Statistical Measurement System Analysis of Over-The-Air Measurements of Antenna Array at 28 GHz

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***Abstract*—Next generation communication systems will use millimeter wave communication to enable higher data rates compared to Long Term Evolution (LTE) system. The coming 5G system will use antennas antenna arrays and multiple radio transceivers to compensate an excess radio signal path loss and conductive testing of an antenna array will be a challenge. Over-the-air (OTA) testing provides solution to cabling and connection problems. This paper provides an analysis of accuracy of OTA measurement at 28 GHz frequency band. A statistical measurement system analysis is used and results show that ± 0.89 dB measurement accuracy is achieved in a typical laboratory environment without an anechoic RF chamber.**

***Index Terms*— Analysis of variance, massive-MIMO, Measurement uncertainty, Microwave measurements, Measurement error, Millimeter waves.**

I. Introduction

Next generation (5G) wireless systems will support data rates up to several Gbps per user. Improvement is significant compared to currently used LTE networks. High data rate 5G networks will operate at millimeter waves (mmW) frequencies and it is proposed that those will operate at Ka-band (26.5 – 40 GHz) [1]. One of the first public demonstration for wide audience of the capabilities of 5G networks will happen during Winter Olympic Games in Korea. A proof-of-concept (PoC) system will use a spectrum allocation between 26.5 GHz and 29.5 GHz and more specifically 27.5 − 28.5 GHz [2]. One of the first wireless telecommunication systems, which will support 5G communication, will be a wireless backhaul, operating as a wireless last mile system. There are proprietary last mile wireless systems such as Terragraph by Facebook [3] but those are operating at 60 GHz frequency band. Systems operating at 60 GHz suffer from a shorter link range than systems operating at 28 GHz. The implemented PoC radio transceiver and the antenna array support frequencies between 26.5 GHz and 29.5 GHz [4] [5].

Telecommunication standardization is moving towards a direction where requirements are defined based on radiated power levels. Conducted measurements have been easier and more robust to perform at the lower frequencies, but this will change when 5G communication systems with massive Multiple Input Multiple Output (MIMO) radio solutions will come into operation. Conductive measurements for massive-MIMO measurement system will be difficult to operate, calibrate, maintain, and guarantee the accuracy of the test signal in each of the antenna port.

There are some studies in literature about the accuracy and the reliability of the OTA measurements at mmW frequencies. A radio frequency (RF) shielded chamber approach is studied in [6]. This kind of line-of-sight (LOS) OTA measurement system has been used to measure a total radiated power (TRP) and a total radiated sensitivity (TRS) of 2G, 3G and 4G User Equipment (UE). The size of the shielded anechoic chamber is 1.5 meters and it supports power level measurements down to –40 dB. An alternative chamber method is a reverberation chamber that emulates Rayleigh fading radio channel environment. It is not suitable for LOS OTA measurements. The uncertainty of the measurement results in the reverberation system is studied, and the standard deviation is lower than 0.5dB and approaching to 0.1 dB above 1 GHz [7]. Transmission and reception antennas form a known electrical field into a measurement volume in [8]. However, they are not providing a guidance of measurement error within the known measurement area.

Some OTA RF measurements are needed to perform the next generation 5G base station and mobile device testing in a typical laboratory environment, since RF shielded chambers are expensive to build. Galvanic connections will not be available between antennas and transceivers in 5G devices, since those will be tightly integrated into the same RF front-end [9][10] and number of antennas and radio paths may grow to up to 128 or even more [11]. A complexity of conductive testing leads RF performance testing towards OTA testing.

In the literature, only few studies are published about a statistical measurement system analysis with a Gage Repeatability and Reproducibility (R&R) method applied to radio frequency topics. A study of galvanic measurement of third order harmonic of pHEMT (Pseudomorphic High Electron Mobility Transistor) RF switch dies on wafer at production is presented in [12]. A Gage R&R case study about the main sources of a measurement error with network analyzer measurements is presented in [13]. A Design of Experiment and a Gage R&R study for Radio Frequency Identification reading is described in [14].

The main contributions of this paper include the following aspects: We are using the Gage R&R method to quantify sources of error and an accuracy of OTA power level measurement in a typical laboratory environment. The results will show that OTA power level measurements at mmW frequencies can be done in a normal laboratory environment accurately without an expensive RF shielded chamber.

