Repeatability of 220 - 330 GHz Variable Waveguide Attenuator and Frequency Extenders for 6G Measurements

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***Abstract*—The future 6G systems will be implemented above 100 GHz, and RF measurements at those frequencies are performed with frequency extenders. Mechanical waveguide attenuators are used to control signal levels in power sweep measurements to avoid compression of the device or extenders. However, manual settings of the attenuators are prone to human errors, and thus the repeatability of each measurement need be studied case basis.**

This paper studies calibration accuracy of extenders and the repeatability and reproducibility of a waveguide attenuator operating at 220 to 330 GHz. For directly connected frequency extenders, the average calibration error of S_{21} with three operators and three repeated calibrations over frequencies was -0.009 dB with 0.072°. The primary source of variable attenuator S_{11} and S_{21} measurement variations was due to repetition of measurements since there was no statistical difference between operators. The measured accuracy of any setting was 1.4 dB ($\pm 2\sigma$) over 15 dB range.

***Index Terms*—Accuracy, Calibration, Gage R&R, Reproducibility, S-parameter.**

I. Introduction

Fifth-generation (5G) networks have been deployed faster than any other wireless network generation, and it is estimated that there will be over 10 billion 5G subscriptions by the end of 2025 [1]. Recently, the research community has started focusing on the sixth-generation (6G) networks, which should provide extreme data rates with the ultimate goal of 1 Tbps data rate [2]. To achieve such a high data rates, the 6G systems look ahead beyond 100 GHz frequencies, that is significantly higher than currently used 5G mmWave frequencies. One potential 6G frequency allocation is from 252 to 325 GHz according to IEEE 802.15.3 standard [3].

Test and measurements of radio frequency (RF) components and systems in beyond 100 GHz frequencies is challenging and the results may be subject to larger measurement errors than in the past. Reliability of the results and repeatability of the measurements are important to understand when reporting the results in the academia and industry. It is expected that the 6G RF measurements will deviate significantly from 5G measurements since frequency extenders for measurement equipment and waveguide system components are used. Human operators need to interact with electro-mechanical RF components during the testing, and such exemplary components are waveguide attenuators. The effect of the human interaction can be studied with a gage repeatability and reproducibility (R&R) analysis presented in the paper.

Frequency extenders and waveguide connections are a necessity to perform RF measurements above 200 GHz frequencies, and usage of these extenders brings yet another source of non-ideality to the measurement setups in the form of, e.g., waveguide reflection losses. Like in any RF-measurement event, repeatability is crucial for later verification and analysis of the measurement results. The repeatability becomes even more challenging when the utilized RF frequencies increase to 100 GHz and beyond. Some research on the effects of incorporating waveguides to RF measurements exists.

The repeatability of 140 to 220 GHz waveguide connection with two fixed-length cross-guide waveguides has been studied in [5]. Such fixed-length cross-guides correspond to a fixed-attenuation waveguide attenuator when the cross-guide is positioned between waveguide ports of frequency extenders. A repeatability assessment has been performed with 12 repeated measurements of both devices. The measured standard deviations for repeatability are between 0.098 to 0.180 dB depending on the frequency and attenuation value [5]. In addition, a cross-guide transmission line from 75 to 110 GHz frequency band has been studied in [6], and the measured standard deviation of S_{21} varies from 0.078 to 0.193 dB based on the frequency.

Measurement repeatability with two different sizes through line (TRL) waveguides supporting 220 - 330 GHz frequencies are studied in [7]. S_{11} measurements for both TRL lines were repeated 30 times and in worst-case 0.0031 on a linear scale or -50.1 dB level. Measurement reproducibility has been mentioned in [8], where it is stated that an experienced operator can improve the repeatability from recommended screw torques. The worst-case theoretical reflection loss (S_{11}) for a 220 to 330 GHz waveguide with a normal UG-387 flange is -8 dB [8]. The frequency extender manufacturers are providing improved precision flanges to improve the return loss performance of waveguide components and extenders. As an example, Virginia Diodes Inc. supports VDI precision flange UG-387/UM in their frequency extender for 229 to 330 GHz frequencies [9]. Such precision flange mitigates the reflection loss of the waveguide at 140 to 220 GHz from -30 dB level to -40 dB level and repeatability of those has been studied with six repetitions in [10].

Connection repeatability of waveguide devices supporting frequencies of 750 GHz to 1100 GHz has been investigated in [4]. The study concentrated on random errors due to dimensional tolerance of flanges' alignments mechanisms, and it was done with three known loads; flush short, offset short, and matched load. The complex-valued reflection coefficients of each load were measured 12 times, disconnecting and reconnecting the load between each re-measurement and standard deviations of the real and imaginary components of S_{11} were in order of 0.005.

