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Performance Evaluation of Sectored MPAC for 5G UE Antenna Systems

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***Abstract* — Over-the-air (OTA) test system performance evaluations is a topic to agree in the industry to be able to guarantee the comparability of the test results from different laboratories. For 5G test purposes at mmWave there are no currently metrics to be used. This paper presents both the recently proposed metrics and some performance evaluation results for UE using these metrics.**

I. Introduction

Any test system or test methodology needs metrics to evaluate its performance. In the 5G mmWave area the metrics are currently under development both in the academia and in the industry. The same is valid even for the test system development where the complexity and the cost are very essential factors in searching for the industry acceptance. The paper [1] presents some comparison between 4G UE and 5G BS testing aspects. More confined presentation on the 5G BS testing and on the metrics are in [2], [3]. Regarding the LTE MPAC systems well–known and established test system validation metrics exist. The proposed setup in [1], [2], [4] is an extension of the LTE MPAC but because of different test system requirements the metrics for the proposed test system aim to different parameters. This paper neither studies the existing LTE MPAC metrics nor analyses the requirements for 5G test systems for UE or BS.

The beam selection and acquisition within a discrete set of clusters is in a central role in a 5G UE. These are the key points where the proposed new test system metrics are targeted. This paper presents four statistical measures where the first two of them are for the beam locations. Their role is to statistically check how well the reproduced channel model in the proposed OTA setup matches to the desired channel model, which is here called the reference. Visually the matching is very easily interpreted from the 3D histograms. Numerical values are calculated as well to quantify the deviation.

The third metric refers to the beams and powers allocated to the beams to form the power angular spectrum (PAS) seen by UE. Normalization is used to limit the calculated value for the range [0, 1].

The fourth metric presented here is an extension from the LTE test setups for the spatial correlation in the test zone. The extension means to give more weight to the higher correlation cases because the higher correlation has a more severe impact on the system performance, e.g. on spatial multiplexing. As in all metrics the error between the OTA performance and the reference is measured. This is also a PAS metric but now by definition limited to the area known as test zone in LTE MPAC. However, the spatial correlation metric is considered as of less importance because of the beam selection procedure.

II. Metrics

A. Beam Peak Distance

Beam peak distance is the angular distance between the centre of gravity (called also expectation in the statistics) of the test system and the reference histograms:

$$BD = \sum_n \Omega_n p_{\text{ref}}(\Omega_n) - \sum_n \Omega_n p_{\text{test}}(\Omega_n) \qquad (1)$$

where Ω_n is the space angle of nth beam, $p(\Omega_n)$ is the probability of detecting the maximum power in beam n and unit is degree (or radian). The smaller the beam peak distance, the more accurate the channel emulation in the MPAC setup. The metrics A and B are easily understood from Figure 1 as well from Figure 2.

B. Total Variation Distance of Beam Allocation Distributions

Statistical distance is the total variation distance of the reference and the test histograms probability measures. This is based on the same data as the beam peak distance. The statistical consideration only is different and here the output of the formula is in the range [0, 1]. 0 means full similarity, and 1 means maximum dissimilarity:

$$SD = \sum_n \frac{|p_{\text{ref}}(\Omega_n) - p_{\text{test}}(\Omega_n)|}{2} \qquad (2)$$

C. Total Variation Distance of PAS

Total variation distance of power angular spectrum (PAS) is meant to measure the similarity of the PAS produced by the OTA system and the reference PAS. In this sense, it is similar to the spatial correlation metrics in section II.D. The additional information in the total variation distance of PAS is the capability to reflect UE size and resolution (antenna array aperture). This is done here through the classical Bartlett beam former with UE array but any respective method would work. The PAS estimate is for the reference as

$$\hat{P}_r(\Omega) = \boldsymbol{\alpha}^H(\Omega)\left(\oint \boldsymbol{\alpha}(\Omega')P(\Omega')\boldsymbol{\alpha}^H(\Omega')d\,\Omega'\right) \qquad (3)$$

where *P(Ω')* is the PAS of the reference model. The respective estimate for the OTA system is

$$\hat{P}_o(\Omega) = \boldsymbol{\alpha}^H(\Omega)\boldsymbol{R}_o\boldsymbol{\alpha}^H(\Omega) \qquad (4)$$

where $\boldsymbol{\alpha}^H(\Omega)$ is the array steering vector of UE to the space angle Ω. $\boldsymbol{R}_o = \{\hat{\rho}_q\}$ is the spatial correlation matrix for the probe locations. Its entries are the cross-correlation coefficients between UE element locations. The formula is given in eq. (7).