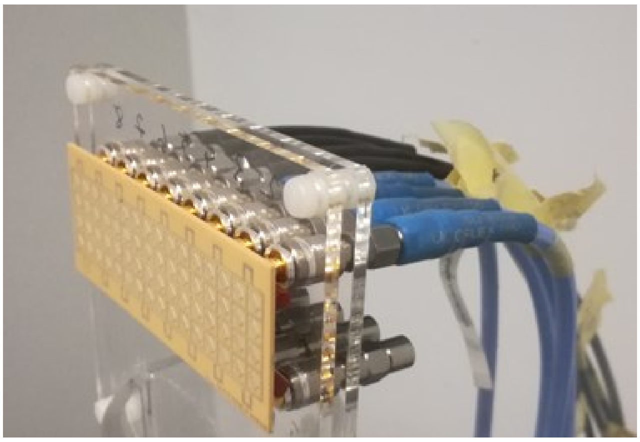


Fig. 1. Photograph of measured of 28 GHz antenna array

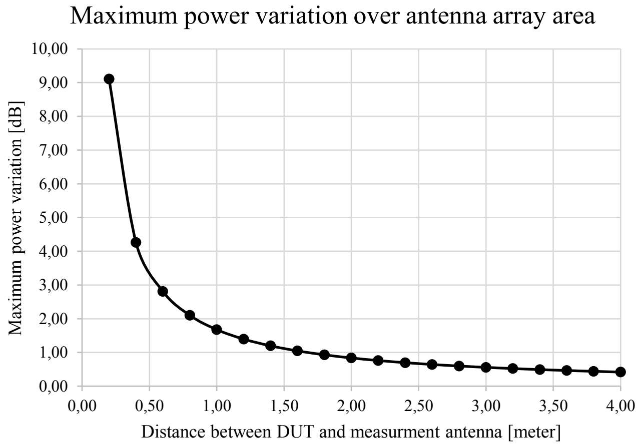


Fig. 2 Power level variation over the antenna array in OTA measurment

II. OTA MEASUREMENT SYSTEM AND SIGNAL LEVEL ANALYSIS

OTA measurements are performed for an antenna array that is used with the 5G PoC system [5]. A photograph of the measured prototype antenna array is shown in Fig. 1. A radio receiver board, which is connected with the antenna array, has 16 signal paths and a full radio unit includes two radio cards. Thus, the OTA testing is preferred method to measure radio performance over a conductive testing.

The antenna array consists of 16 sub-arrays that are 2x2 patch element antennas rotated to – 45° polarization. The size of the array is 90 × 34 mm (W × L) and a diagonal length is 96.2 mm. A far field distance of the antenna is [15]

$$L \geq \frac{2D^2}{\lambda}, \tag{1}$$

where D is a diameter of the minimum sphere enclosing the antenna, and λ is a wavelength of the test signal. The far field threshold for the antenna array is 1.63 meters at 26.5 GHz test frequency according the Eq. 1.

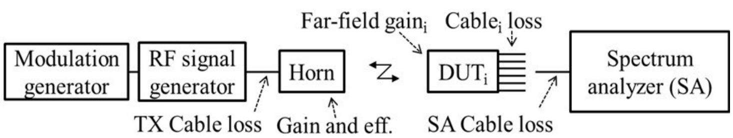
Radiating OTA tests at mmW frequencies introduce a new location accuracy challenge between the reference antenna and Device Under Test (DUT) due to short wavelengths. Fixed positions of the reference antenna and the DUT will overcome the positioning problem. A short wavelength can be used as a merit for mmW frequencies since a typical laboratory environment become relatively large at mmW wavelengths compared to current sub 6 GHz LTE frequencies. A power level variation in OTA measurement depends on the sphere over the antenna array and the measurement distance. The variation can be calculated [11]

$$\Delta P_{max} = 10log_{10}\left(\frac{1 + r/R}{1 - r/R}\right)^2, \tag{2}$$

where r is the radius of the minimum sphere enclosing the antenna, and R is a distance between the reference antenna and the DUT. The calculated power variation over the antenna array is presented in Fig. 2. The maximum power level variation is 1.05 dB at the 1.6 m or at the boundary of the far field of the antenna array. We used 2.0 m measurement distance in OTA measurements and the maximum expected power variation is 0.84 dB.

