A Method for Improving High-Insertion-Loss Measurements with a Vector Network Analyzer*

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***Abstract* — We present a method for improving high-insertion-loss measurements with a calibrated vector network analyzer (VNA) requiring only two additional pieces of hardware. By utilizing an amplifier and an attenuator, and measuring wave-parameters rather than scattering-parameters, we are able to increase the dynamic range of our measurements while decreasing uncertainties due to the noise floor of the VNA. We compare the results of our technique to standard methods for insertion-loss values up to 110 dB.**

***Index Terms* — attenuator, calibration, high insertion loss, measurement, uncertainty, vector network analyzer.**

I. Introduction

The need to accurately characterize high values of insertion loss is critical in applications such as line-of-sight channel measurements and near- to mid-range antenna measurements. In our case, we are currently participating in a cooperative effort between the National Institute of Standards and Technology (NIST) and the National Telecommunications and Information Administration (NTIA) to quantify the agreement among four different types of channel-sounder systems for both conducted and free-field environments at 3.5 GHz. The VNA is serving as a reference to which the other three systems are being compared, since we can use it to provide traceable, calibrated measurements with uncertainties characterized by the NIST Microwave Uncertainty Framework [1].

In a free-field environment, we will encounter channels with insertion losses varying from 50 dB to 100 dB, depending on the separation distance between transmit and receive antennas. Standard methods for measuring the upper end of these values are inadequate, as the noise floor of the VNA limits our ability to accurately characterize such channels.

In this paper, we describe a straightforward method to extend the dynamic range of our VNA measurements by measuring wave-parameters, as opposed to scattering-parameters (*S*-parameters), and utilizing an amplifier and an attenuator. In the following sections, we describe our measurement setup, and compare results from this technique to standard methods.

II. Measurement Setup

Figure 1 shows a simplified schematic diagram of a four-sampler VNA. The source is switched between ports 1 and 2 so all four *S*-parameters can be calculated from the measured incident and reflected signals. Normally, a calibration is first performed to correct for non-idealities in the VNA, and then calibrated *S*-parameters of devices under test (DUTs) can be measured. The setup, shown in Figure 1, works well for moderate insertion losses, but as these values increase, the measurements become noisier due to the inadequate dynamic range of the VNA. In an attempt to overcome this problem, we developed a method that makes use of an amplifier between the source and the couplers on port 1. With the increased power incident on port 1, we need to place a compensating attenuator between the coupler and the receiver responsible for measuring the incident power to prevent damage to the receiver. Figure 2 illustrates these modifications, where a 20 dB amplifier and a 20 dB attenuator have been inserted. For measurements with this setup, we cannot risk damage to the receiver responsible for measuring the transmitted signal on port 2 when power is applied to port 1 and a DUT is connected between the two ports. Thus, for this case, we restrict ourselves to measuring DUTs with at least 20 dB of attenuation.

Prior to making measurements with the modified setup, we perform a calibration with the amplifier removed, but with the attenuator left in. With the amplifier removed, we can ensure the calibration is performed in the linear regime of the VNA. The attenuator must be left in, however, for the calibration to remain valid. Additionally, we are required to measure wave-parameters rather than *S*-parameters, and our calibrations must be performed with an eight-term model rather than a twelve-term model [2]. The reason is that the switch terms, which correct for differences in the reflection coefficients of the terminating resistor switched between ports 1 and 2, will change with the amplifier placed in the system. Wave-parameters automatically compensate for this phenomena since incident and reflected signals are directly measured [3].

The wave-parameter calibration begins by transforming the uncalibrated wave-parameter measurements of each standard into uncalibrated *S*-parameters. Then, we apply a calibration designed to work on switch-term-corrected data. If the user wishes to determine calibrated wave-parameters, two additional terms are required: the magnitudes at each frequency, which can be determined with a calibrated power meter, and the phase relationships among frequencies, which can be determined with a characterized comb generator. We should note that for this particular application, neither magnitude nor phase calibrations are required since we are ultimately taking ratios of the measured wave-parameters and calculating *S*-parameters.

TABLE I

COMPARING HIGH INSERTION-LOSS MEASUREMENTS OF FOUR DIFFERENT CALIBRATIONS

Attenuator Setting (dB)	$\|S_{21}\|$ Mean ± Std. Dev. (dB)			
	S-Parameters (-17 dBm)	S-Parameters (0 dBm)	Wave-Parameters (0 dBm)	Wave Parameters (0 dBm + Amp)
60	-60.69 ± 0.12	-60.71 ± 0.06	-60.71 ± 0.06	-60.70 ± 0.06
70	-70.72 ± 0.34	-70.74 ± 0.08	-70.73 ± 0.08	-70.72 ± 0.06
80	-80.79 ± 1.08	-80.95 ± 0.16	-80.71 ± 0.17	-80.68 ± 0.05
90	-90.81 ± 3.47	-90.87 ± 0.49	-90.64 ± 0.50	-90.63 ± 0.08
100	-97.27 ± 5.44	-100.70 ± 1.51	-100.58 ± 1.55	-100.52 ± 0.15
110	-98.66 ± 5.56	-110.59 ± 4.75	-110.26 ± 4.37	-110.52 ± 0.43

III. MEASUREMENT COMPARISON

We performed four separate calibrations, all of which made use of an Open-Short-Load-Thru (OSLT) calibration kit with Type-N coaxial connectors. Physical models of the calibration standards were developed and validated with a multiline Thru-Reflect-Line (TRL) calibration within the NIST Microwave Uncertainty Framework [4].

