End-Launcher Repeatability in Broadband Methods for Characterization of the Propagation Constant of Transmission Lines Using Two-Port Measurements

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***Abstract*—This work presents an analysis of the influence of connector repeatability in three different methods for estimating the propagation constant of transmission lines from two-port measurements. For this purpose, the repeatability of 16 transitions using 1.85 mm coaxial-to-microstrip end-launcher connectors has been tested. It has shown that using the same pair of connectors instead of the whole set significantly reduces the standard deviation of the transition S-parameters that affects the final estimation of the propagation constant, and especially the attenuation constant. In addition, the hypothesis that the measured data have a normal probability distribution has been validated by performing an Anderson-Darling test on the estimated S-parameters of the transition. The obtained standard deviation has been included in a sensitivity analysis, generating S-parameters from normal distribution and performing a Monte Carlo simulation. The objective is to study the standard deviation of the propagation constant obtained using the proposed methods when there are errors related to connector repeatability. In this case, unlike random errors of the analyzer, it has been found that all the compared strategies for the estimation of the propagation constant (traces, eigenvalues, and determinants) work in the same way concerning launcher repeatability errors. Furthermore, it has been seen that the propagation constant obtained also follows a normal distribution. Finally, to validate the presented theory, methods have been applied to several measurements of two lines in the 0.01- to 67-GHz frequency range, using the same kit and different combinations of different connectors. Results show that higher accuracy is obtained when using the same pair of connectors, considerably reducing attenuation constant ripple, which assesses the suitability of the proposed error analysis.**

***Index Terms*—Broadband measurements, connector repeatability errors, microstrip line, propagation constant, transmission line measurements.**

I. Introduction

The measurement of the propagation constant of transmission lines has been a topic that researchers have paid special attention to over the years, as it is necessary for microwave circuit design with high demanding specifications as broadband directional couplers and filters. Two strategies have been followed throughout the years: resonant and broadband methods. In this paper, we will examine the second ones, based on the one in [1]. They provide a continuous solution in the measured frequency range. Still, their main drawback is that they strongly depend on the precision of the measurements and show worse performance for estimating losses. To address the accuracy of broadband methods, an error analysis, including random errors in magnitude and phase of the S-parameters, as well as errors in the length of the lines, was performed in [2]. This analysis showed that eigenvalue-based methods were less sensitive to random errors than other methods based on traces or determinants. Furthermore, it was demonstrated that length errors are interpreted as a bias in the final estimation. Another problem of this kind of methods is that they are all based on the invariant concept [3], which assumes that the transition is the same in all measurements. However, this statement is not entirely true since connector repeatability is not entirely assured in a real setting. In this sense, in [4], authors demonstrated that results could be significantly better if special attention is paid to the repeatability of the launcher, as they used a destructive method that cut the transmission lines but kept the same connectors through the whole characterization process. In [5] authors identified that half-wavelength errors in Through-Line (TL) calibrations are, in part, due to fixture inconsistencies. Regarding connector repeatability, stochastic models can be used to study their behavior [6], modeling each possible perturbation as an equivalent two-port circuit. A practical way of representing the uncertainty in complex S-parameter measurements was presented in [7]. Repeatability tends to have more variance at high frequencies and affects the phase notably, more than to the magnitude of the measured S-parameters. A similar approach to this work, but at lower frequencies, was attempted in [8], where was stated that repeatability errors may have an influence on the measurement results, that is about an order of magnitude bigger than measurement noise. In [9], authors showed that the size of the noise peaks in a transmission line characterization is somehow related to the connections of the device under test.

This letter studied the connector repeatability influence in broadband two-port methods used for estimating the propagation constant of transmission lines using two-port measurements. For this purpose, firstly, the standard deviation of several connectors is obtained through measurement and a later de-embedding process. This standard deviation is used to carry out a Monte Carlo simulation that includes many transitions, showing how the repeatability of the connectors influences the estimated propagation constant. Finally, the theory developed is assessed through experimental validation.