In order to validate the measurement results, statistical measurement system analysis can be performed for the measurement system to analyse accuracy of the measurement results. For instance, Gage R&R analysis is a mandatory requirement in the automotive industry before measurement data can be accepted from manufactured parts for data analysis purposes [11]. The Gage R&R analysis can divide measured variation caused by parts, the repeatability, and the operators when the same parts are measured multiple times. If measurement error due to the operator can be minimized, then any operator may perform measurement equally.

In this paper, we present the Gage R&R analysis of a mechanically set waveguide attenuator. The results and methodologies of the study can be applied for 6G RF component characterization purposes in terms of the measurement system accuracy and the effect of the human operators on the measurement results.

II. Statistical Measurement Analysis with Gage Repeatability and Reproducibility Method

The Gage R&R analysis is based on variance (ANOVA) analysis of measurement data when multiple operators have repeatedly measured the same products, parts or dimensions. The total measured variance can be divided into different parts if the sources of errors are independent. The measured parts should cover typical process variation or tolerance area. Measurements need to been performed in random order, and it is assumed that the measured parameter of the part is constant during the measurements. The total measured variance can be expressed as [12]

$$\sigma_T^2 = \sigma_P^2 + \sigma_O^2 + \sigma_R^2, \tag{1}$$

where ${\sigma^2}_{\mathrm{T}}$ is a total observed variance of the measurement results, ${\sigma^2}_{\mathrm{P}}$ is a variance of between parts, ${\sigma^2}_{\mathrm{O}}$ is a variance due to the operator, which is called reproducibility, and ${\sigma^2}_{\mathrm{R}}$ a is a variance due to the repeatability.

A general guideline for the Gage R&R measurement system study is: at least two operators perform measurements by using ten or more samples, which are presentative samples oThe Gage R&R f product variation, and perform at least two repeated measurements of each sample in random order [11], [12]. The measurement system is considered capable of performing high-quality measurements if the operator's combined variances and the repeatability are less than 10 percent of total measured variance [11], [12].

In this study, ten attenuation settings spanning over the whole attenuation range have been considered as parts. In the calibration, only one back-to-back setting is measured, and thus all variation seen in results is due to operator-to-operator variation and measurement repeatability.

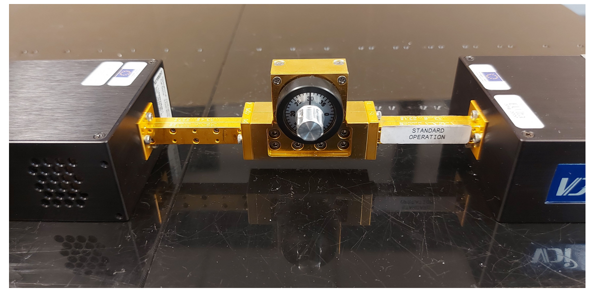

Fig. 1. Photograph of measurement setup of the variable mechanical waveguide attenuator.

III. Waveguide Attenuator Measurement setup with Frequency Extenders

Standard build frequency extenders do not provide gain control functionality [9], but this functionality can be implemented with an external variable gain waveguide attenuator outside of the frequency extender. For example, the variable gain attenuator is needed at the output of the transmission (TX) extender to change the TX power for power sweep and avoid compression of the device under test [13]. Similarly, variable attenuation is needed in the reception (RX) extender's input to avoid saturation.

The variable attenuation waveguide attenuator in the study is from Elmika UAB (model VA-010), which has similar specifications as in [14]. The specified attenuation range is at least 30 dB. The Gage R&R measurements of the variable waveguide attenuator were performed by using a VNA from Keysight Technologies Inc. (N5247A PNA-X) and WR-3.4 frequency extension modules from Virginia Diodes Inc. [9]. The S_{11} and S_{21} measurements have been performed over the whole frequency band 220 – 330 GHz with 6401 measurement points. All results in this paper have been taken with an IF bandwidth of 1 kHz and averaging factor 1. The photograph of the variable attenuator measurement setup is shown in Fig. 1. The attenuation setting was changed by rotating the knob with a numeric disk of the attenuator.

A. Calibration Accuracy of Frequency Extenders

The repeatability and reproducibility of the extenders' calibration accuracy were studied by connecting extenders together without the attenuator. Three persons repeated measurements three times, and in each case, the extenders were disconnected and reconnected between calibrations by the person performing the measurement. The calibration was done over the whole 220 - 330 GHz band with 6401 frequency point and enhanced response calibration was used with following calibration standards: short, load, quarter wavelenght shim with short, and finally extenders were connected back-to-back.

