Review of the accuracy and precision of mm-wave antenna simulations and measurements

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Review of the Accuracy and Precision of mm-Wave Antenna Simulations and Measurements

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Abstract—Accuracy and precision are important metrics that can be used to validate the quality of the antenna simulation model and antenna measurement with respect to the design criteria of the antenna. Both metrics were applied to identify the influences that caused inaccurate and tolerant results of both simulations and measurements which have been done in the past. Identified influences for simulations are the input parameters like the permittivity and loss tangent, but also the simulation conditions like the port definition. For the measurement these influences are mainly determined by the interconnections, motor backlash and test environment.

Index Terms—mm-wave, 60 GHz, antenna measurement, antenna simulation model, accuracy and precision.

I. INTRODUCTION

Accurate and precise measurements and characterization of antenna parameters of various mm-wave antenna concepts, e.g. rod antennas [1], conformal antennas [2], antennas on-chip [3], antennas in package [4] and antennas using a deflector [5] are key issues at this moment. The accuracy and precision of an antenna measurement is very important, for instance, for the calibration of low side-lobe phased arrays [6], [7]. Possible causes of inaccuracies are traced back to the small size of an individual antenna element, the construction tolerances and the influence of the measurement environment. Also, antenna simulations are subject to inaccuracies due to inaccurate values of the permittivity, loss tangent and production tolerances. Therefore, the accuracy and precision of both antenna simulations and antenna measurements need to be investigated in more detail in order to be able to understand the causes of the observed differences.

The metric accuracy shown in Fig. 1 defines how close the simulated or measured value is to the reference or actual value [8]. The reference corresponds to the design criteria of the antenna like the resonance frequency, gain, radiation pattern or efficiency. The first step is to simulate the model based on the design criteria with the aid of a 3D electromagnetic full wave simulator like CST Micro Wave Studio [9] or an analytical model. However, simulation results are not per definition accurate. The outcome depends on the chosen solver, amount of mesh cells and excitation method or port configuration [10]. The same applies for the antenna measurement setup. The outcome depends on the motor accuracy, alignment of the antenna under test (AUT) or device under test (DUT) with respect to the reference antenna (probe) and the measurement environment [11].

Another important metric is precision (Fig. 1) or reproducibility, which is determined by the difference between several simulations or measurements [8]. As discussed in [12], the precision of the simulation is influenced by the input of the simulation model like the permittivity, loss tangent and production tolerances. Characterizing the material is essential for improving the precision. The same holds for the accurate and precise production tolerances – with a maximum of 10% - yielding slightly different antenna dimensions. The precision of the measurements is influenced by the calibration sequence, alignment and phase stability during movement of the cables. In our mm-wave setup the alignment is controlled with the aid of a camera and the environmental conditions stabilized by using a cage of Faraday covered with electromagnetic absorbers. The cables are stabilized by a chain to guarantee an reproducible movement each time that we measure.

Fig. 1. The accuracy and precision model a) inaccurate and tolerant, b) more accurate and precise.

This extensive description of accuracy and precision applied to antenna simulations and measurements shows the necessity for an extended accuracy / precision model. This model can be used to compare antenna simulations and measurements to determine the quality of it all.

The causes of the inaccuracies of the simulation model will be described in section II and a new accuracy model as a reference for the antenna measurements is proposed. In section III the resulting simulation model will be presented and in section IV the mm-wave anechoic chamber will be described. In section V the causes of these systematic and random errors will be described.

II. THE NEW ACCURACY MODEL

In Fig. 1-(a) the green line can be considered as the ideal design parameters of the antenna. Those are specifications to

which both the simulation and measurement should converge and therefore ideally the red and blue line will be on top of the green line. The positions of the blue and red line relative to the green line are related to the accuracy of the simulator and measurement setup, respectively. The width of the curved red line is the measurement precision which is related to the reproducibility of the measurements. The width of the curved blue line is the simulation precision which is related to the tolerance on the input parameters of the simulator, for instance due to antenna production errors. Fig. 1-(b) clearly shows that the overlap between the two curves depends on both accuracy and precision. A larger overlap means a better agreement between measurement and simulations.