Fig. 3. illustrates the used OTA measurement system and summarizes of OTA signal levels at outputs of measurement cables. The OTA system can measure eight sub-arrays simultaneously. A 50 Ω standard load terminates not measured antenna port. A link budget for the expected signal level at the output i at the spectrum analyzer is

RF generator TX power	16.00	dBm
TX cable loss	-6.52	dB
Horn antenna gain (spec)	13.60	dBi
Horn antenna efficiency	-2.95	dB
Free space loss, 2 meters	-66.92	dB
Spectum analyser cable loss	-6.57	dB



Antenna#	1	2	3	4	5	6	7	8	Unit
Cable loss#	-3.07	-3.09	-3.22	-3.25	-2.5	-2.4	-2.47	-2.53	dB
Antenna Gain#	10.00	9.40	9.10	9.80	9.80	9.40	9.00	10.00	dBi
Calculated OTA power	-46.43	-47.05	-47.48	-46.81	-46.06	-46.36	-46.83	-45.89	dBm
Measured OTA power	-46.40	-47.10	-47.26	-47.10	-46.18	-46.56	-46.50	-46.14	dBm
Difference calculated and measured	0.30	-0.05	0.22	-0.29	-0.12	-0.20	0.33	-0.25	dB

Fig. 3. Analysis of power levels of received OTA signals at 26.5GHz frequency at spectrum analyzer

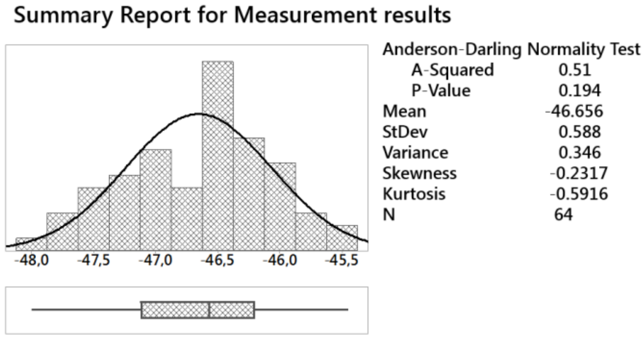


Fig. 4. Distribution of received signal observations at spectrum analyzer

$$Pout_i = P_{TX} - IL_{TX} + Gant_{TX} - IL_{path} + Gant_{RX}^{i} - IL_{cable}^{i} - IL_{SA\ cable}\ , \quad (3)$$

where P_{TX} is the transmission power of the test signal, IL_{TX} is the cable loss to a transmission horn antenna, $Gant_{TX}$ is the gain of transmission antenna including a directivity and a radiation efficiency, IL_{path} is the free space loss between the transmission antenna and the measured antenna array, $Gant_{RX}^{i}$ is the directivity of sub-array i in the measured antenna array, IL_{cable}^{i} is the insertion loss of the connection cable between the antenna array and the receiver and $IL_{SAcable}$ is the insertion loss of cable to the spectrum analyzer. A good correlation between the measured and the calculated OTA power levels as presented in Fig. 3. An average error between the measured and the calculated values is 0.04 dB.

III. Statistical Measurement System Analysis

Statistical measurement system analysis is to understand sources of observed variation in measurement results. A measured variation includes following components [16]

$$\sigma_{total}^2 = \sigma_{product}^2 + \sigma_{repeat}^2 + \sigma_{operator}^2\ , \quad (4)$$

where σ_{total}^2 is a total observed variance of measurement results, $\sigma_{product}^2$ is a variance between products, σ_{repeat}^2 is a variance component of a repeatability and $\sigma_{operator}^2$ is a variance component of a reproducibility.

The repeatability is the variation of the measurement results, when one operator has measured identical product characteristics several times. The reproducibility is the variation in the average of the measurements made by different operators measuring identical product characteristics with the same measurement equipment on the same part [16].

TABLE I. Average and Variation of Measurement Results of Antenna Ports in Spectrum Analyzer

Antenna port	*# of results*	*Mean [dBm]*	*Standard error of mean [dB]*	*Standard deviation [dB]*
1	8	-46,401	0,194	0,548
2	8	-47,096	0,187	0,528
3	8	-47,264	0,150	0,424
4	8	-47,102	0,150	0,424
5	8	-46,181	0,141	0,400
6	8	-47,102	0,150	0,425
7	8	-46,501	0,126	0,356
8	8	-46,142	0,144	0,407

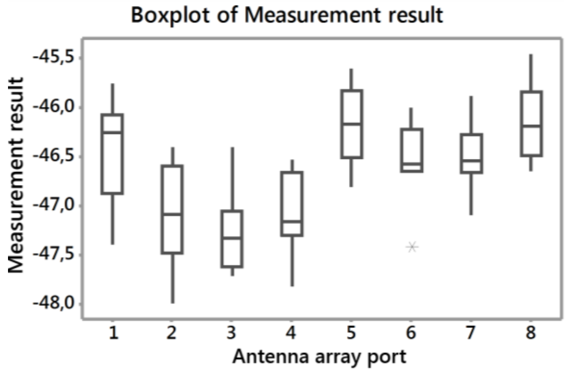


Fig. 5. Boxplot of received signal levels in input of spectrum analyzer

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 of product variation, and perform at least two repeated measurements of each sample [16].