Both estimated spectra are next normalized such that they can be interpreted as 2D probability distributions. The integration over the difference of the normalized spectra is finally calculated as

$$D_p = \frac{1}{2} \int \left| \frac{\hat{P}_r(\Omega)}{\int \hat{P}_r(\Omega')d\Omega'} - \frac{\hat{P}_o(\Omega)}{\int \hat{P}_o(\Omega')d\Omega'} \right| d\Omega. \quad (5)$$

where r denotes for ideal reference and o for the OTA system, and β is the space angle. The range of D_p is [0,1] where zero denotes the full similarity and unity the full dissimilarity.

D. Spatial Correlation

The spatial correlation metric is meant to measure the similarity of the produced power angular spectrum (PAS) to the reference but considering also the power of the beams on a particular test zone within the setup. It is the way how the test zone size is measured in LTE MIMO OTA. But now at mmWave the beam selection process is the focus. Therefore, the spatial correlation metric is of less significance. Another reason is that this metric is not suitable for the dynamic, i.e. non-stationary channel models.

The difference to the LTE spatial correlation definition is that weighting is applied here. The weight is used for the correlation level so that the not all correlation levels are treated equally; the deviations within the low correlation cases is not equally important, for example, to the spatial multiplexing performance as it for the high correlation cases.

The correlation with any pair of spatial locations q = ($\boldsymbol{p}_{q1}$,$\boldsymbol{p}_{q2}$) can be written as

$$\rho_q = \oint P(\Omega)\exp(j\Omega \cdot (\boldsymbol{p}_{q1} - \boldsymbol{p}_{q2}))d\Omega \quad (6)$$

where $\boldsymbol{\Omega}$ is the wave vector for the given space angle Ω. The spatial correlation function achievable with an MPAC setup is then

$$\hat{\rho}_q = \frac{\sum_{k=1}^{K} g_k^2 L(d_{p1,k}) L(d_{p2,k}) \exp(j\|\boldsymbol{\Omega}\|(d_{p1,k} - d_{p2,k}))}{\sqrt{\sum_{k=1}^{K} L^2(d_{p1,k}) g_k^2 \sum_{k=1}^{K} L^2(d_{p2,k}) g_k^2}} \quad (7)$$

where K is the number of probes, g_k is the weight of the kth probe, $d_{p1,k}$ and $L(d_{p1,k})$ are the distance and the path loss term between the kth probe and the location p_{q1}, respectively.

The weighted RMS correlation error is finally

$$e_\rho = \sqrt{\frac{1}{Q}\sum_{q=1}^{Q} |\rho_q - \hat{\rho}_q|^2 \max(|\rho_q|, |\hat{\rho}_q|)} \quad . \quad (8)$$

III. Simulation Results

The simulation results are for the standard GSCM UMi LOS and NLOS models ([4]) where more emphasis is on the NLOS models. While the focus of the metrics presented in section II is in the beamforming the LOS model is simpler and the non-LOS clusters are very weak leading to situation where the contribution of the other clusters is close to be negligible. It should be noted that the models in [4] are generated for system level simulations by 3GPP RAN1 working group and they might be modified along the development of the mmWave test system evolution.

The GSCM models are statistical in their nature. Therefore, to have a descriptive figure of the test system performance a high enough amount of simulation runs should be performed. However, the research for the test system evaluation is yet in an initial phase and not such a coverage can be presented. The idea is to continue the research and to present, e.g., the histograms for 1000 or similar number of runs for every case. The cases and parameters are still to be defined. Using the histograms, the results could be easily presented in a visual way where the percentage values of the ranges for good, moderate and poor performance of the test system are also given.

Another way to look at visually the results is to plot the angular maps where the angular values are the probe locations and the bars on the map indicate the beam probability in that location. Figure 1 below is for LOS case and Figure 2 is for NLOS case. The reference is the target channel model and the plots should be interpreted in such a way that the similarity of the plots indicates the test system can reproduce the intended channel model. In the LOS case the probability of the strong beam to in a direction is high and it is clearly seen. In the NLOS case the spread is higher.

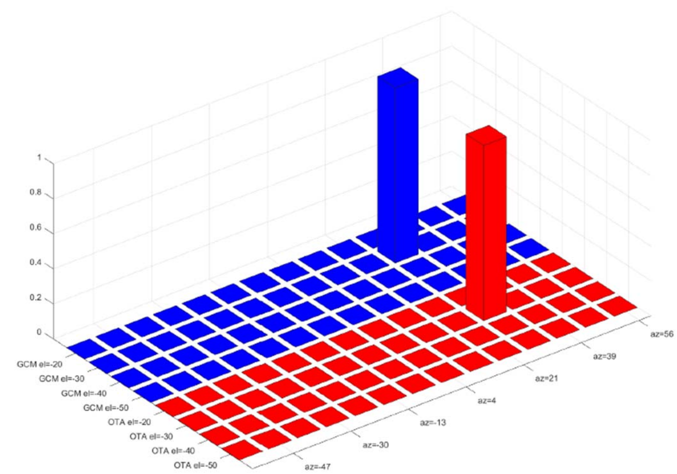

Figure 1. Beam probabilities in a LOS case for the reference model (blue) and the test system under study (red).

