise Figure



This shows that the variation in Noise Figure is equally caused by the input matching network microstrip line width and the Output Resistor, R1.

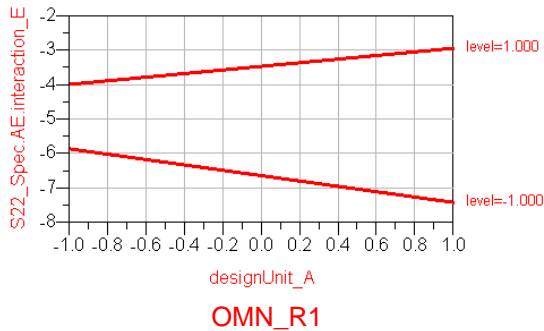
Below is shown the Pareto Plot for S22. Please read on, because I want to illustrate in this plot the concept of interactions between the elements in DOE.

Notice that 54% of the variation in S22 is caused by the variation effects of OMN_C1, followed by a 32% caused by the output matching network lines widths, and followed by an interaction effect from the Output R1 with the line widths.



The plot above is the main effect plot of OMN_C1 and line widths.

Let us now see what we can learn from the interaction plot between R1 and line widths.



This is an Interaction plot between R1 and "Lines Width"

Notice that we can reduce the S22 variability if we choose R1 to be smaller (X-axis).

When R1 is smaller, the effects of the line widths on S22 is narrower (the distance between the linear lines).

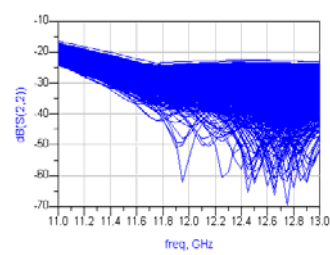
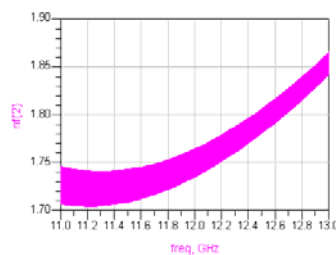
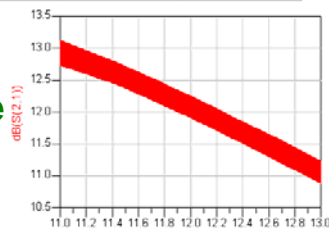
When R1 is bigger, the S22 variability is much bigger (we don't want this).

The DOE experiment on this simple LNA example helped us to fix the design prior to manufacturing and make it less sensitive to process variation. The plots below show the LNA response before DOE and after DOE. Notice that the output response variations (Gain, NF, and S22) after DOE are much smaller than before DOE.

Yield Analysis Results of Initially Optimized LNA

NumFail	NumPass	Yield
774.00	226.00	22.60

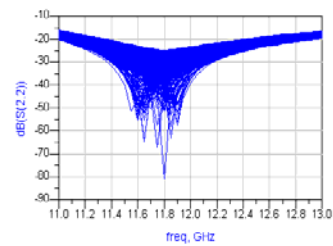
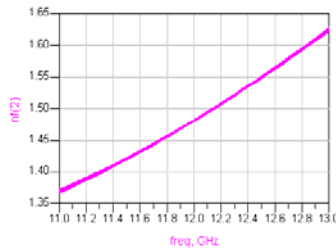
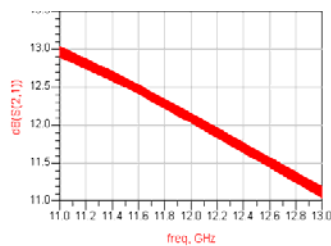
Before