The first three calibrations were made with the standard VNA setup, as illustrated in Figure 1. In the first one, we measured *S*-parameters at an input power of -17 dBm, the default power setting on the VNA. The second calibration was also measured with *S*-parameters, but at an increased input power of 0 dBm. The third calibration was performed with wave-parameters also at 0 dBm, so we could verify that measuring wave-parameters and *S*-parameters provides comparable results. And the fourth calibration made use of the modified setup of Figure 2, where the amplifier was removed during calibration, and re-inserted for the actual DUT measurements. Our DUT was a variable attenuator with a range of 0 to 110 dB with steps of 10 dB. All of the measurements were performed on a frequency grid between 2.7-3.7 GHz (the bandwidth of our amplifier) with a spacing of 1 MHz (1001 points) and an IF bandwidth of 100 Hz with no averaging.

Table 1 lists the mean values and standard deviations of the magnitudes of S_{21} calculated over the measured frequencies at attenuator settings of 60-110 dB for the four calibrations.

Although all of the calibrations provided comparable mean values up to 90 dB, the standard deviations increased much more drastically with increased attenuator settings for the case where *S*-parameters were measured at an input power of -17 dBm. At this input power, the 100 dB and 110 dB measurements were limited by the VNA's noise floor, and thus the values were incorrect. At the highest attenuator settings, both the *S*-parameter and wave-parameter measurements at an input power of 0 dBm were still able to provide reasonable mean values, but their respective standard deviations became increasingly large. In contrast, the wave-parameter measurements with the amplifier and attenuator resulted in standard deviations approximately ten times lower than with the standard setup at these highest settings.

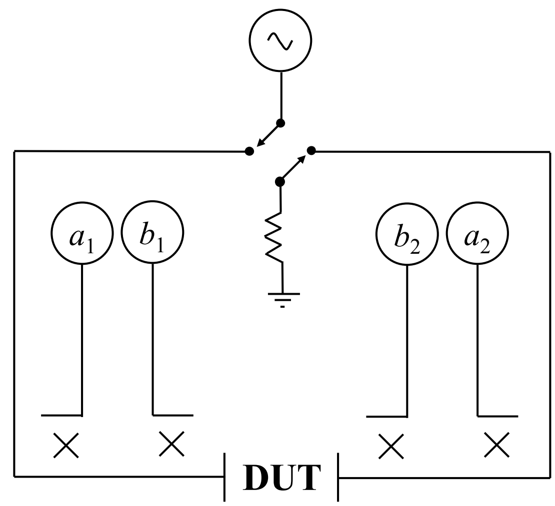

Fig. 1. Simplified schematic diagram of a four-sampler VNA.

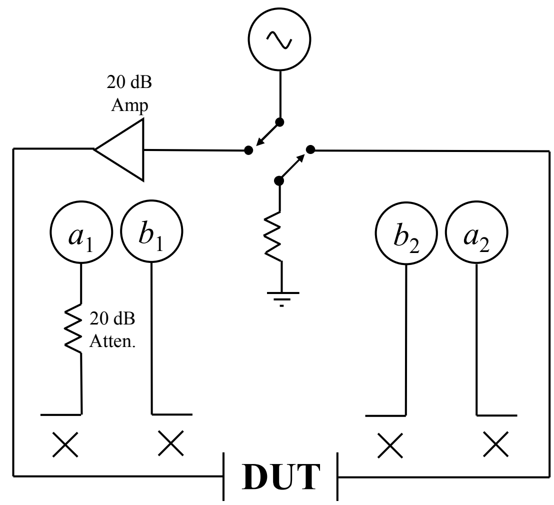

Fig. 2. Simplified schematic diagram of a four-sampler VNA with a 20 dB amplifier and 20 dB attenuator inserted for improved high-insertion-loss measurements.

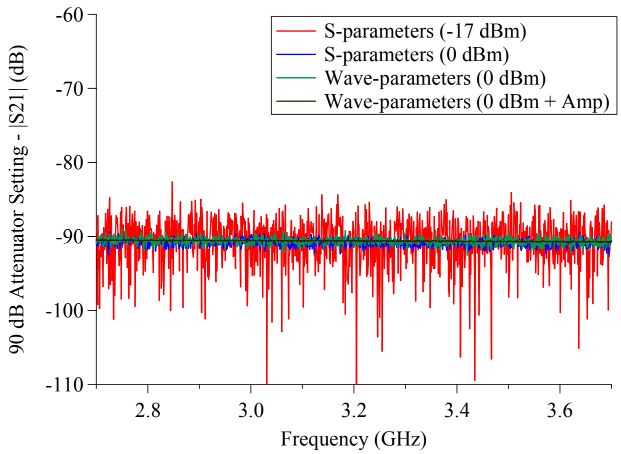

Fig. 3. Comparing measurements of $|S_{21}|$ at the 90 dB attenuator setting for four different calibrations.