III. THE SIMULATION MODEL

There are several commercial software tools to model an electromagnetic structure, like an antenna. Depending on the design criteria the most optimal solver type and excitation method should be chosen [10]. In our case, the model shown in Fig. 2 was simulated in CST MWS with the time domain solver [2]. Depending on the working frequency the most accurate material properties should be chosen. The material libraries included in CST have valid parameters for a limited frequency range but certainly not for the mm-wave range. For our test antenna shown in Fig. 2, we used a permittivity of 3.1 and loss tangent of 0.004, which have been characterized at 60 GHz. The production tolerances could also be included into the simulation model [13].

Fig. 2. Simulation model of a patch antenna in CST Micro Wave Studio.

IV. THE MM-WAVE ANECHOIC CHAMBER (MMWAC)

The mm-wave anechoic chamber shown in Fig. 3 was designed and realized in 2011. The system can perform a variety of antenna measurements fully automated. It is enclosed as a cage of Faraday and covered with electromagnetic absorbers. The anechoic chamber has a diameter of 1 meter and a height of 0.5 meter. The maximum gain that can be measured at 60 GHz is approx. 23 dBi or maximum effective area with a diameter of 30 mm. The operational frequency range is from 50 GHz up to 90 GHz.

Fig. 3. mm-Wave anechoic chamber half open for illustration purposes.

A. The antenna measurement setup

The AUT or DUT is situated in the middle of the chamber as shown in Fig. 3 (dashed yellow rectangle). It is a mechanically stable area guaranteeing that the probe nor the AUT does not move during measurements. The translation table together with the alignment camera is used to position the AUT in the middle with respect to the reference antenna. The alignment is important due to the limited distance between the AUT and reference antenna. The exact position of the middle of the antenna is determined by the design. This alignment is important due to the limited distance between the AUT and reference antenna. The antenna can be connected with a connector shown in Fig. 4-(a) or probe shown in Fig. 4-(b). The latter is supported by the probe station and a microscope camera while setting up a connection. For both type of connections a calibration sequence can be executed inside the room. As an extra aid for improving the reproducibility, the vector network analyzer (VNA) monitors the impedance and stores this value after the connection is made in the measurement file. Also all coordinates of the motors for setting up a measurement are stored after each measurement in the same measurement file.

Fig. 4. a) The antenna under test connected to a v-connector and, b) connected to a ground-signal-ground probe.

B. Orientation of and movements within the MMWAC

In Fig. 5 the orientation of the specific motor movements for performing antenna measurement are illustrated. These motor movements are related to a spherical coordinate system where the co- and cross-polarization are defined according to [14]. The implementation of this definition should insure the correct alignment during measurement of both E- and H-plane.

Fig. 5. a) Side view mm-Wave anechoic chamber and b) top view mm-wave anechoic chamber with orientation of the different movements.

There are three movements defined namely ‘polarization axis’, ‘rotation axis’ and ‘scan arm axis’. Those movements are used to position the reference antenna for a S_{21} measurement, so that the gain and radiation patterns of the linearly- or circularly-polarized AUT can be determined. The ‘rotation axis’ (0° to 180°) moves the ‘scan arm axis’ (-90° to 90°) so that another plane can be measured. The ‘polarization axis’ (0° to 359°) is used to move the reference antenna to be able to measure the co- or cross-polarization of the specific plane of the AUT. With these movements half a sphere of the AUT’s radiation pattern can be measured.

V. CAUSES OF ACCURACY AND PRECISION ERRORS AND WAYS TO REDUCE THESE ERRORS

The accuracy and precision model shown in Fig. 1 is now applied to the reference mm-wave patch antenna [12] shown in Fig. 2. This antenna is used to illustrate some of the effects of the aforementioned inaccuracies and tolerances.

