Impact of Phase Curvature on Measuring 5G Millimeter Wave Devices

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***Abstract*— Wireless industry through 3GPP has standardized 5G in both FR1 (sub 6 GHz) and FR2 (24.25-52.6 GHz) frequency ranges. While FR1 will be using frequencies already in place for LTE-4G technology, FR2 is dealing with mmWave frequencies. Due to the high free space path loss (FSPL), 5G at mmWave would impose the use of directive antennas on both ends of the communication link, the User Equipment (UE) and the Base Station (BS). A black box approach (i.e. the location of the antenna within the device is unknown) has been agreed to be used for Over The Air (OTA) measurements. The physical center of the device must be aligned with the center of the measurement setup. Hence, the test antennas will likely be offset with respect to the center of the coordinate system. The measurement distance will be for most systems sufficient to minimize the amplitude error while will introduce a phase deviation between the actual spherical wave and the desired plane wave which may cause an effective phase shaping of the radiated beam of the small phased array under test. In this paper we will analyze the impact of the phase curvature on the beam antenna pattern and spherical coverage for the different testing environments. Specifically, simulation of a 5G terminal device with multiple beams will be considered and realistic spherical near field measurement at different finite distances will be emulated also taking into account different measurement antennas (probes).**

I. Introduction

Wireless industry through 3GPP has standardized 5G in both FR1 (sub 6 GHz) and FR2 (24.25-52.6 GHz) frequencies ranges. Mainly, conformance testing requirements have been agreed and reported in [1] for FR2 (mmWave) frequency range. Due to the very high path loss, phased antenna arrays will be used at both ends of the communication link, the User Equipment (UE) and the Base Station (BS). Phased antenna arrays would have a limitation on the scan angle while meeting the gain requirements. In addition, a UE would not always point the beam towards the gNB (i.e. base stations for the 5G cellular technology) so that in order to guarantee a "good connection", multiple array modules will be integrated in a UE. Specifically, spherical coverage in terms of Effective Isotropic Power (EIRP) and Effective Isotropic Sensitivity (EIS) have been standardized as conformance testing requirements along with the traditional EIRP and EIS. The spherical coverage is the ability of a wireless terminal to reliably form the beam in any direction and polarization.

Different testing methodologies such as Direct Far Field (DFF), Indirect Far Field (IFF) with reflector (CATR) or a Plane Wave Generator (PWG) and Near Field with Transformation (NFTF) have been studying, each having pros and cons [2]. In each test environments, a "black box" approach will be used. This would imply that the antenna arrays locations are unknown so that any alignments between the UE beam direction and measurement antenna is precluded before starting the test. The device under test will be placed with its physical center aligned with the center of the measurement system so that it is likely that the antenna array would be offset with respect to the center of the measurement coordinate system. At the same time, no interfaces have been standardized in order to control the UE beam management. For example, UE beam selection in Uplink is achieved based on the Downlink signal direction. This is the main reason to consider the amount of phase variation in measurement system quiet zone.

II. Test Methods

DFF and IFF methods are the most likely solution to be used for conformance testing. In the following subsections a brief description is provided.

A. Direct Far Field (DFF)

This setup must be capable of emulating a plane wave at a certain distance between the measurement antenna and the Device Under Test (DUT). The standard Far Field (FF) measurement distance is given by $2D^2/\lambda$ where D is the whole DUT dimension. As described in [3], at such distance the spherical wave front at the edge of the device under test has a deviation of 22.5° with respect to an ideal plane wave. The associated measurement distances and Free Space Path Losses (FSPL) for a D=15cm device are listed in Table 1.

In order to address the very high path loss due to the range length, D is considered to be 5cm which is the size of the radiating portion of the aperture, not the size of the whole DUT. Assuming the array has a radiating aperture of 5cm at 28GHz, a range length of 90cm is sufficient to achieve a 22.5° phase variation from a plane wave at the radiating aperture.

TABLE I. FF measurement distance and FSPL for a D=15 UE under test.

