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Author(s)	Zheng, Liqiang; Mathewson, Alan; O'Flynn, Brendan; Hayes, Michael; Ó Mathúna, S. Cian
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Statistical method of modeling and optimization for wireless sensor nodes with different interconnect technologies and substrates

Liqiang Zheng*, Alan Mathewson, Brendan O'Flynn, Michael Hayes and Cian O'Mathuna
Tyndall National Institute, Lee Maltings, Prospect Row, Cork, Ireland
* Phone number: +353-214904299 Email: liqiang.zheng@tyndall.ie

Abstract

A comparison study was carried out between a wireless sensor node with a bare die flip-chip mounted and its reference board with a BGA packaged transceiver chip. The main focus is the return loss (S parameter S11) at the antenna connector, which was highly depended on the impedance mismatch. Modeling including the different interconnect technologies, substrate properties and passive components, was performed to simulate the system in Ansoft Designer software. Statistical methods, such as the use of standard derivation and regression, were applied to the RF performance analysis, to see the impacts of the different parameters on the return loss. Extreme value search, following on the previous analysis, can provide the parameters' values for the minimum return loss. Measurements fit the analysis and simulation well and showed a great improvement of the return loss from -5dB to -25dB for the target wireless sensor node.

Introduction

As wireless sensor node being used widely in environment monitoring and medical applications, reducing the weight and size and increasing the mobility are becoming essential. To achieve these goals, lots of technologies are applied to the nodes, such as flip chip, and flexible substrate. There are lots of researches and publications focus on the characterization [1-4] of the above technologies.

However, from RF system point of view, very little effort was done in considering these technologies as components which could change the final RF performance of the system. The aim of this paper is to develop a methodology to model the advanced packaging technologies for RF circuit simulation and obtain an optimized solution of the whole system. Statistical methods, like standard deviation, coefficient of variation, regression, curve fitting, are utilized during the parameter sweep procedure to get the optimization results.

In this paper, the impacts of a wide range of parameters on RF performance were studied and a statistical based method is proposed to improve the return loss. The paper is organized as the following:

- Main focus description: poor return loss caused by improper impedance matching.
- Modelling of the RF circuit, including the packaging and substrate.
- Description of the statistical methods used during analysis.
- Optimization performed to improve the return loss. Measurements were carried out to match the optimized solution.

System overview and the problem

The radio chip used in this paper is the high performance, ISM Band, FSK/ASK transceiver IC ADF7020. The wireless sensor node is also equipped with a MSP430 low power microcontroller, and an energy source.

An evaluation board of ADF7020 is provided by Analog Devices. Based on the reference design from the ADF7020 evaluation board datasheet, a credit card shape flat mote (named as "Tyndall mote" in this paper) with flip chip bare die of ADF7020 is developed with the same circuit connection.

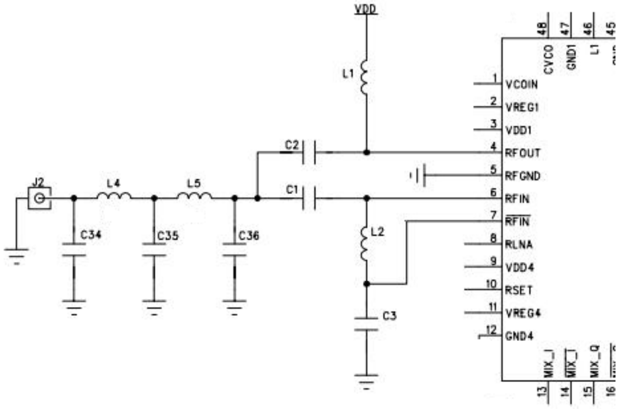

Figure 1. The balun circuit of the transceiver

The RF circuit, shown in Figure 1, between the ADF7020 chip and the antenna is critical to impedance matching. The RFIN and $\overline{\text{RFIN}}$ are the differential ports for receiving, while the RFOUT is for transmitting data. A balun circuit matches the chip ports with the SMA antenna connector J2. The balun consists of L1, L2, L4, L5, C1, C2, C3, C34, C35 and C36.