We performed the Gage R&R study with two human operators, who are familiar with OTA measurements, eight sub-array antenna ports and two different reference antennas with one repeat of each antenna. We conducted the Gage R&R study twice on consecutive days enabling to identify daily variation of the measurement system. We selected two different reference antennas with one repeat to emulate worst-case repeatability. We measured the received signal level of the OTA test signal from the main slope direction of the antenna array. We measured one sub-array of the 16-antenna antenna array at the time and the gain of the sub-array is the antenna gain in the analysis presented in Fig. 3.

Operators reconnected all measurement cables in each measurement round and recorded measurement results from the spectrum analyzer. We used a 100 MHz wide digital 16QAM modulated test signal at 26.5 GHz center frequency for the OTA measurements. All OTA tests were performed in a typical radio laboratory environment.

Fig. 4. summarizes the Gage R&R OTA measurement results. The measurement results follow a normal distribution based on Anderson-Darling (A-D) normality test, since p-value is > 0.05. P-value is a test static used in statistical hypothesis testing and a threshold value α is a significance level of test, traditionally 5% [17]. An analysis of variance (ANOVA) table assume that observations follow a normal distribution, which is a valid assumption with the analyzed

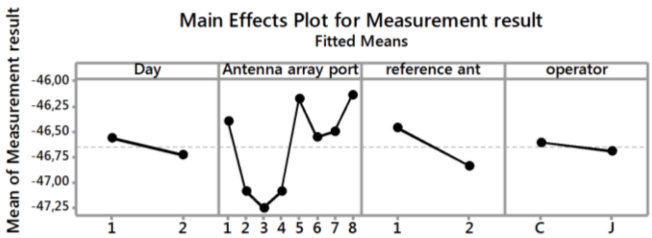


Fig. 6. Main effect plot of OTA antenna array measurements

TABLE II. GENERAL LINEAR MODEL FOR MEASUREMENT RESULTS VERSUS DAY; ANTENNA ARRAY PORT; REFERENCE ANT; OPERATOR

Factor	Type	Levels	Values
Day	Fixed	2	1; 2
Antenna array	Fixed	8	1; 2; 3; 4; 5; 6; 7; 8
reference ant	Fixed	2	1; 2
operator	Fixed	2	C; J

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Day	1	0.4422	0.4422	2.87	0.096
Antenna port	7	10.8032	1.5433	10.03	0.000
reference ant	1	2.2801	2.2801	14.82	0.000
operator	1	0.1278	0.1278	0.83	0.366
Error	53	8.1530	0.1538		
Total	63	21.8064			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.392212	62.61%	55.56%	45.48%

data. Under normality assumption, the statistical importance of a factor p-value in the ANOVA table is valid. A summary of measurement results of each antenna port is shown in Table I. and a box plot figure of the results is shown in Fig. 5. Averages of the received signal levels are within one dB. Measured maximum standard error of mean is 0.19 dB and a 95% confidence interval ($\pm$ 2 σ) for mean value is $\pm$ 0.38 dB.

A main factor plot of the measured variance is shown in Fig. 6 and a corresponding a General Linear Model (GLM) ANOVA table is shown in Table II. Statistically significant main factors are the antenna sub-array and the reference antenna because p-value lower than 0.05. The measurement day and the human operator factors are statistically non-significant main effects because p-value is higher than 0.05. The significant contribution of the measured variance (49.5%) is coming from the product or the antenna sub-array, as desired. On average, the mean value difference between reference antenna results is 0.38 dB. The non-significant main factors, the measurement day and human operator, have on average difference 0.16 dB and 0.09 dB, respectively. A regression model can explain 62.6% of variance and a

