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MM-wave Partial Information De-embedding: Errors and Sensitivities

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Abstract — **De-embedding methods making significant structural assumptions have become popular in recent years, particularly in PC board and cable assembly spaces, because of the relative immunity to repeatability and standards availability problems at the DUT plane. Some of the same issues occur in mm-wave fixtures where repeatability can be even more of a challenge. The intrinsic errors, repeatability behavior and configuration sensitivities of one such method, based on phase localization of structures in the fixture using reflection data alone, are studied in this work with examples in the WR-10 and WR-2.2 bands. For some classes of fixtures, the repeatability immunity and standards sensitivity can be orders of magnitude better than with classical methods while showing similar sensitivities to first tier calibration issues. The absolute errors can, however, be substantial for certain distributions of mismatch within the fixture.**

Index Terms — **network analysis, de-embedding, mm-wave.**

I. Introduction

Dozens of de-embedding routines are commonly used at mm-wave frequencies (e.g., [1]-[4]) and most are based on limited assumptions, often reciprocity and perhaps symmetry, about the fixture parameters. It has been found at lower frequencies (e.g., [5]-[9]) that if the DUT interface has repeatability or standards issues, these classical approaches may be sub-optimal. Reasons include: (1) the thru-reflect-line (TRL) family of approaches are sensitive to changes in launch impedances/admittances, (2) defined-standards approaches rely on geometrically well-controlled structures at the DUT plane (not always possible) and (3) the classical methods deterministically solve for inner and outer plane match and, as those match levels degrade, there is a nonlinear coupling to insertion loss extraction.

At mm-wave frequencies, all of these potential problems get worse. This paper will focus on DUT planes consisting of UG-387 waveguide flanges modified for DUT support where those modifications tend to reduce mechanical stability of the interface. At high enough frequencies, it has been shown by many groups (e.g., [10]) that even the conventional UG-387 flange may not be very repeatable.

Thus an approach used at lower frequencies, that of partial information de-embedding (e.g., [5]-[9]), may be even more useful in the mm-wave fixture problem. While there are many permutations on these methods, one variety uses spatial separability of dominant mismatch centers from the main path. In a sense, it is a spatial model-based fixture extraction. A single standard, usually a full reflection or a thru, is often needed at the DUT interface. This method will be studied in this paper for a series of waveguide fixtures in WR-10 and WR-2.2 that have relatively low insertion loss (a more challenging type of problem). Of interest will be differences relative to classical methods in terms of repeatability, absolute accuracy and sensitivities to process issues. The problem precludes an easy global analysis of all of the dependencies but the intent is to explore some common trends semi-quantitatively.

II. Methods

For comparison purposes, two classical methods will be used (many others are possible and may have their own advantages but these two are believed to be somewhat representative of the class). TRL, pursued as a two tier calibration in order to allow comparison of fixture parameters, is one method. Bauer-Penfield [1] will also be used which is based on one-port calibrations (for each fixture arm) at both inner and outer planes. Bauer-Penfield can be viewed as a generalization of open-short de-embedding that is popular in on-wafer measurements (but makes lumped network assumptions).

The partial information method used is based on a single reflect measurement (per fixture arm) [8]. The reflection coefficient of the standard is assumed known. The reflection data is correlated with a series of propagation kernels to separate the portions of the response due to the reflect standard from those due to the internal mismatch centers. The process is shown schematically in Fig. 1. Because the contribution separation is based on phase resolution, there is a limit when a mismatch center near the DUT interface cannot be separated from the reflect standard at the DUT interface. Variations on this approach using time domain processing also exist.

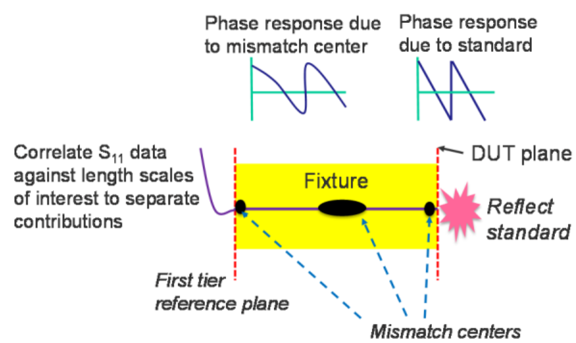

Fig. 1. An illustration of the partial information method.

