Evaluation of Relative Humidity and Temperature Effects on Scattering Parameters in Transmission Systems

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1 This research was partially supported by the Center for Signal Integrity, Penn State Harrisburg.
Abstract
This paper is focused on the development of a simulation method in order to evaluate relative humidity and temperature effects of scattering parameters on transmission systems from DC to 26 GHz. The first step in the analysis is to design a number of experiments to quantify environmental impacts on S-parameters. Through comparison with several experiments, the proposed method demonstrates that humidity and temperature effects on transmission systems can be accurately modeled and predicted. This method can be applied to different Printed Circuit Board materials, and it will be useful to engineers and manufacturers interested in predicting environmental impacts on system performance.

Author Biographies
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Mike Resso is the Signal Integrity Application Scientist in the Component Test Division of Agilent Technologies and has over twenty-five years of experience in the test and
measurement industry. His background includes the design and development of electro-optic test instrumentation for aerospace and commercial applications. His most recent activity has focused on the complete multiport characterization of high speed digital interconnects using Time Domain Reflectometry and Vector Network Analysis. He has authored over 30 professional publications including a book on signal integrity. Mike has been awarded one US patent and has twice received the Agilent “Spark of Insight” Award for his contribution to the company. He received a Bachelor of Science degree in Electrical and Computer Engineering from University of California.

I. Introduction

Printed circuit boards (PCB) and interconnects, and in general electronic systems, are expected to work under various environmental conditions such as high humidity and/or high temperatures. Moisture and temperature conditions do have an impact on the performance of the PCB’s and other electronic systems. As a consequence, the signal integrity community has shown interest in learning about the reliability of these systems as they work at high frequencies, especially at 10 GHz and higher. To the authors knowledge, few papers have investigated this problem [1-3].

Sheets and D’Ambrosia [3] explored environmental impact on XAUI backplane performance. They found an increased S-parameter sensitivity in the backplane at different temperatures and humidity levels, with more pronounced effects at high humidity and high temperatures (60 C and above). However, this research was performed at relatively low frequencies of less than 8 GHz. Echigo et al. studied [1] the effects of humidity and temperature in a five-layered PCB composite of aramid paper and epoxy resin. In [1], the authors found that the device under test (DUT) had weight increment with an exponential behavior under humidity and temperature conditions, and became saturated at about 100 hours of exposure. They also found that more moisture is absorbed as the humidity increases for the same temperature. However, the focus of the above paper was more focused on the effect of temperature and humidity on space charge distribution profiles and not on S-parameters performance.

Hamilton et al. [2] investigated the temperature and relative humidity impacts on transmission line system. In [2], transmission lines, from PCBs, were subjected to drying and moisture absorption conditions. Based on the obtained results, they presented a model to predict absorption rates and transmission line loss. In the first of two test steps, Rogers and FR-4 boards were stored in less than 10% relative humidity (RH) and room temperature, a so called “dry state”. Second, the boards were placed in an environmental chamber set at 38 degrees C and 95% RH, a so called “wet state” over a period of time. One of their conclusions [2] was that the measured insertion loss of microstrips and
striplines on Rogers RO 4350 showed a smaller magnitude change due to moisture than FR4 boards.

The focus of the proposed paper is to not only evaluate the temperature and RH impact on microstrips as in [2], but also to accurately and efficiently simulate the behavior of transmission lines from environmental impacts. The major goal here is to develop a simulation tool that can accurately predict the magnitudes and phases of S-parameters due to the environmental impacts at high frequencies.

The simulation method evaluates RH and temperature effects on S parameters of transmission systems from DC to 26 GHz. The first step in the analysis is to design a number of experiments to quantify environmental impacts on S-parameters of transmission systems. Based on the S-parameter measurements and analysis, insertion loss variations that are due to the environmental changes will be simulated in Mathwork’s MATLAB. Through comparisons with several experimental results, the proposed method can demonstrate that humidity and temperature effects on transmission systems can be accurately modeled and predicted by the proposed algorithm. This method can be applied to different PCB materials and could be useful to PCB engineers and manufacturers interested in predicting environmental impacts on system performance. In Section II the experimental set up is described. Based on these results, a simulation tool is presented in Section III where an evaluation of the simulation tool is also discussed. Summary and conclusions are given in section IV.