Frequency [GHz]	FF distance [m]	FSPL [dB]
30	4.5	75
40	6.0	80

B. Indirect Far Field (IFF)

This method does employ the use of either a reflector (Compact Antenna Test Range, CATR) or an array of suitable excited elements (Plane Wave Generator, PWG) [4]. In a CATR, the spherical wave front from the feed is transformed into a plane wave at the DUT in both TX (DUT is transmitting) and RX (DUT is receiving). In a PWG instead a plane wave front is created at certain distance from the array. In Figure 1 a CATR, and PWG implementations are reported respectively. Both are used as IFF methods.

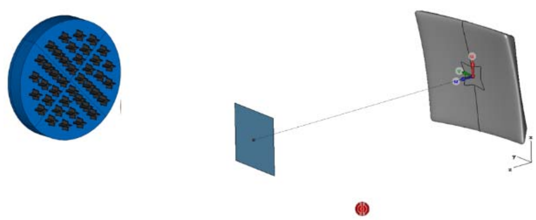

Figure 1. IFF implementations – PWG (left), CATR (right)

The main characteristic is that the plane wave can be emulated in specified quiet zone (QZ). Amplitude and phase variation in the QZ of an IFF method do depend on the geometry of the system setup and are the key factors for selecting an IFF method's implementations.

III. SIMULATION DESCRIPTION AND FIGURE OF MERITS

From [3], it is known that 22.5deg is the estimated phase curvature of the plane wave at 2D^2/λ and its effect on a generic directive pattern can be seen in Figure 3. How to translate the phase variation [deg] in measurement uncertainty [dB] has not yet addressed in literature.

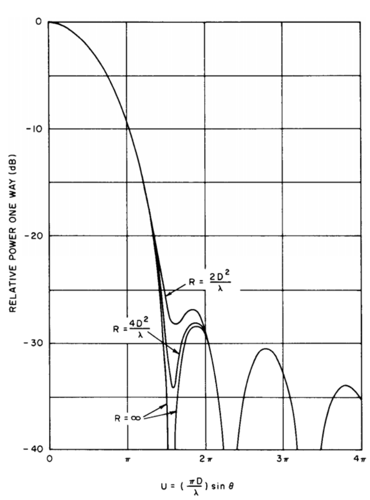

Figure 2. Example of radiation pattern errors [3].

A possible approach could be by using the so-called transmission formula widely used for probe correction purposes in spherical NF measurements as described in [5]. The mathematical expression of the transmission formula is reported in equation (1)

$$w(R,\chi,\theta,\phi) = \frac{1}{2}\sum_{\substack{smn\\ \sigma\mu\nu}} Q_{smn}^{(3)}\, e^{jm\phi} d_{\mu m}(\phi) e^{j\mu\chi} C_{\sigma\mu\nu}^{sn(3)}(kR) R_{\sigma\mu\nu}^{p} \qquad (1)$$

where $w(R,\chi,\theta,\phi)$ is the measured signal at distance R from the origin of the coordinate system, $Q_{smn}^{(3)}$ are the Spherical Wave Coefficient (SWC) of the DUT and $R_{\sigma\mu\nu}^{p}$ are the probe SWC. This formulation allows to emulate the signal transmitted by the DUT and sampled by a receiving probe all over the measurement sphere. From this formulation, the measurement uncertainty due to the measurement distance can potentially be estimated since the phase curvature in the QZ is represented by $R_{\sigma\mu\nu}^{p}$, while the UE antenna array pattern by $Q_{smn}^{(3)}$. It shall be noted that this measurement uncertainty is seen as DUT dependent.

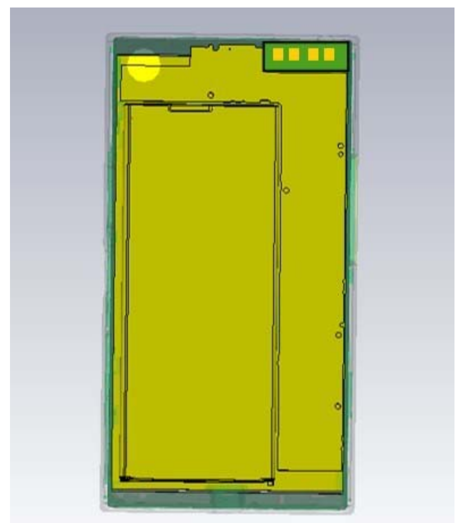

Figure 3. 4x1 linear antenna array on a phone-size ground plane.