III. Repeatability Behaviors

The central assumption for this analysis is that the DUT reference plane is repeatability-challenged in some way: modified flange to support DUT mounting, access lines for bias, mechanical superstructure for other instrumentation, etc.

In general, there will be some outer reference plane where repeatability is not as much of a concern (although it certainly can be if the frequencies are high enough and the requirements are tight enough). We will return to sensitivities to outer plane (first tier) behavior in section V.

As a demonstration of the level of repeatability problems that can happen, a somewhat controlled Monte Carlo measurement experiment was run using the various methods on a WR-10 fixture. The DUT plane lacked an anti-cocking support, had a concavity of the flange surface (about 200 μm) and two additional holes were drilled in the flange surface (2 mm from the aperture narrow walls) used for DUT mounting. The waveguide screw torque was randomized with a uniformly distributed range of 0.5-0.7 cN-m (on each screw for each connection). The same first tier calibration was used for all runs and twenty second tier runs were done. With the partial information method (see Fig. 2), the scatter was limited to largely one portion of the frequency range. This is believed to be related to an induced resonance that was load-sensitive.

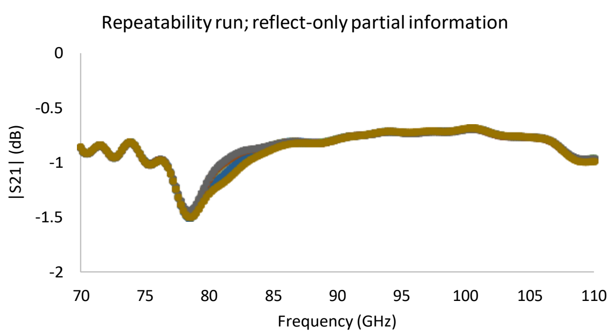

Fig. 2. The repeatability results for insertion loss using the partial information method here using the approach discussed in the text.

The scatter on Bauer-Penfield (using a short-short-load (SSL) set of standards), was larger (see Fig. 3). Not surprisingly, the distribution is not particularly well-behaved as there are a number of non-linear geometrical mechanisms involved with both positional alignment [10] and skew gap formation.

A second-tier TRL comparison was also done. As is well-known, however, TRL is sensitive to lumped admittance inconsistencies at the launch points as it violates the line ideality assumption quite severely. The present fixture is unfortunate in this regard (although perhaps not unusual) as the DUT-accommodating flange presents a cornucopia of wayward admittance opportunities. The repeatability run is shown in Fig. 4. A multiline TRL approach (e.g., [11]) could improve this outcome from its increased repeatability immunity but constructing a large number of line lengths in this fixtured medium may be a challenge and the statistical behavior of the repeatability in such an environment may not be as amenable to an optimization approach.

IV. Absolute Accuracy Considerations

The absolute errors of this partial information method are a strong function of the spatial structure of the fixture in question because of the phase correlation (or time domain) techniques that are used. As one might expect, the processing details can also play a significant role (much how in regular time domain processing, the window selection can be a dominant uncertainty source [12]) so global conclusions will be difficult. The present method uses un-windowed data fed into a correlator against the waveguide propagation kernel.

A central question is how well one can separate the phase response due to various mismatch centers in the fixture from that generated by the reflection standard. This is a function of the location and size of the reflection centers relative to the frequency span as well as any conditioning applied prior to the correlation.

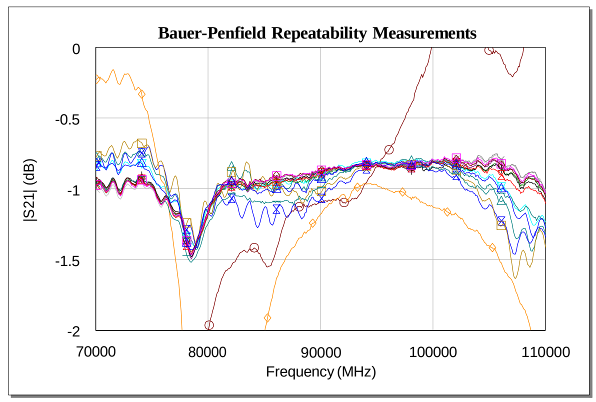

Fig. 3. The repeatability results for the Bauer-Penfield method on the example fixture are shown here.