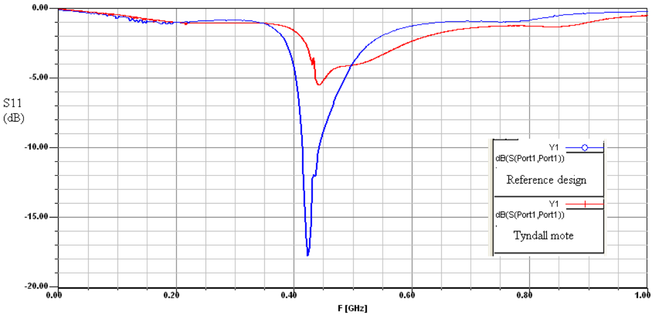

Figure 2.Return loss measurements of the two nodes

The working frequency of 433MHz for the ADF7020 transceiver was selected and measurements of S11 were carried out at the antenna SMA connector for the reference evaluation board and the Tyndall mote.

S11, also known as return loss, is the loss of signal power resulting from the reflection caused at a discontinuity in a transmission line. Smaller S11 means better circuit impedance matching and less power loss. Figure 2 illustrates that the reference design has a good impedance matching (around -20dB of return loss), while the other is behaving poor (only -5dB of return loss).

The modifications between the Tyndall mote to the reference design should be the reasons for the problem, including substrate thickness (6 layers PCB vs. 2 layers PCB), interconnect change (flip chip vs. packaged wire bonding) and the related PCB tracks.

In the following chapters, modelling, analysis and optimization were performed to provide a reliable method for the return loss optimization.

Modelling of RF circuit

The model was based on the circuit shown in Figure 1, with some packaging and microstripline parameters added. To ensure the modelling being precise, all related parameters should be considered. These parameters included mainly the passive components, PCB layout details (track and layer stack-up) and RF ports characterization. The model and parameter values were imported into Ansoft Designer for simulation and analysis.

A. Passives

The discrete passives in Figure 1 can be modelled as ideal or real components, depending on the accuracy requirement. The real components have parasitic like ESR and ESL, which could be obtained from the manufacturer or Ansoft Designer vendor library. The pads of the surface mount components are treated as micro-stripe transmission lines.

B. PCB substrate

Not only the discrete components, but also the PCB tracks and substrate should be modelled. Figure 3 gives the schematic of the substrate and the micro-stripe line. All the PCB tracks are modelled as micro-stripe lines.

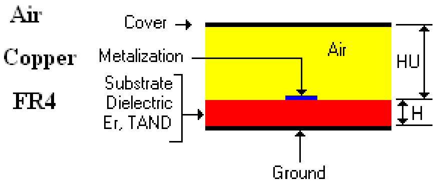

Figure 3. Schematic of the substrate stack-up

Parameter	Value
H	0.154mm
HU	100mm
ε_r (FR4)	4.5
tanδ	0.002
Copper thickness	35µm

Table 1. PCB and cover material properties

C. PCB tracks

Once the stack-up has been defined, individual transmission line sections are modelled by specifying the trace width and physical length of each section. Interconnect features such as corners and bends, whose effects can be significant at high frequencies, and are modelled for accuracy.

Special modelling of the following 50µm PCB tracks, in red colour in Figure 4, to the RF die ports was performed. These tracks play the same role of the wire-bonding to connect the die with the outside PCB. The width is as narrow as 50µ, while it is 0.25mm wide for the reference design (BGA packaging).

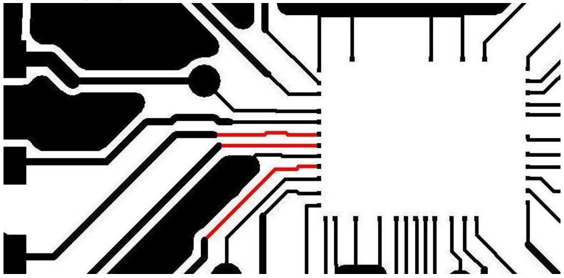

Figure 4. The 50µm width PCB tracks of the flip-chip interconnect

D. RF ports of the transceiver

The three RF ports are essential for modelling as passive components because it is difficult to simulate the circuit with some active components. The lumped element models of the ports, presented in Figure 5, are given by [6]. The values of the passive components are also listed in [6], or can be obtained by impedance measurements of the ports.