A. Simulation input precision

The precision of the simulation results (width of the red curve in Fig.1) is influenced by the input parameters. The input parameters are:

- the permittivity and loss tangent of the substrate,
- the production tolerances applied to the model,
- and the alignment of the individual layers with respect to each other.

The effects of an incorrect permittivity and loss tangent are significant. As an example, the permittivity of an LCP substrate at 60 GHz was used [12]. However, the reported permittivity values vary from 2.92 till 3.25. This causes the

resonance frequency to shift from 59.5 GHz to 62.6 GHz. So a permittivity difference of 0.33 resulted in a frequency difference of 3.1 GHz, an error of 10%. To find out which value was accurate, the material was characterized with the aid of a ring resonator. To reach an accurate value, the mechanical tolerances of the realized resonators were examined and corrected for in the model. With the three- Γ method [12], the final relative permittivity was found to be 3.102 ± 0.043 . The loss tangent ($\tan \delta$) of 0.004 was in good agreement with the already available value, and thus was used for this simulation model.

The tolerances and alignment errors are restricted to a maximum of 10%. This error could be reduced, but will influence the production yield. In [13] the production tolerances were added to the simulation model and the effects have been presented as a minimum and maximum result. Based on such a model the measurement results should fit within those min / max values. It is possible to get a more accurate production result, but this normally goes at the expense of the yield of the production.

B. Simulation accuracy

The simulation accuracy (distance between blue and green line in Fig. 1) is influenced by the:

- solver type,
- amount of mesh cells,
- and port definition.

There are several methods to simulate an antenna design. The accuracy of the outcome is influenced by the choice of the specific solver, time domain, frequency domain, Eigen mode, or integral equation solver, which fits with the specific simulation model. Furthermore, the amount of mesh cells and port definition will influence the outcome significantly. Especially the port definition of the design was the subject of discussion [10]. The differences in outcome between different software tools was attributed to the way the design was excited. Although the software helps the user by going through a selection menu, specific knowledge of computational electromagnetics and antennas is essential [10].

C. Measurement precision or reproducibility

For all antenna measurements the precision or reproducibility (width of the red curve in Fig.1) is affected by the stability within the system. The precision is influenced by:

- the interconnection,
- movement within the RF cables,
- and the environment.

For instance, in case of connector-fed antennas, the measurements are very reproducible, due to the fact that the connection is fixed or stable. But for a probe-fed antenna, the placement of the probe tip is flexible. We will illustrate this with the experiment shown in Fig. 6. In Fig. 6-(a) the probe is placed correctly on the edge according to the port definition in the simulation. In Fig. 6-(b) the probe is placed with an offset of approx. $100\mu\text{m}$ from the edge to show the effect.

Fig. 6. a) Probe placed on the edge and, b) probe placed with a small offset

In Fig. 7-(a) the effects of such a small displacement is shown. Each time the setup was rebuilt and the measurement repeated so the standard deviation could be presented. The result is a significant error. The effects are not only caused by the position of the probe tip but also by the amount of force that is used to place the probe on top of the pads which influences the impedance. Therefore during placement of the probe the impedance is monitored by the VNA and the value stored after measurement. With this extra information the measurement could be reproduced.

Fig. 7. a) Standard deviation (dB) of the measured S_{11} with probe on the edge of the pad and measured with a small offset on the pad and, b) the effect of this offset on the accuracy of the S_{11} measurement.

As shown in Fig 7-(b) the measurement without offset is accurate around the resonance frequency of the antenna. Because the probe model was not implemented into the simulation design the discrepancies could be explained but

need further investigation. The precision of the measurements are further improved by storing the motor positions (x, y and z-axis) of the probe station.