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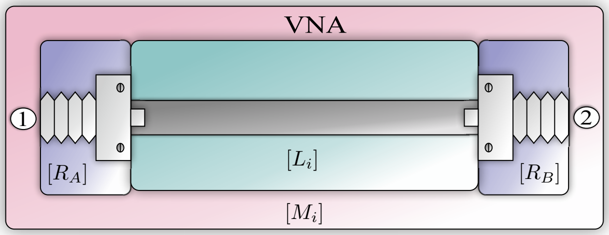

Fig. 1. Cascade connection diagram of different two-port circuits involved in the transmission line T-parameters measurement using a vector network analyzer.

II. Connector repeatability

Methods compared in this letter were studied in [2]. All methods start from the measurement of two-port S-parameter matrix of transmission lines of different lengths using a vector network analyzer. To cascade the matrices of the transitions and the line, transmission parameters are used. The measurement scheme is shown in Fig. 1. In this scheme, matrices $[R_A]$ and $[R_B]$ are the transition T-parameters (transformed from the transition S-parameters), that contain the effects between the VNA connector and the reference plane of the TRL calibration, whereas $[L_i]$ includes each transmission line effects. Measured matrix $[M_i]$ can be expressed as $[M_i] = [R_A][L_i][R_B]$. All methods considered assume that transitions and, therefore, matrices $[R_A]$ and $[R_B]$ are the same in every measurement. However, this fact is not entirely true since real connector repeatability is not considered. For this reason, what is proposed is to analyze the standard deviation of $[R_A]$ and $[R_B]$ in a set of measurements. They can be considered as error boxes in a Through-Line-Reflect (TRL) calibration. For this purpose, a multiline TRL kit [10] is manufactured and measured, using two lines of length 2.39 and 52.59 mm, to isolate the effects of the transitions in the whole frequency band of interest. Substrate Rogers RO4350B, with 20 mil thickness, $\varepsilon = 3.66$, $\tan\delta = 0.0031$, and 17.5 μm thick copper metallization was used, whereas the lines were ended with 1.85 mm Southwest 1892-03A-6 end launchers connectors (dielectric diameter of 39 mils, pin diameter of 7 mils). As seen in [11], the frequency response of connectors slightly deteriorates at higher frequencies, but the invariant nature of the methods [3] allows the connectors to be used up to 67 GHz. The microstrip line width was set to 1.095 mm, to get a 50 Ω characteristic impedance, Z_0. Measurements were taken using the vector network analyzer Agilent PNA-X (N5247A), between 0.01 and 67 GHz, the whole range of the available instrumentation. The VNA configuration was set up as follows: $f_{start} = 10$ MHz, $f_{stop} = 67$ GHz, and 6401 data points were taken, using a delay before measuring each point of 250 μs. The bandwidth of the IF bandpass filter was set at 10 kHz, whereas the port power to -5 dBm.

The experiment was carried out in two different ways, but always taking sixteen measurements for each connector (as in [6], [12]), which is disconnected and disassembled after every measurement to simply introduce actual random errors. Sixteen measurements of each element in the TRL kit (an open reflect, a thru, and two lines) were taken using the same connectors. For example, for the Open Reflect standard in Port 1, sixteen measurements using connector A, 16 using connector C, 16 using E, and 16 using G are taken. For port 2, sixteen measurements using connector B, 16 using D, and so on. For Thru and Line standards, the same pair of connectors were kept. Later, a de-embedding process was performed in MATLAB to obtain the error boxes of each set of measurements. On the one hand, if the de-embedding is performed using all the measurements with the pair of connectors AB, CD, EF, or GH, what it is called "same connector". On the other hand, reflect measurements are performed with AB, Thru measurements with CD, and line measurements with EF and GH, which is called "Multiple connector kit". Finally, the standard deviation of these error boxes' real and imaginary part was calculated and represented in terms of in-phase/quadrature covariance-matrix [13]. Figure 2 depicts the magnitude (σ_m) and phase (σ_p) standard deviations, calculated from the in-phase/quadrature covariance-matrix. As seen, the standard deviation is higher when using different connectors, which will influence on how the methods work, as the transitions are different from each other. Furthermore, it is important to evaluate the probability distribution of the estimated transition S-parameters. For this purpose, what is proposed is to carry out an Anderson-Darling test [14] that validates whether the transition S-parameters follow a normal distribution or not. In [15], the authors conclude that the Anderson-Darling test is more robust and powerful than the Kolmogorov-Smirnov test for this purpose. This hypothesis is valid for the distribution in magnitude and phase of all the obtained transition parameters, both for a connector and for the joint distribution of different connectors, at 5% significance level. Although in [12], the authors state that the phase distribution is triangular, they mention that the triangular distribution can be approximated to a normal distribution.