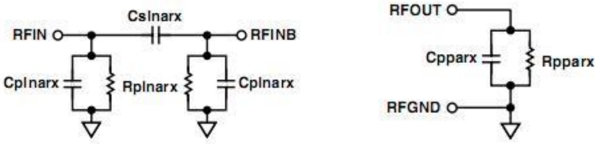

Figure 5. The LNA (left) and PA (right) models

E. Parameter sweep simulation

To show the idea of the proposed statistical analysis, there is no need to list and analysis all the huge amount of parameters. Instead, some parameters of different types are selected:

- Substrate related: dielectric constant and thickness of the substrate.
- Interconnect related: Interconnect track width, which differs from 0.25*mm* for the packaged chip to only 50*µm* for the flip-chip die.
- Passive components: C1 and C2 are selected as an example. Other parameters can be chosen as well.

Parameters	Reference value
Dielectric constant	4.5
Substrate thickness	0.154mm
Interconnect track width	0.25mm
C2	10nF
C1	4.7nF

Table 2. Reference values for the parameters

All the parameter values were all normalized by their reference design value, listed in Table 2. The return loss is showed by original value rather than in dB for analysis purpose.

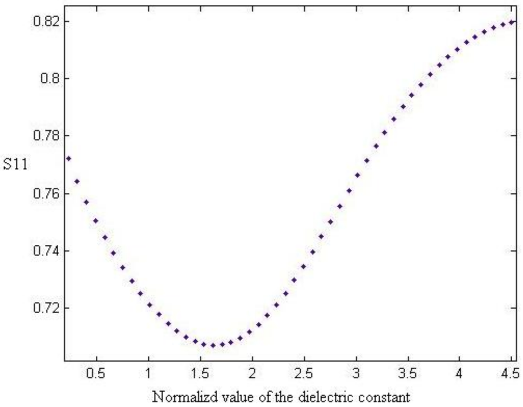

Figure 6. S11 simulation results for the dielectric constant sweep

Figure 6 shows an example of the parameter sweep simulation by Ansoft designer. The frequency is set at 433MHz. By sweeping the parameter value of the substrate dielectric constant, the corresponding return loss simulation results can be obtained.

Statistical Analysis

It is complicated and almost impossible to give a precise formula of the return loss or some similar concepts, taking into account of all the parameters of the PCB board and layout. Optimization for wireless sensor node has been performed using a try and see method [5], which is very inefficient. However, building the statistical relationship between the parameters and the return loss is achievable. Based on the simulation and measurement data, statistical analysis can be applied to show relationship of the parameters.

A. Measure of the parameter impacts on S11

Since there are lots of parameters potentially can change S11, it is not an easy task to tell which parameter should be analyzed first, or which parameter has the greatest impact on the target output.

The standard deviation is a widely used measure of the variability or dispersion, which can be a measure of impacts on S11. The standard deviation shows how great the target parameter is changed from its mean value.

Let X be a random variable with mean value μ:

$$\boldsymbol{E}[X] = \mu \tag{1}$$

Here the operator $\boldsymbol{E}$ denotes the average or expected value of X. Then the standard deviation of X is the quantity

$$\sigma = \sqrt{\boldsymbol{E}[(X-\mu)^2]} \tag{2}$$

The standard deviation is related to the mean value μ, which might be different for all parameters. In probability theory and statistics, the coefficient of variation (CV) is a normalized measure to get rid of the impact of the mean value. It is defined as the ratio of the standard deviation to the mean:

$$C_V = \frac{\sigma}{\mu} \tag{3}$$

The coefficient of variation is useful because the standard deviation of data must always be understood in the context of the mean of the data. The coefficient of variation is a dimensionless number.

The standard deviation and coefficient of variation for the five selected parameters are listed in Table 3.

Parameters	Standard deviation	Coefficient of variation
Dielectric constant	0.038467	0.05097
Substrate thickness	0.065957	0.103914
Interconnect track width	0.01144	0.01612
C2	0.292387	0.927165
C1	0.073586	0.084148

Table 3. Standard deviation and coefficient of variation for the parameters

C2 had the largest standard deviation and coefficient of variation, which means C2 held the greatest impact on the return loss compared with the other parameters. Thus, during optimization step later, C2 should be the first thing to be considered.

Substrate thickness and C1 were at a lower level of coefficient of variation. The two parameters should also be analyzed for optimization following C2.

The impact of substrate dielectric constant was weaker and the interconnect track width had the smallest coefficient of variation.

The priority for the parameters during optimization can be decided by the ranking and order of the standard deviation and coefficient of variation.