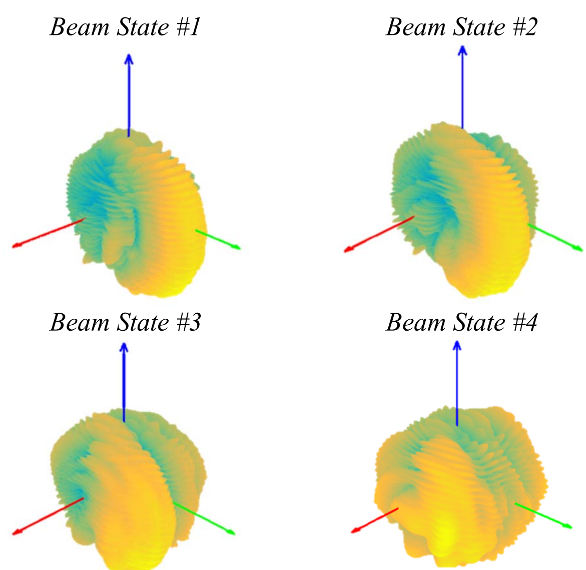

Figure 4. UE model: radiation pattern of different beam states.

The simulated UE under test considered in this analysis is the 4x1 linear antenna array working at 28 GHz and shown in Figure 3. The maximum dimension of the device is 15 cm. The 4-element array is mounted on a phone-size ground plane enclosed in a realistic plastic case. Such model of UE has been used in 3GPP RAN4 to derive the EIRP spherical coverage requirements [1-2].

For this test case a number of four beam states have been analyzed. Each beam state corrisponds to a beam direction. The simulated FF radiation patterns of the four different beams are shown in Figure 4.

For each of the above simulated scenarios, the FF radiation patterns (field at infinite distance from the DUT) are used as baseline for the comparison. In order to address the impact of the phase curvature of the field to the antenna array beam patterns, three measurement antennas have been considered as probes:

- an ideal Hertzian dipole;
- simulation of a realistic probe implemetation at mmWave (currently used in the StarLab 50GHz series [6-7]);
- simulation of a PWG at mmWave.

In case of ideal dipole and probe, two range lengths (distance between DUT and the measurement antenna) have also been simulated: $R = 45$ cm and $R = 90$ cm. The obtained pattern have then been compared with the baseline (thorethical FF) and with the emulated measurements with the PWG. As figure of merits, the following were used when comparing the beam patterns:

- Beam Peak Error (dB)
- Beam Peak Location Error (deg)
- ENL (Equivalent Noise Level) for total E-field (Etotal)

ENL is used to express with a single value the correlation between the reference/baseline radiation patterns and the test radiation pattern under analysis. This is accomplished by converting into an equivalent noise all the deviations with respect to a reference pattern. The ENL formula is given in (2) where $E(\theta, \varphi)$ is the reference and $\tilde{E}(\theta, \varphi)$ is the test pattern.

$$ENL = 20\log_{10}\left(RMSE\left|\frac{E(\theta,\varphi) - \tilde{E}(\theta,\varphi)}{E(\theta,\varphi)_{MAX}}\right|\right) \qquad (2)$$

IV. Simulation Results

In this section the simulation results for test case scenarios described in section III are presented.

As discussed, four beam states (directions) have been simulated and analyzed. Results in terms of the level and location of the beam peak are reported in Table 2 and Table 3 respectively. The ENL results are instead reported in Table 4.