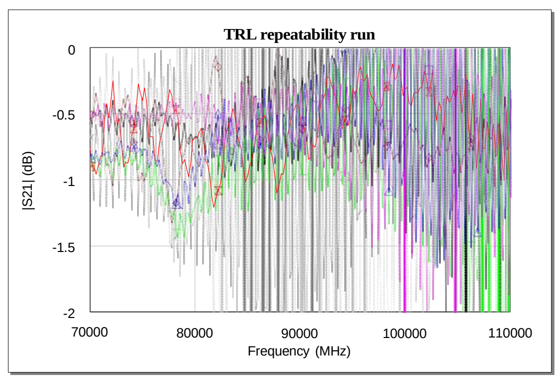

Fig. 4. The repeatability results for the two-tier TRL approach.

To explore this, a fixture was employed (also WR-10) with a normal UG-387 interface at the DUT plane but with holes drilled into the broad wall of the waveguide near the DUT plane so tuning probes could be inserted (see inset to Fig. 5). Mismatch centers at different distances from the DUT plane (and with different admittance levels) can be inserted and conventional de-embedding results compared against the partial information results without the results being dominated by repeatability issues.

With the probes retracted, the fixture return loss is higher than 15 dB up to 100 GHz and higher than 12 dB to 110 GHz. In this state, the Bauer-Penfield and partial information S_{21}

results differed by less than 0.13 dB across the range (see Fig. 5 top). The uncertainty on Bauer-Penfield for this setup (based on the calibration kits used on both planes and the VNA hardware) was 0.1 dB and the repeatability on this particular setup was 0.02 dB so the differences are not considered large.

With a tuning probe inserted fully at position 1 (1.5cm from the DUT plane), the match degrades substantially and a resonance is introduced into the structure as suggested by the middle image in Fig. 5. In regions where the resonance is not dominant (defined arbitrarily as places where the insertion loss is less than 5 dB), the differences are less than 0.25 dB. At the higher insertion loss levels, the reflection-based partial information method is starting to incur a subtraction-of-nearly-equal numbers problem and absolute accuracy starts to degrade.

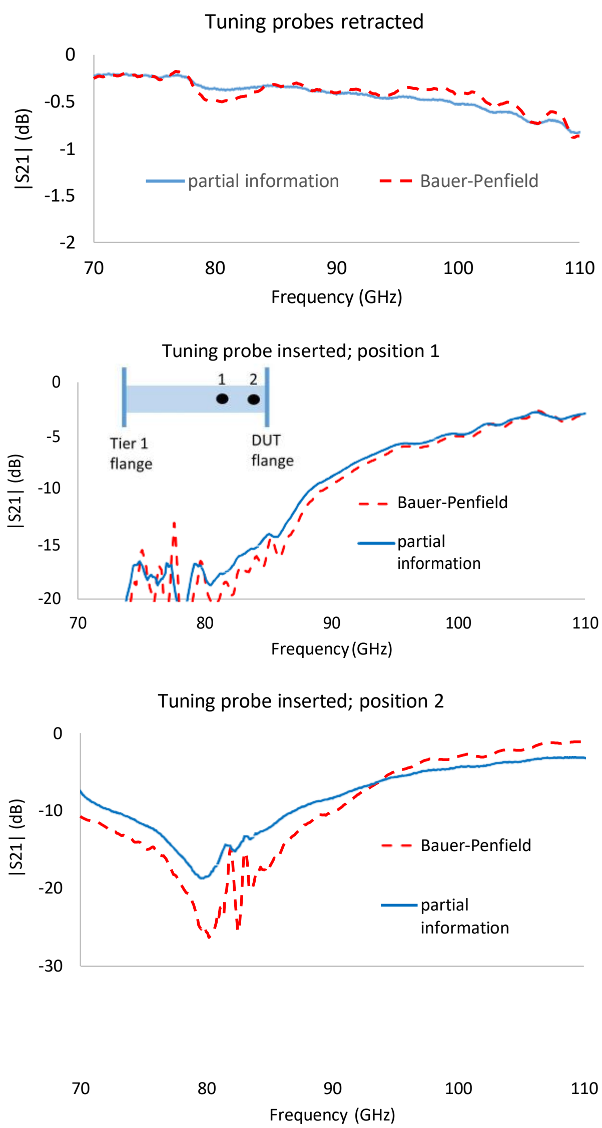

Fig. 5. The extracted insertion loss for the tuner-like fixture are shown here for Bauer-Penfield and partial information. Top: tuning probes retracted, middle: probe inserted far from DUT plane (position 1), bottom: probe inserted close to DUT plane (position 2).