The average calibration error in S_{11} based of all measurement results (N=38406) was 0.01008 or -39.93 dB with σ of 0.0050 (-46.02 dB). The mean frequency response based on nine results (three operators and three repetitions from each) at all frequency points was subtracted from individual measurement results, and the residual presents the repeatability

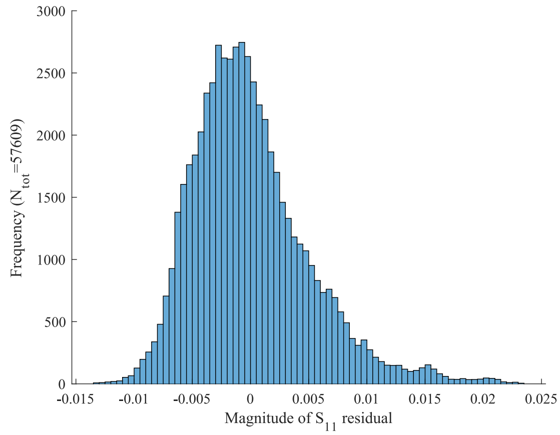

Fig. 2. S_{11} amplitude residuals after the average of calibrations subtracted (linear scale).

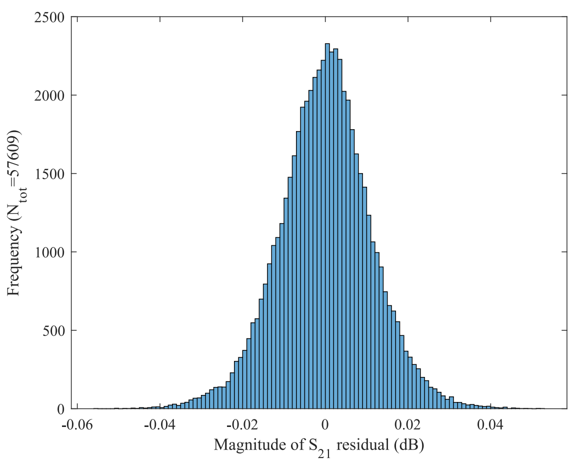

Fig. 3. S_{21} amplitude residuals after the average of calibrations subtracted (dB scale).

and reproducibility errors. The residuals of linear magnitude of S_{11} are shown in Fig. 2 as an empirical distribution, which follows log-normal distribution. The average phase of S_{11} from all calibration results was -0.4010°. The empirical distribution is a non-normal distribution with σ of 1.253° leading $\pm 3\sigma$ phase calibration range of 7.52°.

The amplitude of S_{21} of all results was -0.009 dB with σ of 0.011 dB. The empirical distribution follows normal distribution based on the Anderson-Darling normality test, which validates the ANOVA analysis's validity, which is shown in Fig. 3. The average phase of S_{21} was 0.072° with σ of 0.119°. However, the empirical distribution of phase residuals S_{21} has two modals, which increased the variation. The variations of S_{11} and S_{21} in the calibration measurements indicate that operators and measurement repetition have a small effect on calibration accuracy.

IV. Gage R&R analysis of the Waveguide Attenuator at 330 GHz

After each calibration measurement, as described in section III, the waveguide attenuator was connected between TX and RX extenders, and Gage R&R measurements of S_{11} and S_{21} with 11 attenuation settings were performed. Three operators repeated measurements three times and each operator connected and tightened waveguide connections of the attenuator, set the attenuation values, performed measurements, and recorded results in a randomized order of setting values.

The averaged S_{21} results of nine measurements rounds over the frequency band 220 - 330 GHz are shown in Fig. 4. It can be seen from the figure that pass-through attenuation varies over the frequency band with the fixed attenuator setting. The frequency dependency of the attenuator is taken into account when the Gage R&R analysis is performed for each frequency separately, since individual results are normalized by subtracting the average attenuation in ANOVA analysis, which was performed with Minitab-software [15].

The variations of S_{21} results with ten attenuation settings over the frequency band are shown in Fig. 5. The standard deviation of S_{21} up to the setting 26 was less than 0.35 dB with any of three operators in the study enabling measurement accuracy range of 1.4 dB ($\pm 2\sigma$) or 2.1 dB ($\pm 3\sigma$), which can be considered acceptable in most of power or power sweep measurements. The Gage R&R analysis should be performed to all frequencies separately with the variable attenuator when frequency dependency or accuracy of the attenuation at the frequency is analyzed. Thus, the Gage R&R should be repeated 6401 times to cover the whole frequency band of the analyzed attenuator for S_{11} and S_{21}, and a full characterization needs additional S_{12} and S_{22} analyses.