II. Experimental Set up and Procedure

Two-layer microstrip lines of different materials and thicknesses of 0.062, 0.060, 0.031, and 0.030 inches of dielectric material were studied. The board length and width were 5 inches and 1 inch, respectively. FR4 and Rogers RO 4350 were chosen as substrate materials. Lighthorse Technologies female SMA end launch jack connectors (part number LTI-SASF55ZGT) were soldered on both ends at each test device. These SMA connectors have a rated frequency range from DC to 26.5 GHz. On some boards, a solder mask was applied both on the top conductor and the bottom layer, in order to determine its effects on S-parameter performance due to change in environmental conditions. Pictures of some DUTs are shown in Fig. 1.
A temperature and humidity chamber, Cincinnati Sub-Zero Products Model Number: ZHS-32-2-H/AC was utilized to change the environmental conditions imposed on the DUTs. A calibrated electronic scale Mettler AE 100 was used to measure the mass of the DUTs. An Agilent Technologies Performance Network Analyzer (PNA) E8364B was the chosen measurement instrument, which offers a wide test frequency range from DC to 50 GHz. The PNA was calibrated using an electronic calibration kit N4693A, and short-open-load-through (SOLT) calibration method was performed. The latest version (v.5.2) of Physical Layer Test System (PLTS) available at the time of measurements was used.

In order to accurately measure the DUT S-parameters, it is necessary that the experiments be repeated under the same conditions. This means that the measurement processing time and temperature change needs to be as small as possible. Since operator’s hands can be a heat source during the measurement process minimal hands touching time was required. Cable movement was also restricted after calibration and connector cleaning was performed every 12 hours.

Before the S-parameters measurements, the DUTs were baked in a temperature chamber at 80 degrees C for 5 days to remove any initial moisture. After this step, the DUTs should contain less than 5% RH as indicated by [2] and then they were weighed at room temperature. In [2], the authors considered this a “dry state”. After the PNA calibration, and initial measurement at “dry state”, the DUTs were placed in the environmental chamber where temperature and RH were controlled.
The two test conditions used during the measurement process were 35 degrees C at 95% RH and 55 degrees C at 95% RH. Measurements of S-parameters were made at regular increasing time intervals. The flow chart for the experimental procedure is shown in fig. 2. The DUTs were in the environmental chamber for a maximum of 7 days. After this time, variations in weight (i.e. moisture content) were within the error range of the scale, which meant that the DUTs were saturated. This observation is in line with [1]. The S-parameter measurement taken after the saturation point also showed negligible change. These findings were also be noted in the experiments performed by [2].

Fig. 2: Measurement process

Pictures describing the measurement system, environmental and temperature chambers, and precision electronic scale used in this experiment are shown in figs. 3 to 6.
Fig. 3: Performance Network Analyzer setup

Fig. 4: Temperature chamber for baking the DUTs

Fig. 5: Mettler AE 100 lab scale
III. Experimental Results

Based on the test conditions described for the experiments, i.e. 35 degrees C at 95% RH and 55 degrees C at 95% RH, the following results are presented. Fig. 7 shows an FR4 microstrip weight change versus time. The weight change has an exponential-like behavior from dry state to saturation point in 168 hours. Similar trends were observed for the other DUTs as well as in research reported by [1]. Fig. 8 displays weight increment from its baseline at dry state. Since weight changes were more pronounced at the beginning of the experiment, measurements were taken every three hours in this first twelve hours. Afterwards, twelve hour intervals were used.

$S_{21}$ measurement plots from dry state to saturation (168 hours) for FR4, FR4 with solder mask, and Rogers RO 4350 microstrips are shown in Figs. 9 through 11. The two DUTs with FR4 display more pronounced loss at higher frequency than the Rogers RO 4350, approximately 14 dB for FR4 and 6 dB for Rogers. After 168 hours there were no noticeable changes in insertion loss $S_{21}$. These trends in $S_{21}$ behavior were also observed by [2], although the placement in the temperature chamber (55 days) was much longer than our experiments. However, after 7 days, changes in $S_{21}$ were minimal as reported in [2].
Fig. 7: Weight versus time for FR4 microstrip

Fig. 8: Weight increment from dry state for FR4 DUT
Fig. 9: S$_{21}$ measurements, microstrip using FR4 without solder mask

Fig. 10: S$_{21}$ measurements, microstrip using FR4 with solder mask
Fig. 11: $S_{21}$ measurements, microstrip using Rogers 4350 with solder mask