III. Susceptibility to repeatability errors

The main objective is to study how several approaches traditionally used to obtain the propagation constant ($\gamma = \alpha + j\beta$) behave concerning connector repeatability. For this purpose, the three methods proposed in [2] are examined: Method 1 is based on traces of matrices, Method 2 on eigenvalues, and Method 3 on determinants. Regarding random errors in VNA, the strategy based on eigenvalues was the one that performed the best since it did not have resonances when the difference in electrical length was equal to $\pi/2$. To carry out the study, standard deviations plotted in Fig. 2 are the starting point of a Monte Carlo simulation that takes $[R_A]$ and $[R_B]$ as two random matrices, generated using a normal distribution (hypothesis validated in the previous section) as

$$\begin{bmatrix} (\delta+\sigma_{m_{S11}})e^{j\sigma_{p_{S11}}} & (1+\sigma_{m_{S12}})e^{j\sigma_{p_{S12}}} \\ (1+\sigma_{m_{S12}})e^{j\sigma_{p_{S12}}} & (\delta+\sigma_{m_{S22}})e^{j\sigma_{p_{S22}}} \end{bmatrix}, \qquad (1)$$

and they are then transforming it to T-parameters. The parameter δ is introduced to ensure that S_{11} and S_{22} are non-zero terms in case the magnitude error is 0. A value of $\delta = 0.0001$ is used. Actually, the value of $[R]$ T-parameters

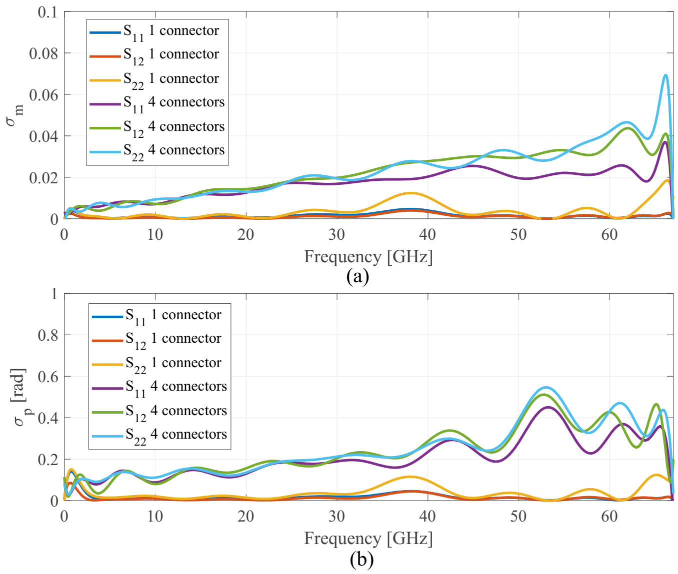

Fig. 2. Standard deviation in magnitude (a) and phase (b) of transition S-parameters obtained after measuring sixteen 1.85 mm connectors, using 1 and 4 different connector kits.