The precision is also influenced by the movement of the cables during measurement. This is especially an issue at high frequencies, e.g. at 60 GHz. To determine the effect, we have carried out the same radiation pattern measurement several times. At the start of each measurement the system was restarted, recalibrated and the antenna reconnected and aligned with respect to the reference antenna. The results are presented in Fig. 8. There is a small error between -70° and $+70^\circ$ degrees caused by the movement of the coax cables during measurement. The decreasing precision starting from $\pm 70^\circ$ is caused by the limited dynamic range of the system and thus the deterioration of the SNR.

Fig. 8. Standard deviation (dB) of the radiation pattern of both E- and H-plane of the patch antenna, $f = 60$ GHz.

The environment will influence the measurement mainly due to reflections and as discussed in [11] time gating is an option. But this technique is time consuming and due to the limited bandwidth only applicable for far away objects while the most distortive objects are located close-by. The influence of the environment is eliminated by creating an anechoic environment enclosed with a metal box as a cage of Faraday as shown in Fig. 3.

D. Measurement accuracy

The accuracy (distance between the red and green line in Fig.1) is influenced by:

- existing interconnection,
- and motor movements for performing the antenna measurements.

As described in [15], the connector causes reflections which cannot be eliminated. Even not with time gating due to the short distance between AUT and connector, normally less than a centimeter, and limited resolution. The probe on the other hand provides more flexibility to minimize the influence as shown in Fig 4-b and as discussed in [16]. Basically the influence of the probe is most severe in case of radiation pattern measurements. The probe causes a blockage for a part of the measured radiation pattern and limits the dynamic range due to probe radiation [15]. The solution is to use a bent probe as shown in Fig. 4-(b) and further described in [15]. The observed improvement in accuracy is remarkable.

The accuracy of the motor movement with respect to the related angle was also determined. The variations due to the calibration sequence and backlash of the motors is very small. This error was applied on the measured radiation pattern of the AUT used during this research and resulted in a gain deviation for the E-plane at 0° of 0.06 dB and for the H-plane 0.02 dB. The positive effect of these small tolerances on the motors together with the usage of the bent probe resulted in accurate and precise radiation pattern measurement as shown in [15]. Table I summarizes the errors that we have observed in our test set-up for the reference antenna of Fig. 2 at 60 GHz.

TABLE I. SIMULATION PRECISION AND ACCURACY VALUES

	accuracy and precision values		
	Description	Predicted (%)	Actual (%)
Precision	Permittivity (LCP)	10	1.39
	Production	10	0 ~ 10
	Loss tangent	0	0
Accuracy	Solver type	TBD ^a	TBD
	Mesh cells	TBD	TBD
	Port definition	TBD	TBD

^a. To be defined

TABLE II. MEASUREMENT PRECISION AND ACCURACY

	accuracy and precision values	
	Description	Measurement
Precision	Connection	0.5 dB
	RF cable stability	±0.1 dB
	Reflection-free environment	0.05 dB
Accuracy	Probe connection	TBD
	Polarization axis	0.21 %
	Rotation axis	0.28 %
	Scan arm axis	0.28 %

VI. CONCLUSIONS

Accurate measurement of antennas in the mm-wave range is a challenge. Introducing an accuracy / precision model helps to identify the influences that cause discrepancies between simulation and measurement. It also improves the understanding of what causes the most dominant effect on these discrepancies. Concerning the simulation model the main errors are due to the input parameters, like substrate parameters and production tolerances, and overall settings like the port definition, solver type and amount of mesh cells used. Due to the limited mm-wave characterization of materials in the available libraries of commercial software, the permittivity and loss tangent need to be determined accurately. Concerning the measurement, the main error sources are due to interconnections, the environment and the tolerances in the motor movement, although the effect of the latter appears to be minimal. The applied anechoic environment improved the stability within the measurement area as accounts for the previously investigated effects of the probe connection. For future work we will investigate the earlier mentioned

influences like the simulation settings, port definition and probe connection on the S₁₁.