Fig. 12 shows the wrapped (and unwrapped) phase for $S_{21}$ of FR4 0.030 inch with noticeable phase variations starting at 6 GHz and up. A zoom-in at 10 GHz depicts in detail phase variations at different times. The phase difference between the dry and saturation states is about 40 degrees and increases to 80 degrees at 20 GHz.
**Fig. 12:** $S_{21}$ phase of FR4 0.030 inch thick microstrip line at 55 degrees C at 95% RH with zoom-in at 10 GHz

Return loss ($S_{11}$) measurements are depicted in fig. 13. It shows that $S_{11}$ changes are minimal. Similar results were also reported in [2]
Fig. 13: $S_{11}$ measurement data of microstrip line (FR4 without solder mask), at 55 degrees C at 95% RH

IV. Simulation Tool

Obtained experiment results validate previously reported findings in [1, 2], which provides foundation for developing a simulation tool to predict microstrip line behavior under different temperature and humidity conditions using intelligent curve fitting. A good curve fit would have minimal error between its approximated values and the original ones. Mathematically, for $n$ data points of $(x,y)$ where any $x$ corresponds to only one $y$, there exists a polynomial $y = p(x) = a_{n-1}x^{n-1} + a_{n-2}x^{n-2} + ... + a_0x^0$ with degree $(n-1)$ that fits all of those data points. However, as $n$ gets larger it takes much more time to compute. There is trade-off between computation time and accuracy of the interpolation results, which will be described further. Examination of the DUT weight change versus time is studied next.

DUT’s weight change versus time

Experimental data of the weight change versus time is shown in fig. 14. It is assumed that the DUT starts at dry state at $t = 0$ and is fully saturated at 168 hours. The DUT’s ability
to hold moisture increases in exponential-like fashion up to the saturation point. A data curve fit is used, and shown in red, with the following sixth order polynomial

\[ y(x) = -2.17 \times 10^{-10} x^6 + 1.18 \times 10^{-7} x^5 - 2.51 \times 10^{-5} x^4 + 2.62 \times 10^{-4} x^3 - 1.34 \times 10^{-1} x^2 + 3.69 x + 9.88 \]

**Fig. 14:** Fit weight increment data to a sixth degree polynomial

**DUTs S-parameters and Time**

The graph of S\(_{21}\) magnitude at any spot frequency (up to 26 GHz) versus time shows an interesting trend as depicted by a third order polynomial curve fitting. Sample curve fittings at 1 GHz and 20 GHz are shown in fig. 15. The trend of S\(_{21}\) is always decreasing and offers an opportunity to develop an interpolation scheme. Note that it is also possible to devise a prediction scheme since random reconnection errors can be taken into account. The flow chart of an interpolator is described in fig. 16. Based on a third order polynomial fit of the weight change, an equation is created for each spot frequency and the coefficients are recorded in a look-up table. Similar procedure for phase interpolation was used. The interpolator now can be used for any instant of time, not necessarily a measured data point, during the process and can interpolate S\(_{21}\) plots, both for magnitude and phase.
To test the interpolator, the algorithm is input with $t = 36$ hrs. The result shows that the DUT FR4 0.0300 inch thick board is at 54.1% of the saturation point. Using the described prediction procedures, the simulated $S_{21}$ magnitude is obtained and then compared with the actual measurement in fig. 17 (a). Fig. 17(b) shows the $S_{21}$ magnitude difference between simulation and measurement and indicates a good agreement. Figs. 18(a) and (b) depict phase interpolation results and phase difference, they also show very good agreement between the interpolation and measurement results.

**Conclusions**

The discussed humidity-temperature experiments confirm results reported by [1, 2]. Based on the confidence of the results, a simulation tool to predict $S_{21}$ magnitude and phase was proposed and developed. Coefficients were stored in look-up tables for interpolating (predicting) new S-parameter values. Simulation results show good agreement. However, more experiments need to be performed to generalize the simulator for arbitrary geometries. Striplines will also be studied in future experiments. In addition,
a predictor can be designed if reconnection random errors are taken into account. A graphical user interface (GUI) can be also designed.

Fig. 16: Flow chart for the interpolation algorithm
Fig. 17: Error between actual data and prediction

Fig. 18: Error between actual phase and prediction
Bibliography


http://www.commsdesign.com/design_corner/showArticle.jhtml?articleID=20300581