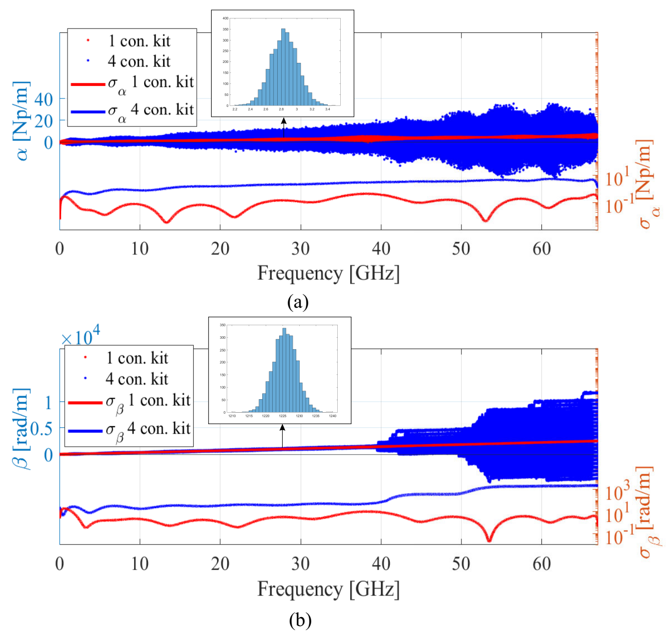

Fig. 3. Attenuation (a) and phase (b) constants and their standard deviation obtained by using 1 and 4 connector kits through Method 2.

would not affect if there were no errors since all the methods eliminate the effects of the transitions if they are the same in each measurement. $[L_i]$ matrices are generated from an electromagnetic simulation using ANSYS HFSS, considering two lines of lengths 11.31 and 52.59 mm, respectively, without taking into account any VNA error. Figure 3 depicts the results of the Monte Carlo simulation. In this case, and unlike random errors of the network analyzer, the three considered methods work in the same way with respect to connector repeatability errors. This fact can be effortlessly checked when evaluating matrices $[M_1]$ and $[M_2]$ using 2 different connectors $[R]$ for each line. The argument of the final function to solve in the

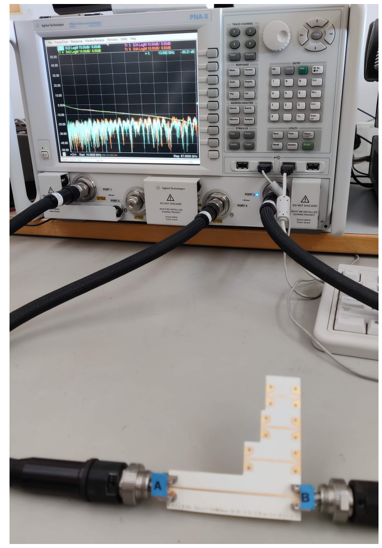

Fig. 4. Photograph of four microstrip transmission lines and the measurement setup using vector network analyzer for S-parameters measurement. The picture shows a pair of labeled connectors, A and B, that are used through the measurement process and correspond to R_A and R_B transitions.

three Methods is the same. For this reason, only results of Method 2 are displayed, as they are similar to Methods 1 and 3, to simplify figures. As seen, results are considerably better when using just one connector kit (red trace in Fig. 3) for both lines instead of using different kits (blue trace) for each line. As expected, the attenuation constant (α) is significantly more sensitive to repeatability errors than the phase constant (β). However, the phase constant is deteriorated considerably starting at 40 GHz to 67GHz. This fact is because it is obtained from equation

$$\beta = \frac{\theta + 2n\pi}{\Delta l}, \tag{2}$$

which has infinite possible solutions. To get the correct one, it is necessary to unwrap the phase, but when there are large random errors at higher frequencies, the unwrap function can fail and take the phase constant to another solution that is not physically correct. As shown in the histograms of Fig. 3, the propagation constant obtained after applying the method considering normal errors maintain a normal probability distribution. This hypothesis has been validated as well through an Anderson-Darling test, at 5% significance level. In addition, there is a similarity between the standard deviation of $[R]$ displayed in Fig. 2 and the one of the propagation constant (σ_α and σ_β), shown in Fig. 3 (note that Y-axis is displayed logarithmically in this figure).