TABLE III. GAGE R&R ANALYSIS, TWO-WAY ANOVA WITH INTERACTION

Source	DF	SS	MS	F	P
Antenna array	7	10.8032	1.54332	9.16136	0.005
operator	1	0.1278	0.12781	0.75867	0.413
Antenna array * operator	7	1.1792	0.16846	0.83395	0.565
Repeatability	48	9.6961	0.20200		
Total	63	21.8064			

α to remove interaction term = 0.05

Source	StdDev (SD)	Study Var (6 × SD)	%Study Var (%SV)
Total Gage R&R	0.444672	2.66803	73.51
Repeatability	0.444672	2.66803	73.51
Reproducibility	0.000000	0.00000	0.00
operator	0.000000	0.00000	0.00
Part-To-Part	0.410120	2.46072	67.80
Total Variation	0.604923	3.62954	100.00

standard deviation of error between regression model and measurement results is 0.39 dB. Residuals between the measurement results and the regression model have been studied and the residuals are normally distributed (A-D test, p-value = 0.462) without any visible trend, shift or cycle. This indicates that random causes have introduced the rest of the unexplained error.

A graphical summary of Gage R&R study is shown in Fig. 7 and a corresponding ANOVA table is shown in Table III. An Xbar chart analyzes the average shift of the process and an R chart analyzes the spread or dispersion of the process [18]. The Xbar chart presents averages of the repeated measurements of antenna array ports in this Gage R&R study. The R chart shows the ranges of repeated measurements and a group of repeated measurements of each port is as a sub-group. The OTA measurement process is a stable process because all sub-groups in the Xbar and the R control charts are within control limits marked with an Upper Control Limit (UCL) and a Lower Control Limit (LCL). The reproducibility is omitted from Gage R & R analysis and marked zero in the variation summary chart in Fig. 7, because the operator factor is not statistically significant (p-value > 0.05) seen from Table

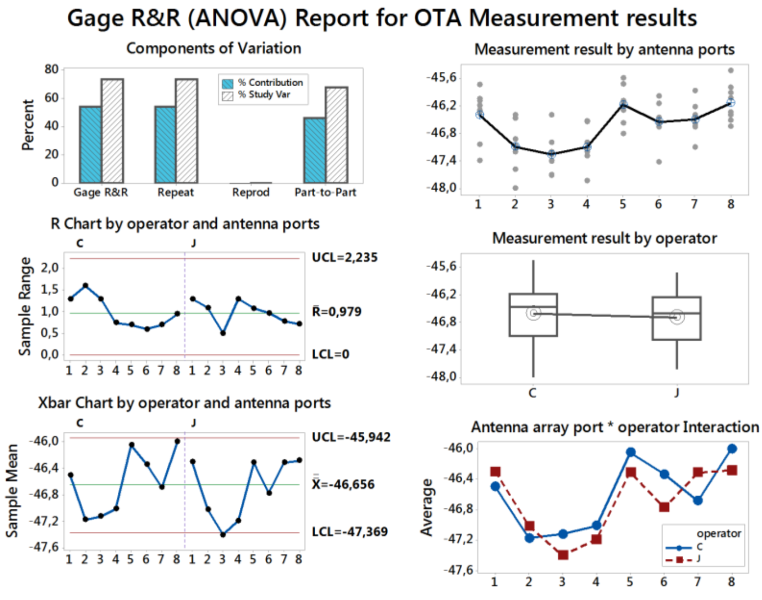


Fig. 7. Gage R&R analysis of OTA power levels with operator and antenna port interactions

III. The reproducibility and the repeatability are pooled together to a total measurement error, which contributes (0.128 + 1.179 + 9.696)/21.806 = 50.4% of the total variance of the measurement results. A standard deviation of the measurement error is 0.445 dB and 95% confidence interval for measurement accuracy is ± 0.89 dB. The measured worst-case measurement confidence interval is a double compared with the theoretical maximum expected power variation is 0.84 dB, but a usage of one measurement antenna will improve the measurement accuracy.

Conclusion

Next generation 5G communication systems will operate at mmW frequencies and those will utilize antenna arrays. OTA based testing will be needed for radio performance measurements. We have performed a statistical measurement system analysis of OTA power level measurement for antenna array targeted to 5G backhaul system. The measured OTA power measurement accuracy in a typical laboratory environment is ± 0.89 dB based on the Gage R&R analysis. This results show that a fast OTA testing can be done, for a mmW antenna array pattern, without dedicated RF shielded chamber. In addition, a measurement error introduced by a human operator was not statistically significant in the measurement process.

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