B. Regression and curve fitting

In statistics, regression analysis focuses on the relationship between a dependent variable and one or more independent variables. Regression analysis tries to explain how the typical value of the dependent variable changes when any one of the independent variables is varied, while the other independent variables are held fixed.

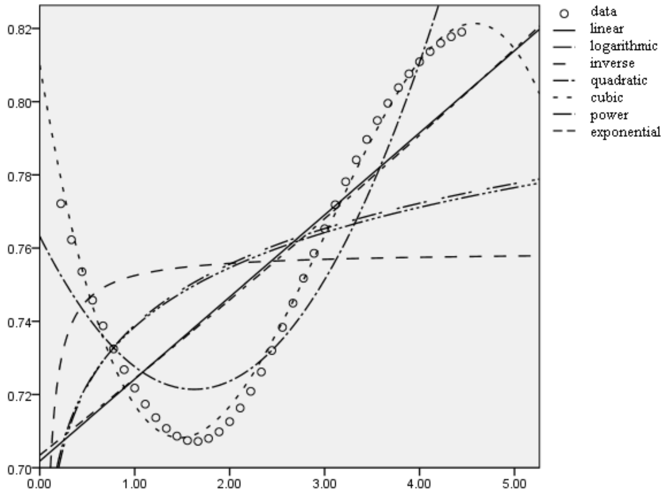

Figure 7. Different regression models for the data of substrate dielectric constant simulation

The estimation target of regression is a function of the independent variables called the regression function. The data are fitted by approximations.

SPSS and Matlab can help to finish the regression tasks. Figure 7 and Table 4 are the regression results by SPSS.

function	Model				
	R^2	F	df1	df2	Sig.
linear	.554	45.950	1	37	.000
log	.229	10.997	1	37	.002
inverse	.022	.849	1	37	.363
quadratic	.899	159.455	2	36	.000
cubic	.994	2043.102	3	35	.000
power	.223	10.608	1	37	.002
exp	.545	44.404	1	37	.000

Table 4. Regression results for different models

Several function models were used to fit the data. The parameter R^2, or the coefficient of determination, should be as close to 1 as possible; while the Sig., the significance, should be close to 0 for a good regression.

Cubic function fits the dielectric constant best because of its $R^2 = 0.994$. And the regression function is also obtained:

$$y = -0.008x^3 + 0.069x^2 - 0.154x + 0.81 \qquad (4)$$

$$x \in [0.2, 4.5]$$

The values of the results should be different from the other motes' and were used to show the whole analysis procedure.

Repeated the regression procedure for the other parameters:

Substrate thickness, $R^2 = 1.000$ for

$$y = -0.001x^3 + 0.018x^2 - 0.119x + 0.829 \qquad (5)$$

$$x \in [0.2, 4.5]$$

Interconnect track width, $R^2 = 1.000$ for

$$y = -0.009x + 0.731 \qquad (6)$$

$$x \in [0.2, 4.5]$$

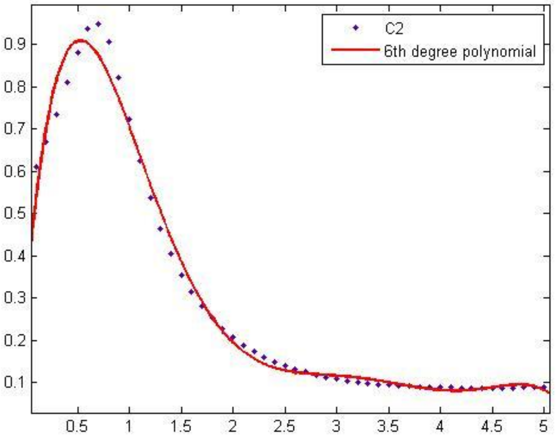

Figure 8. Curve fitting for C2 parameter sweep

As SPSS doesn't support high order degree regression and curve fitting, Matlab cftool (curve fitting tool) is utilized for high degree regression, to ensure a reliable R^2. Figure 8 and 9 provides two examples for high order nonlinear regression.