IV. Experimental validation

To validate the analysis performed, the two lines simulated in the previous section with lengths 11.31 and 52.59 mm are manufactured using Rogers 4350B to extract the propagation constant. These lines are measured using the same network analyzer as in Section II, between 0.01 and 67 GHz. At this point, it is important to mention that measurements were taken without any calibration of the analyzer since the proposed methods do not require it to work properly [2]. A photograph

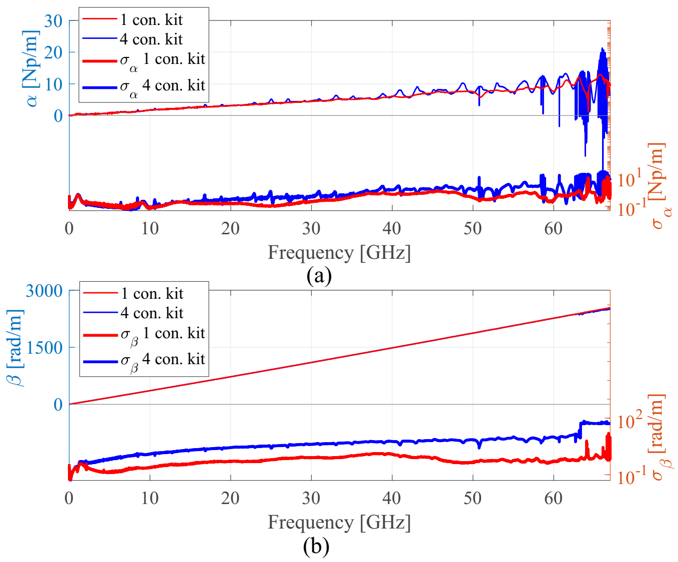

Fig. 5. Mean of the estimated attenuation constant (a) and phase constant (b) and their standard deviation obtained by using 1 and 4 connector kits through Method 2.

of the measurement setup is shown in Fig. 4. Sixteen measurements of each line have been taken using the same pair of connectors, and another sixteen measurements combining four different connector kits. From these measurements, Method 2, which is the least sensitive to the VNA's random errors, has been applied to all the possible combinations of lines, using 1 or 4 different connector kits for each line. Each connector is assembled and disassembled before each measurement to emulate a real measurement process. Results of the estimated propagation constant are depicted in Fig. 5 in terms of attenuation and phase constants. Both the mean and the standard deviation of these results have been represented. As seen, keeping the same pair of connectors reduces the standard deviation of the estimated propagation constant considerably, as discussed in the previous section. The measured propagation constants continue to fit a normal distribution, as validated through an Anderson-Darling test at a 5% significance level. Furthermore, it is noteworthy that the attenuation constant has less ripple and is more accurate at higher frequencies when only one connector kit is used. Losses are one of the main drawbacks of this kind of methods, and this can be a simple way of reducing uncertainty in the estimation of α and β significantly.

V. Conclusion

In this letter, an analysis of errors due to connector repeatability in three broadband methods for estimating the propagation constant of transmission lines from 2-port measurements has been performed. These three methods rely on the invariance of the transitions to isolate the effects of the lines and estimate the propagation constant. They should yield the same solution if there were no errors. Although this does not happen in the presence of VNA random errors, in this work, it has been demonstrated, through a Monte Carlo simulation, that in the case of connector repeatability errors, the methods behave in the same way regarding this kind of errors. Furthermore, it has been shown that using the same connector kit instead of different ones in all the transmission lines used to characterize the propagation constant is an appropriate way to reduce the uncertainty of the final estimation considerably. This analysis has been corroborated with real measurements, showing that taking measures with the same kit reduces the standard deviation of both, attenuation and phase constants and, therefore, corroborates the analysis proposed in this letter. This fact is especially relevant in estimating the attenuation constant, which is quite more sensitive to measurement errors, as it drastically reduces its ripple and is much more accurate at higher frequencies if only one connector kit is used.

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