With the tuning probe inserted at position 2 (5 mm from the DUT plane) the divergence increases. Since the bandwidth of the measurement is 40 GHz, the available phase change to analyze between the tuning probe and the reflection standard is getting small so the fixture match and insertion loss responses convolve with each other to some degree. The probe response was weaker in this case compared to the previous one (details of probe geometry) so the subtraction-of-nearly-equal numbers became less severe but this was swamped by the convolution of responses. In this case, differences exceeded 1 dB even at the more favorable frequencies. When probes are inserted in both positions, the results degrade further. This is in part because multiple reflections between the two probe positions have phase signatures approaching those of the reflection standard alone and separation is even more difficult.

The mismatch centers being introduced here were large in order to explore the envelope. Extraction of mismatch shows a similar relationship between methods (see Fig. 6) in the context of a directivity limit of about 0.03 (linear scale). This exercise was not intended to explicitly define absolute uncertainties but can illustrate the effects of mismatch center size and location.

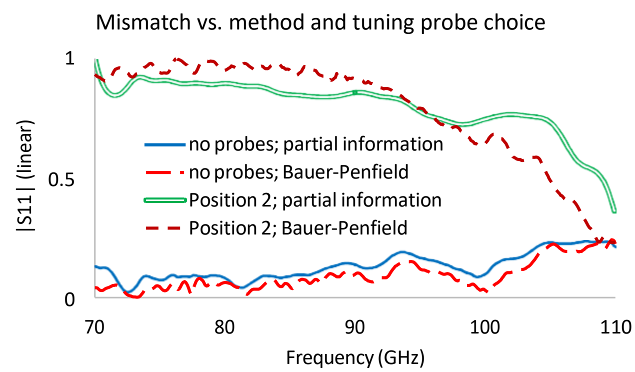

Fig. 6. A method/fixture state comparison (methodology as in Fig. 5) is shown here for extracted fixture match.

V. SENSITIVITIES

The sensitivities to standards errors may also be of interest. For the Bauer-Penfield (sensitivities covered more generally in, for example, [13]), we have been using an SSL standards set but conclusions for an SSS set are transparently related. As one of the shorts is common to the two methods, a basis for comparison is a Monte Carlo simulation based on an error in the short offset length. Plots are shown in Fig. 8 that yielded roughly equal peak excursions but the distributions of the length errors were wildly different for Bauer-Penfield (+/- 10 μm) and for the partial information method (+/- 2 mm).

The relatively heightened sensitivity of Bauer-Penfield is not surprising since the phase interval used in the correlation was on the scale of cm so an offset length error resulted in relatively minor magnitude impact for the new method. The phase of S_{21} is transparently affected for the partial information method if the offset length was used explicitly (instead of using an auto-rotation scheme). Two aspects of the Bauer-Penfield behavior: (1) the two offset short lengths were chosen for a 180 degree reflection phase difference at 90 GHz so the sensitivity to length error is minimized at that frequency, and (2) altering the length entry directly effects the S_{22} as well as the S_{21} extraction and there is feedback between these terms.

A set of measurements was also performed on a WR-2.2 fixture where short offset length errors were introduced. The DUT interface was a higher-than-specification-precision UG-387 flange so repeatability was not dominant (about 0.05 dB on extracted S_{21}). The results are shown in Fig. 8 and again one can see the sensitivity variance and an offset between the methods. The two partial information results differed by no more than 0.05 dB and essentially overlaid.

Another sensitivity class of interest is to defects in the first tier calibration. For this work, the reference planes for the first tier are usually more repeatable (conventional waveguide, coax or well-defined probes) so it may be considered to be less of a concern but sensitivity anomalies may be interesting.

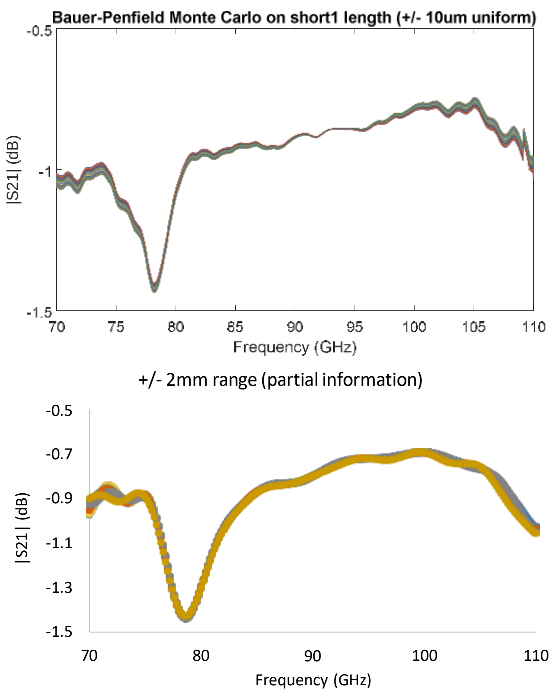

Figure 7. Insertion loss for the two methods are shown here where the variable was the offset length of a short standard. The distribution ranges differ by 200x but the insertion loss spread is about the same.