The regression coefficient of C2 is $R^2 = 0.994$ by the polynomial regression function:

$$y = -0.01137x^6 + 0.1882x^5 - 1.231x^4 + 3.986x^3 - 6.44x^2 + 4.237x - 0.01554 \qquad (7)$$

$$x \in [0.2, 4.5]$$

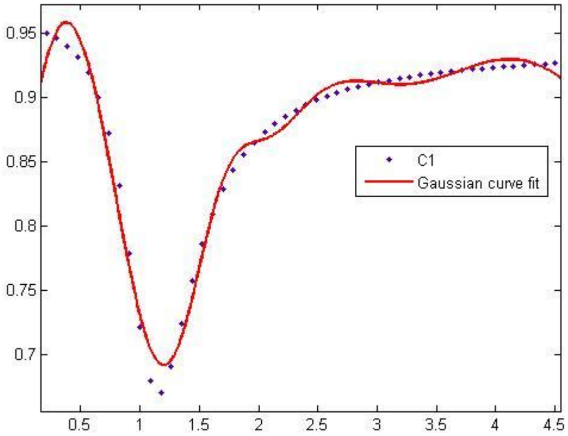

Figure 9. Curve fitting for C1 parameter sweep

The regression coefficient of C1 is $R^2 = 0.982$ by the Gaussian regression function:

$$y = 0.767e^{-\left(\frac{x-0.3001}{0.8176}\right)^2} + 0.9268e^{-\left(\frac{x-4.192}{3.047}\right)^2} + 0.2409e^{-\left(\frac{x-2.21}{0.9235}\right)^2} + 0.1432e^{-\left(\frac{x-1.672}{0.4072}\right)^2} \qquad (8)$$

$$x \in [0.2, 4.5]$$

Despite the complexity of the regression functions, expressions are available for extreme value analysis, which is impossible to perform on raw data.

C. Optimization by extreme value analysis

Extreme value points are the points having a local minimum or maximum for a function. In order to get the best (smallest) return loss, the extreme value should be found.

There are lots of methods to get the extreme value, among which the second derivative test [7] is a common one. The second derivative test stated: If the function f is twice differentiable at a stationary point x, meaning that $f'(x) = 0$, then:

If $f''(x) < 0$ then f has a local maximum at x.

If $f''(x) > 0$ then f has a local minimum at x .

If $f''(x) = 0$, the point x is neither a maximum nor a minimum.

Since it was found in previous chapter that C2 had the largest impact on return loss, the second derivative test was carried out on the C2 regression function (4). Figure 10 shows the curve of the value, first order derivative and second order derivative of the C2 regression function.

For first order derivative, $f^{'}(0.6) = 0$ and $f^{''}(0.6) < 0$, thus 0.6 is a maximum point and not suitable for return loss optimization. For the region above 2.5, $f^{'}(x) \approx 0$ with $f^{''}(x) > 0$. This is minimum extreme value which leads to improvement of return loss. Take the middle of the range $[2.5, 4.5]$ =3.5. The real value of 3.5 for C2 is 3.5*10pF =35pF. However, there is no 35pF for the real capacitor, and thus the 36pF capacitor is selected.

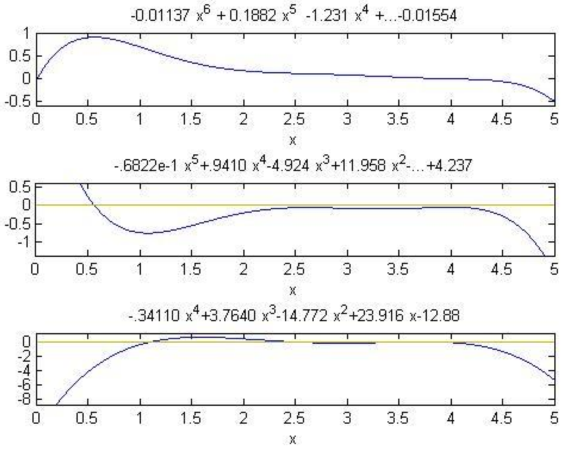

Figure 10. Top: regression function (4), Mid: first order derivative of (4), Bottom: second order derivative of (4)

The same procedure can be performed to C1 and a related value of 1.2 is chosen. The real value of 1.2 for C1 is 1.2*4.7pF=5.64pF. So the new value of 5.6pF capacitor is selected for C1.

Simulation and Measurement

Following the optimization procedure proposed, sweep of passive components' values was performed to get an optimized return loss simulation result. The reason to sweep the passives is that replacing the passives with new values is much easier than replacing all other parameters.