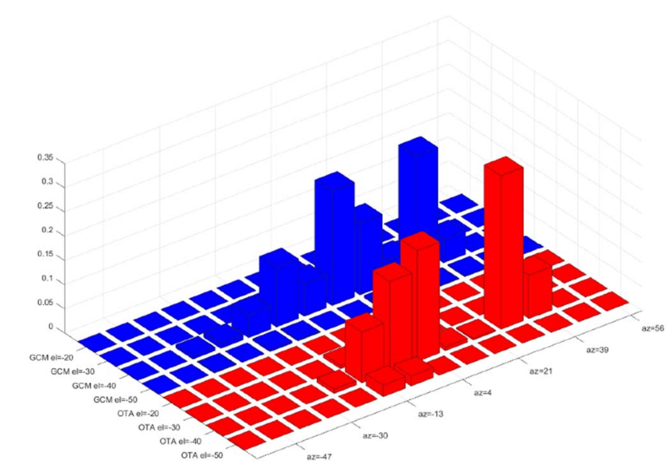

Figure 2. Beam probabilities in an NLOS case for the reference model (blue) and the test system under study (red).

The figures above are not from the same simulation runs as Figure 3 and Figure 4. They are exemplary only and the intention is to give an idea about the beam selection and the use of the metrics to highlight the beam selection procedure.

Figure 3 and onwards present drops of the GSCM UMi channel model onto the sector (see [1] for the sector presentation). The sector size in these examples is 120° in azimuth and 60° in elevation. The UE antenna array is 4x4 with $\lambda/2$ separation @ 28 GHz. The figures show a relatively high number of probes installed in the test system and a significantly lower number of active probes — a subset of the installed probes —used to reproduce the channel model. The active probes are selected based on the mapping of the channel model. The mapping procedure is out of the scope of the paper; however, any appropriate method should work. The method to take into use the active probes can be mechanical or electrical, e.g., through a switching circuit. The reason to limit the number of active probes (through a switching circuit or respective methodology) is to save costs in the actual method implementation. It is not the cost of the probes because they can be manufactured using the printed circuit board technologies. The cost comes from the HW resources needed and when less probes are used through the switching circuit the investments to the HW resources are less. The moderate but from performance point of view high enough number of active probes makes the proposed test system more attractive.

Part of the metrics is also to decide the numerical values for the ranges good, moderate and poor. The figures presented here are a visual way to estimate the test system performance but it is not enough; more exact method should be used. For this purpose, the metrics are the answer.

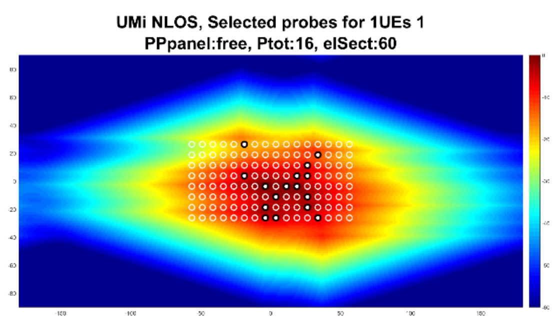

Figure 3. The sector of probes, probes selected (black circles) and the cluster spread for UMi NLOS channel model.

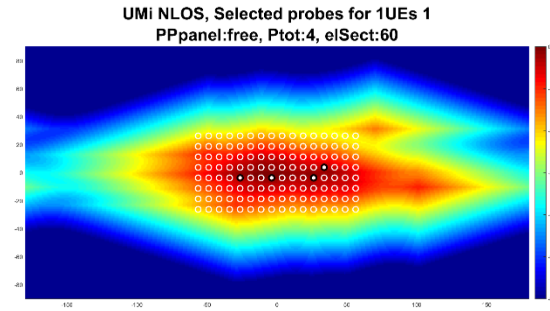

Figure 4. Similarly to Figure 3 but now a different drop of the stochastic channel model and only four probes used.

CONCLUSION

New metrics for the mmWave OTA test system were presented. The metrics emphasize the beam acquisition and the beam refinement process as the devices at mmWave frequencies are expected to contain highly directive antenna arrays. The test zone size correlation known very well from LTE MPAC systems is thought to be of less significance.

Some figures were also presented. The beam angular position maps are a useful operation to check visually the matching between the ideal reference and the implemented test system. The drop figures of the channel model onto the sector highlight well the probe mapping and the selection of the active probes.

The histograms for a set of simulation runs were not ready by the submission deadline. The histogram presentation mode would probably be a better way of evaluation as it enables in an easily interpreted way both the numerical and the visual presentation of the results.

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