TABLE II. Beam Peak Errors

Beam States	Dipole (R=45cm)	SL Probe (R=45cm)	Dipole (R=90cm)	SL Probe (R=90cm)	PWG
1	-0.7 dB	-0.6 dB	-0.3 dB	-0.3 dB	-0.3 dB
2	-1.0 dB	-0.9 dB	-0.6 dB	-0.6 dB	+0.2 dB
3	-1.1 dB	-1.0 dB	-0.5 dB	-0.5 dB	+0.3 dB
4	-0.2 dB	-0.2 dB	+0.1 dB	+0.0 dB	-0.1 dB

TABLE III. Beam Peak Location Errors (Theta, Phi)

Beam States	Dipole (R=45cm)	SL Probe (R=45cm)	Dipole (R=90cm)	SL Probe (R=90cm)	PWG
1	+6°, +0°	+6°, +1°	+0°, -2°	+0°, -1°	+0°, +0°
2	-4°, -14°	-4°, -14°	-4°, -14°	-4°, -14°	+0°, +0°
3	+6°, +1°	+6°, +1°	+6°, +0°	+6°, +0°	+0°, +0°
4	+4°, +0°	+4°, +0°	+4°, +0°	+4°, +0°	-5°, +0°

TABLE IV. Equivalent Noise Level

Beam States	Dipole (R=45cm)	SL Probe (R=45cm)	Dipole (R=90cm)	SL Probe (R=90cm)	PWG
1	-26.1 dB	-26.4 dB	-31.7 dB	-31.8 dB	-44.5 dB
2	-26.3 dB	-26.5 dB	-32.1 dB	-32.2 dB	-44.8 dB
3	-26.6 dB	-25.7 dB	-30.9 dB	-31.0 dB	-44.0 dB
4	-23.7 dB	-23.8 dB	-28.7 dB	-28.7 dB	-43.5 dB

Figure 5 to Figure 7 show the radiation patterns comparison, both azimuth and elevation cuts ($\varphi = 0°$, $\varphi = 90°$ and $\theta = 90°$), for the beam state #2 (worst case scenario according to the results in the tables) and for the simulated two range lengths 45cm and 90cm.

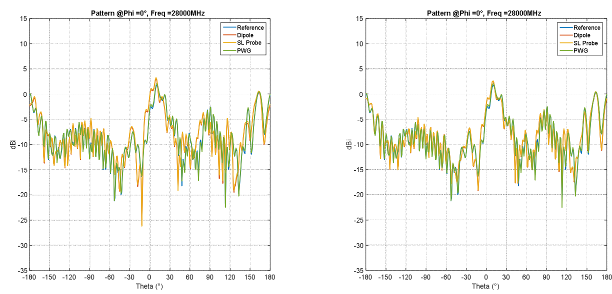

Figure 5. Radiation patterns pomparison at $\varphi = 0°$: 45cm (left) and 90cm (right)

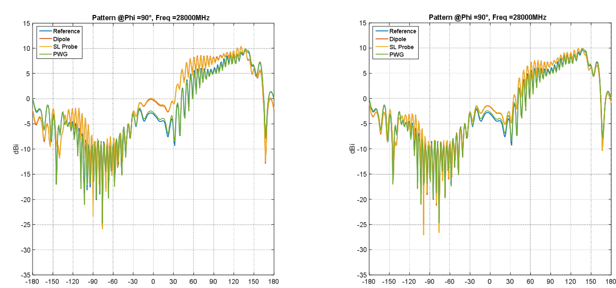

Figure 6. Radiation patterns pomparison at $\varphi = 90°$: 45cm (left) and 90cm (right)

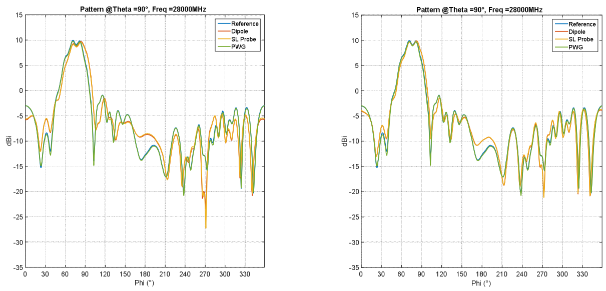

Figure 7. Radiation patterns pomparison at $\theta = 90°$: 45cm (left) and 90cm (right)