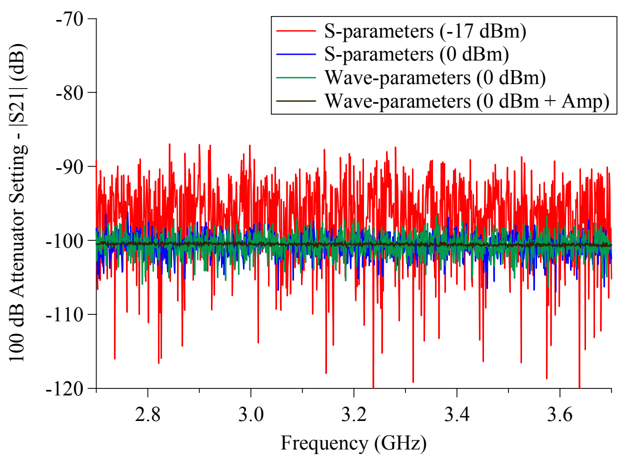

Fig. 4. Comparing measurements of $|S_{21}|$ at the 100 dB attenuator setting for four different calibrations.

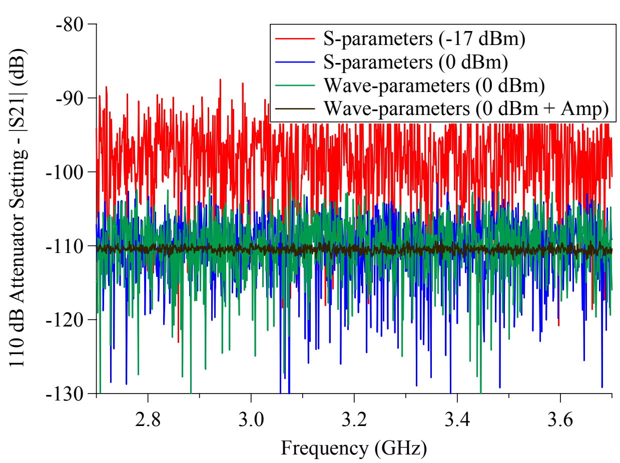

Fig. 5. Comparing measurements of $|S_{21}|$ at the 110 dB attenuator setting for four different calibrations.

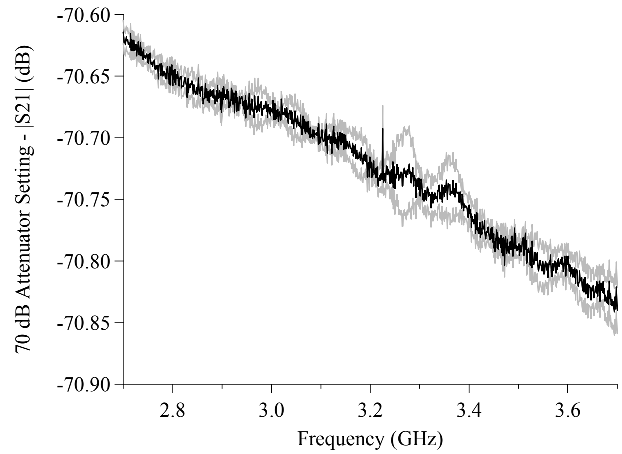

Fig 6. Nominal calibrated measurements (black curve) and 95% confidence intervals (grey curves) of $|S_{21}|$ for the 70 dB setting by use of the wave-parameter measurements at an input power of 0 dBm with the amplifier and attenuator.

Figures 3-5 illustrate the measurements of $|S_{21}|$ at the 90, 100, and 110 dB settings for the four different calibrations. Figure 6 plots the measurements and 95 % confidence intervals of $|S_{21}|$ for the variable attenuator at the 70 dB setting (a typical value we will likely encounter during free-field measurements) for the wave-parameter measurements at an input power of 0 dBm with the amplifier and attenuator.

IV. Conclusions

By utilizing only two additional pieces of hardware and measuring wave-parameters rather than *S*-parameters, we were able to increase the dynamic range of our VNA while decreasing uncertainties due to the noise floor. This modified setup decreased the standard deviations of $|S_{21}|$ by an order of magnitude for attenuator settings over 90 dB. Although we were limited to a maximum insertion loss of 110 dB due to our attenuator, we believe this method can provide adequate measurements for values up to approximately 130 dB.

For even higher values of insertion loss, encountered in applications such as non-line-sight channel measurements, we would most likely require additional hardware, including external couplers and a different calibration technique, such as Short-Open-Load-Attenuator. Additionally, we plan on examining the effects of performing high-insertion-loss measurements utilizing calibrations that include isolation terms. These topics remain the subject of future studies.

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