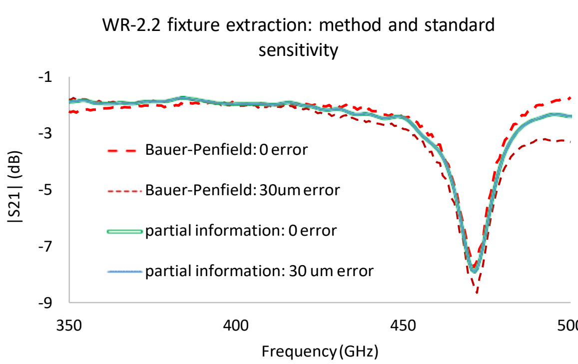

Fig. 8. Measured effects of a 30μm error (4 specific measurements) in short offset length on extracted insertion loss of a WR-2.2 fixture.

In Bauer-Penfield, the first tier error coefficients are cross-coupled into the second tier result so an elevation of sensitivities is expected. Plots of the effects of variations of 1% in magnitude and 10 degrees in phase (uniform distribution) of the first tier source match and reflection tracking terms are shown in Fig. 9. The error coefficient variations were assumed to be correlated as if linked to a short or open offset deviation.

In the case of the partial information technique, the sensitive frequency range is the same in the repeatability experiments. The structure at 77 GHz is a small resonance in the fixture and, as such, is the dominant contributor to nonlinear phase in the overall reflection response and the correlation process will highlight nonlinearities. The errors being introduced in the first tier calibration are introducing source match shifts which will interact with the resonance. The size of the effects for Bauer-Penfield and the partial information method were similar in this case.

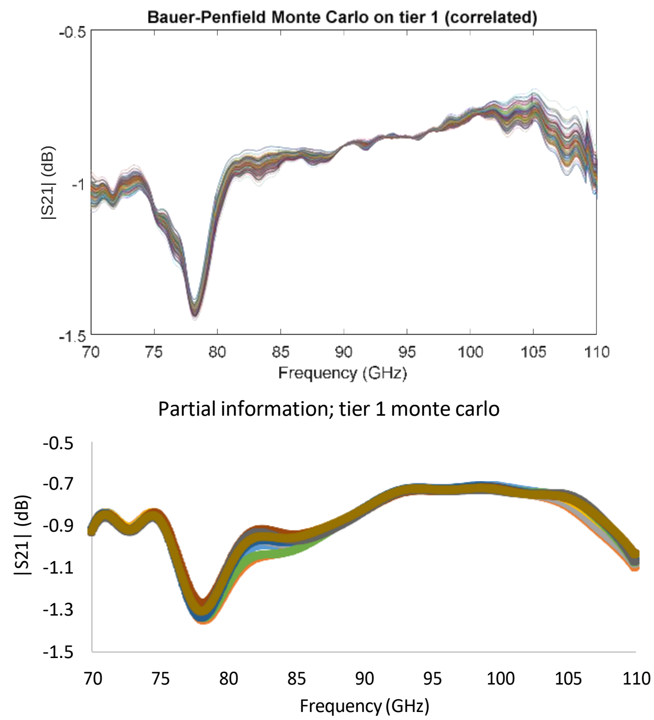

Fig. 9. The (relatively comparable) effect of errors in the tier 1 calibration are shown here for the two methods.

VI. Conclusion

In some repeatability-challenged mm-wave fixtures, classical de-embedding techniques can cause noticeable measurement problems. One of a class of partial information techniques (using a single reflect standard and essentially a spatial model-fitting process) was found to have good repeatability immunity and low sensitivities to standards problems. It does have absolute accuracy limitations if the fixture has a strong reflection center near the DUT plane (relative to 1/measurement bandwidth) or if there are multiple large reflection centers with a specific range of separations.

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