For this simulated scenario the EIRP spherical coverage curve has been also compared for the DFF when using the dipole and the probe at the two considered distances (45cm, and 90cm) and with the PWG implementation. EIRP spherical coverage is the ability of a wireless terminal to reliably form a beam in any directions and polarization. It is computed from the DUT EIRP pattern measured all over the sphere (3D) with a certain sampling grid defined in [2]. At each angle, the DUT is allowed some dwell time to select the beam state after which the test equipment measures the power in the traditional way. An empirical cumulative distribution function (CDF) is then calculated so that how the UE will work at different probability levels. 50% percentile is the probability level agreed in [1]. In Figure 8, the EIRP spherical coverage is computed and compared for the UE model under analysis.

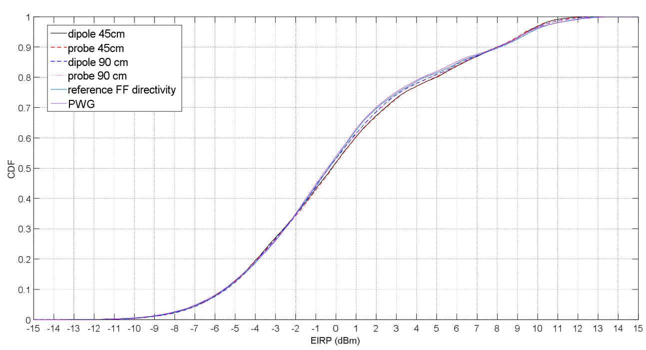

Figure 8. Spherical coverage comparison.

A. *Discussion of Results*

Based on the obtained results, the following observations can be made.

First of all, no major differences between the measurement emulations with the Hertzian dipole and the realistic probe at both range lengths are observed, meaning that the probe does not perturb significantly the measured field.

As expected, the radiation patterns obtained with the PWG agree very well with the baseline leading to excellent accuracy of the considered figure of merits. This is due to the good performances of the PWG's QZ in terms of amplitude and phase variation with respect to an ideal plane wave.

At 45 cm range length, the maximum beam peak error is around 1 dB while at 90 cm range length, this error is around 0.5dB. Such deviations get much smaller, around 0.2dB when the PWG is used. Beam peak location error seems not to be significantly impacted by range length.

As expected, the ENL is improved of about 5 dB when the range length is increased from 45 cm to 90 cm (from approx. -25 dB to approx. -31 dB). The ENL obtained with the PWG is instead much lower (approx. -44 dB)

Finally, no major differences can be observed in the spherical coverage curves between 45 cm, 90 cm range lengths, and PWG implementation with respect to the baseline curve.

Although the considered measured distances modify the pattern of the device, it can be concluded that some figure of merits like the spherical coverage are not significantly affected by the reduced measurement distance.

V. Conclusion

Different measurements of a realistic model of a multibeam UE device working at 28 GHz have been emulated considering different scenarios. Measurement emulations have been carried out with the transmission formula considering two probes (an ideal Hertzian dipole and a realistic mmWave probe) at two measurement distances: 45 cm and 90 cm. Such emulations are intended to reproduce a direct FF approach at distances much smaller than conventional FF distance, which, considering the size of the device (D=15cm), is approx. 4.5 m. The measurement emulation has also been performed with a PWG model reproducing an indirect FF approach. Results in terms of pattern, beam peak level/position, ENL and EIRP spherical coverage have been compared with the baseline/reference.

As expected, the performances obtained with the PWG are fully in line with the reference. The radiation pattern measured with the considered probes at the two finite distances is modified with respect to the reference one. Nevertheless, some figure of merits like the spherical coverage are not significantly affected by the reduced measurement distance.

Next steps are to perform tests on real devices with both direct FF (at 45cm mainly) and PWG implementation in order to compare the results with the simulated ones presented here.

References

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