As an example, a Gage R&R analysis of normalized amplitudes of S_{21} at 330 GHz frequency is presented. The example frequency is selected where the maximum variability is observed, and a summary of the analysis is shown in Fig. 6. The reproducibility is reported to be zero since there is no

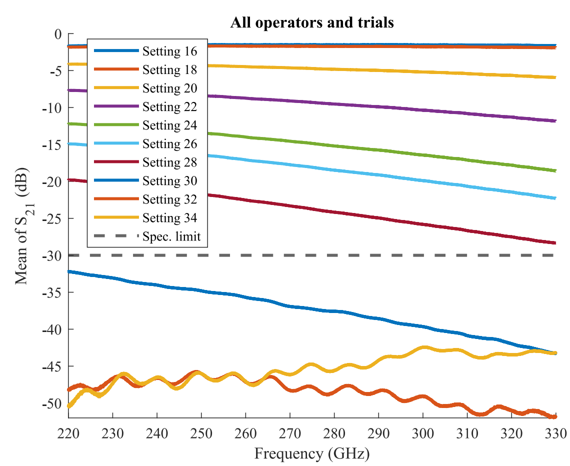

Fig. 4. Average S_{21} attenuations of the setting values.

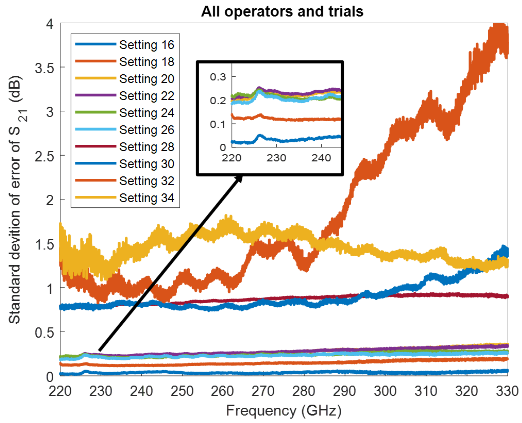

Fig. 5. Variability of attenuation settings over frequencies.

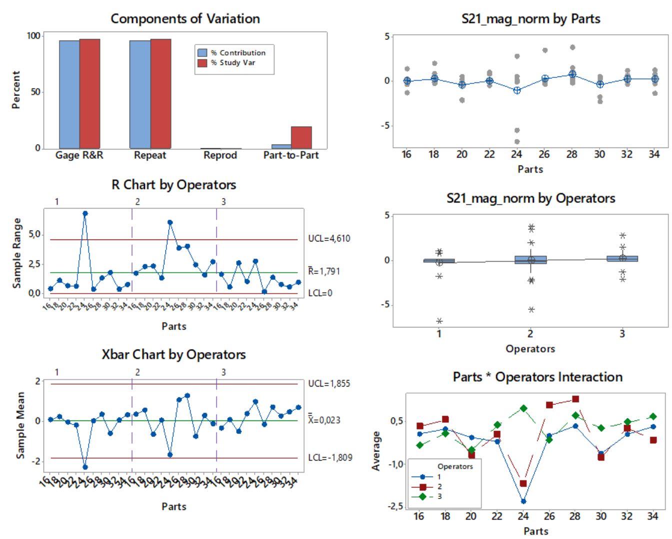

Fig. 6. Gage R&R summary of S_{21} normalized magnitudes at 330 GHz.

statistical difference between operator results. In this case, all measurement error is reported as the repeatability error. The similarity of the average results of the operators can be seen from the middle right sub-figure of Fig. 6.

The main variation in the 330 GHz results is the measurements where the attenuation changes most over the frequency band, which can be seen from the top and bottom right sub-figures of Fig. 6, where attenuation settings and measurement results from operators are visible. These results indicate that any of the operators in the study may perform equal measurements, but the same measurement performed at different times by the same operator may vary. If the Gage R&R analysis is done variation setting amplitudes, then the same variance and standard deviation for the R&R error is obtained since the ANOVA normalizes average values of individual parts in the variance analysis.

V. Conclusions

This paper has studied the repeatability and reproducibility of the mechanical waveguide attenuator to be control signal levels in frequency extender measurement at 220 - 330 GHz. The signal level can be set with the variable attenuator setting accuracy of 1.4 dB ($\pm 2\sigma$) over 15 dB control range based on repeated measurements by three operators. There is no statistical difference between the mean values of the operators, and thus measurement results from each operator are equal.

The Gage R&R is a requirement in the automotive industry measurements, and it can distinguish errors due to repeatability and operators. For example, the Gage R&R of the measured S_{21} of the mechanical waveguide shows that the repeatability of operators is the primary source of the variability. Therefore, improvement in the repeatability of the operators can be addressed by training the operators, and appropriate handling of waveguide components, standardizing the measurement procedures, and fixing the positions of extenders and attenuators in the measurement system.

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