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REFERENCES

- [1] Rousstia, M.W. & Herben, M.H.A.J. (2013). High performance 60-GHz dielectric rod antenna with dual circular polarization. Proceedings of the European Microwave Week, Nuremberg, Germany, 6-11 October 2013, 1-4.
- [2] Huang, M.D., Herben, M.H.A.J. & Kazim, M.I. (2011). Design of cylindrically bent antenna array on LCP substrate with large coverage at 60 GHz. Proceedings of the 5th European Conference on Antennas and Propagation (EUCAP), 11-15 April 2011, 1117-1121.
- [3] Johanssen U., Smolders A.B., Mahmoudi R., Akkermans I., "Substrate Loss Reduction in Antenna-on-Chip Design", Proc. of the IEEE AP-Symposium 2009, pp. 1-4, June 2009.
- [4] Pfeiffer U., Grzyb J., Liu D., Gaucher B., Beukema T., Floyd B., and Reynolds S., "A chip-scale packaging technology for 60- GHz wireless chipsets," IEEE Transactions on Microwave Theory and Techniques, vol. 54, no. 8, pp. 3387 –3397, aug. 2006.
- [5] Kazim M.I., and Herben M.H.A.J., "Trade-offs in multifaceted passive electromagnetic deflector for the 60 GHz frequency band". Proceedings of the 5th European Conference on Antennas and Propagation (EUCAP), Rome, Italy, 11-15 April 2011, 1044-1048.
- [6] Smolders A.B., and Hampson G.A., "A fast and accurate scheme for calibration of active phased-array antennas", Proceedings IEEE Antennas & Propagation Symposium Orlando, pp 1040-1043, 1999.
- [7] Lee K.M., Chu R.S., and Liu S.C., "A built-in performance-monitoring/fault isolation and correction (PM/FIC) system for active phased-array antennas", IEEE Transactions on Antennas and Propagation, AP-41, 1993, pp.1530-1540.
- [8] http://www.bipm.org/utis/common/documents/jcgm/JCGM_200_2008.pdf
- [9] www.cst.com.
- [10] G. A. E. Vandenbosch, "State-of-the-Art in Antenna Software Benchmarking: 'Are We There Yet?'," vol. 56, no. 4, 2014.
- [11] Akkermans, J.A.G.; van Dijk, R.; Herben, M.H.A.J. Millimeter-wave antenna measurement. *EUMC year 2007*, pp 83 – 86.
- [12] Huang, M., Herben, M.H.A.J., Reniers, A.C.F. & Smulders, P.F.M. (2013). Causes of discrepancies between measurements and EM-simulations of millimeter-wave antennas. *IEEE Antennas and Propagation Magazine*, 55(5), 139-149.
- [13] Rousstia, M.W., Reniers, A.C.F. & Herben, M.H.A.J. (2013). Switched-beam rod antenna array with RF-MEMS switch for millimeter-wave applications. Oral : *Proc. of 2013 Asia-Pacific Radio Science Conference (AP-RASC'13)*, 3-7 September 2013, Taipei, Taiwan, Taipei, Taiwan. (invited).
- [14] A. C. Ludwig, "The definition of cross polarization, IEEE Trans. Antennas Propag. Vol 21, No. 1 pp 116-119, January 1973.
- [15] Reniers, A.C.F., Dommele, A.R. van, Smolders, A.B. & Herben, M.H.A.J. (2015). The influence of the probe connection on mm-wave antenna measurements. *IEEE Transactions on Antennas and Propagation*, 63(9).
- [16] Titz, D.; Pilard, R.; Ferrero, F.; Giancesello, F.; Gloria, D.; Jacquemod, G.; Luxey, C. Improved Measurement Accuracy of Probe-Fed mm-Wave Antennas Using the Three Gamma Method. *IEEE Antennas and Wireless Propagation Letters*, Year: 2014, Volume: 13, Pages: 103 – 1.