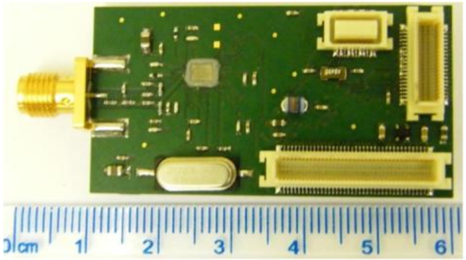

Figure 11. The wireless mote with a flip-chip bare die

Finally the new values of the passives were applied for PCB assembly. Measurements were compared with the simulation results until a good match was achieved. The optimization procedure was ended at this step.

In our case, optimization suggested changing the value of C2 from 10pF to 36pF and C1 from 4.7pF to 5.6pF. This change is to overcome the return loss degrade caused by substrate thickness change and layout impact of the flip-chip interconnect.

The measurement of return loss was carried out on the mote shown in Figure 11. The mote had an ADF7020 die flip-chip mounted on the left part of the board.

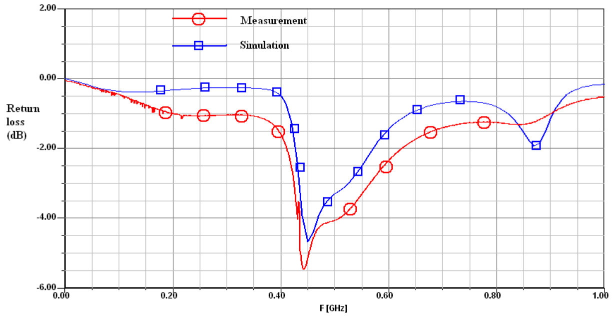

Figure 12. Simulation and measurement of the return loss with the recommended values of the passives

The result in Figure 12 partly explained the necessity to do simulation and optimization for the wireless mote using new interconnect technology or different substrate stack-up or PCB layout. There were lots of reasons about the poor return loss in Figure 12, including the substrate thickness change, the special requirement of the PCB layout for the bare die routing.

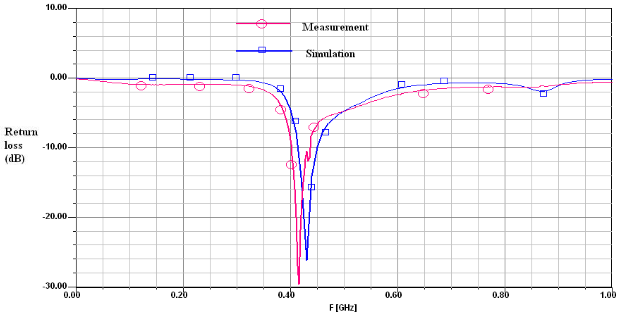

Figure 13. Simulation and measurement of the return loss with the optimized values of the passives

Simulation and measurement of the return loss, shown in Figure 13, were carried out again according to optimization solution. The return loss at 433MHz improved to -25dB for both simulation and measurement results (Figure 13). This level of return loss meant good impedance matching of the balun circuit. Finally Figure 14 illustrates that the return loss degrade was compensated with the help of new C1 and C2 values.

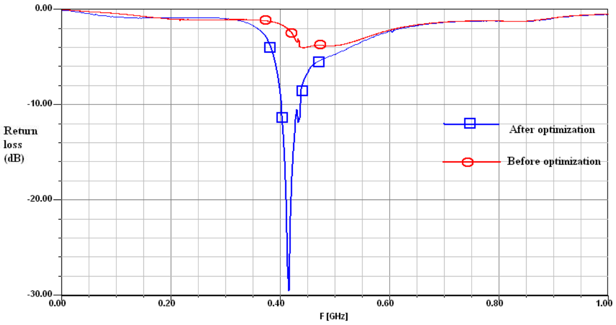

Figure 14. Measurements of the return loss before and after optimization

Conclusions

In this paper, the return loss of a wireless sensor node with a flip-chip bare die and more complex layer stack-up is compared with the reference transceiver board’s return loss. Modeling counting on passive components, RF ports, substrate and interconnect parameters was developed and simulated by Ansoft Designer. Place conclusions here. Several statistical methods, including the coefficient of variation, regression and curve fitting, were applied to analysis and optimize the return loss impacts and behaviors. Then based on the regression functions got in the previous study, an extreme value search was carried out on the functions to get an optimized return loss (minimum). Measurements, before and after optimization, not only fit the Ansoft Designer simulation, but also showed a major improvement of the return loss from -5dB to -25dB.

Acknowledgments

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