Yield Analysis Results of Final LNA Design

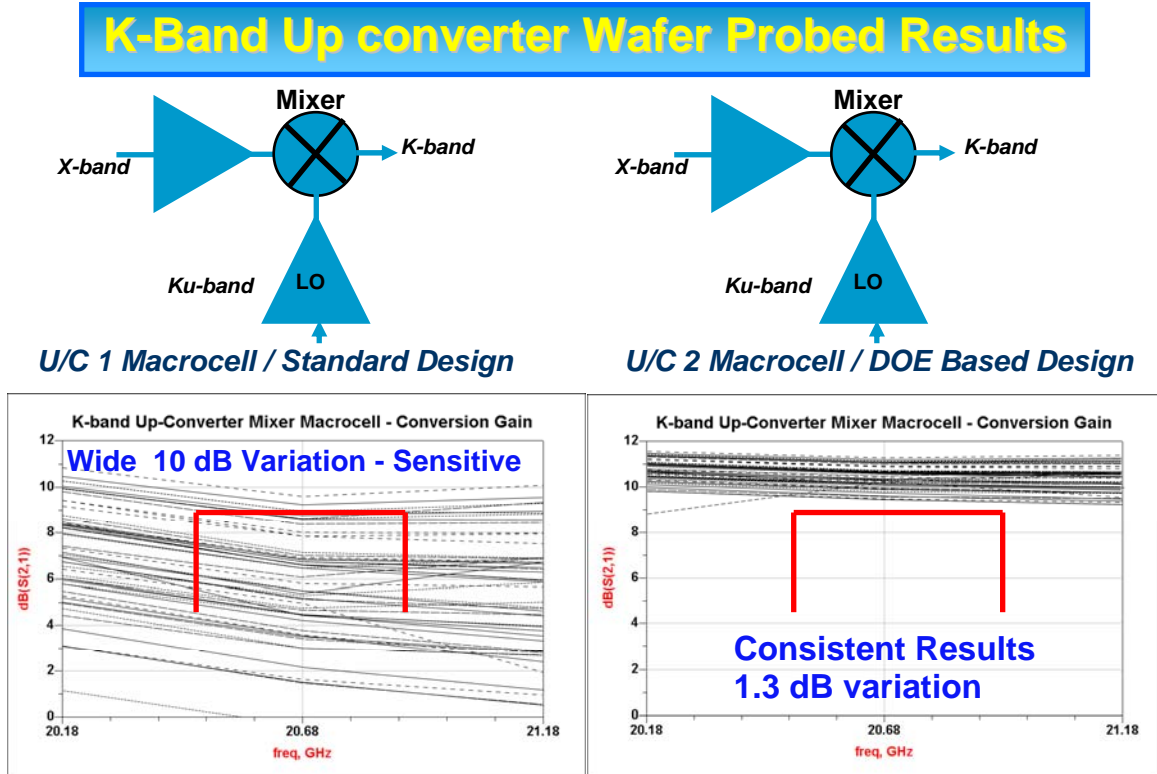
NumFail	NumPass	Yield
0.00	500.00	100.00

After



Real Life Examples

Here are a couple of real life designs that were fabricated on the same wafer and at the same time. The results speak for itself. It is very clear that the designs that went through DOE analysis came out much better and more consistent in their output measures.

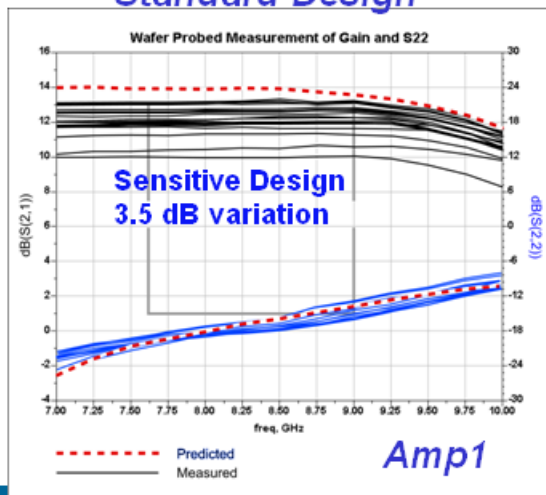


Wafer Probed Results

Note: Foundry process shifted to the left during this run. Amp2 shift was less sensitive to that

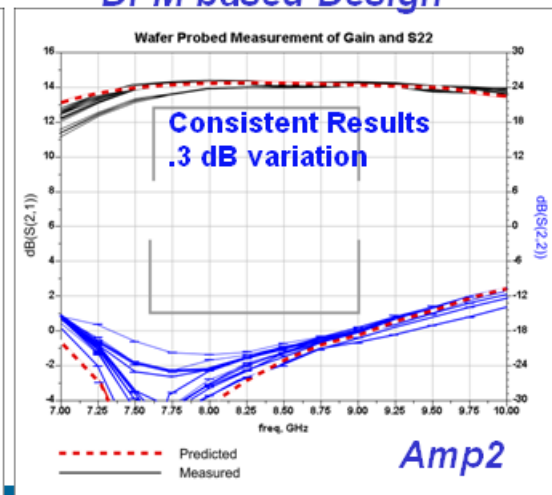
Amp1

Standard Design



Amp2

DFM based Design



Conclusion

Design of Experiments (DOE) techniques enable designers to determine simultaneously the individual and interactive effects of many factors that could affect the output results in any design. DOE also provides a full insight of interaction between design elements; therefore, helping turn any standard design into a robust one. Simply put, DOE helps to pin point the sensitive parts and sensitive areas in your designs that cause problems in Yield. Designers then are able to fix them and produce robust and higher yield designs prior going into production.