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Impact of Mounting Materials on Phased Arrays for the 5G New Radio

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Abstract

As the wireless industry continues the move to 5G, the development and subsequent testing of mmWave radios for both base stations and user equipment still face numerous hurdles. The need to test most conformance and performance metrics through the antenna array at these frequencies poses significant challenges and has resulted in excessively large measurement uncertainty estimates to the point where the resulting metrics themselves may be useless. A large contribution to this measurement uncertainty is the impact of the over-the-air (OTA) test range used, driving the industry towards expensive compact range reflector systems in order to overcome the path loss considerations associated with direct far-field measurements. However, this approach necessitates the use of a combined axis measurement system, which implies the need for considerable support structure to hold the device under test and manipulate it in two orthogonal axes. This paper explores some of the limitations and considerations involved in the use of traditional "RF transparent" support materials for mmWave device testing.

1 Introduction

There are still numerous hurdles [1]-[2] to performing the various 5G conformance test cases for mmWave user equipment (UEs) listed in 3GPP TR 38.810 [3]. All of these tests propose manipulating the device under test (DUT) in two orthogonal axes in a "free space" (device only) configuration. However, one topic that has had little consideration to date is the impact of support structure used to hold the DUT in the test volume. It has never been possible to test a wireless device in a truly free-space condition, although for traditional sub-6 GHz wireless device testing where the integrated power pattern metrics of TRP and TIS were the key performance indicators of interest, the impact of support structure was of minor concern as long as it was made of low-loss dielectric materials. At those frequencies, for typical mobile devices, even the supporting components of the positioning system itself could be made of low-loss dielectrics. For theta arm and multi-sensor systems where the DUT only needs to move in one axis, an expanded polystyrene (EPS) foam column, occasionally in conjunction with unloaded polyurethane foam rubber, and possibly combined with some fiberglass or other structural components far from the DUT, is commonly used to support the DUT against gravity. For combined axis systems that must manipulate the DUT in two axes, more robust attachment schemes are required and often include rubber bands, cellophane tape, Velcro, or other means to attach to various plastic or fiberglass support structure components of the positioning system, as illustrated in Figure 1.

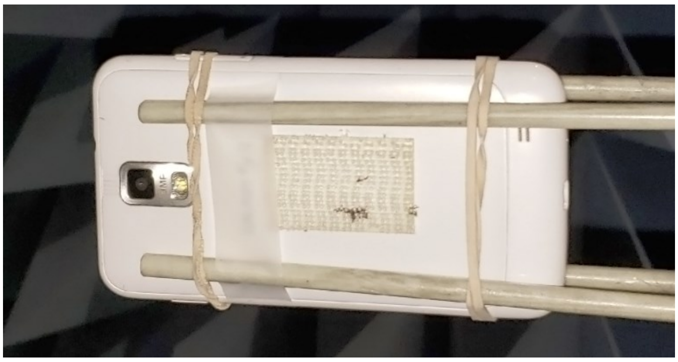

Figure 1. Common mounting schemes for "free-space" mobile phone testing.

Given the system constraints for both direct and indirect far field (i.e. compact antenna test range) approaches for RF parametric testing, as well as the multi-probe scenarios for testing radio resource management and demodulation functionality, mmWave test systems are expected to require the latter combined axis positioning system for the DUT. While typical DUT designs will still attempt to produce isotropic spherical coverage by using multiple beam-steerable antennas, the measurement process and extracted metrics will be considerably different from that for traditional sub-6 GHz performance tests. In addition, the RF properties of common dielectric materials used as "RF transparent" support structure cannot be assumed to perform the same at mmWave frequencies. Even if the material can still be assumed to be lossless, the phase change resulting from travel through even a few millimeters of dielectric with a permittivity above 1.0 can result in significant alteration of the measured radiation pattern. Since, unlike TRP and TIS, many of the target metrics rely on the beam peak performance for a set of available patterns generated by the DUT, even minor alterations to each individual beam pattern can have a significant impact on the target metric. This paper will evaluate the impact of various common support materials on the beam patterns generated by a mmWave phased array.

2 Test Setup

To perform these tests, we acquired an 8x8 phased array [4] from the University of California San Diego (UCSD) and measured various patterns every 100 MHz across the frequency span from 27 to 29 GHz with the array phase shifters tuned to 28 GHz. The array was mounted in the center of the test volume on a multi-axis positioning system behind a black polylactic acid (PLA) 3D printed radome intended to simulate the outer case of a mobile phone or similar device. A dual polarized broadband horn was used as the measurement antenna with a range length of 1.25 m from the center of rotation where the face of the array was mounted. The diagonal length of an 8x8 half-wavelength array at 29 GHz corresponds to a far field distance of 0.66 m, so this test range length was roughly twice the required direct far-field distance for the entire array. Reference tests were performed for array configurations representing typical array sizes expected to be implemented in common user equipment, ranging from 1x4 elements up to the 2x8 element array size specified as the maximum reference in 3GPP's TR 38.810, so the required far-field distance is even less. The tests were then repeated with a variety of common dielectric materials mounted to the radome to simulate mounting or support structure that might be placed in contact with the 5G UE DUT near an embedded array, as shown in Figure 2. These materials include: a) three layers of cellophane tape; b) two rubber bands, double-thickness; c) 2.3x9.5x11 cm expanded polystyrene (EPS) bead foam block; d) 5x10x10 cm extruded polystyrene (XPS) foam block; and e) 0.25" (6.35 mm) O.D., 0.125" (3.175 mm) I.D. FR4 fiberglass tube. In general, the materials were placed to have a greater impact "below" the centerline.

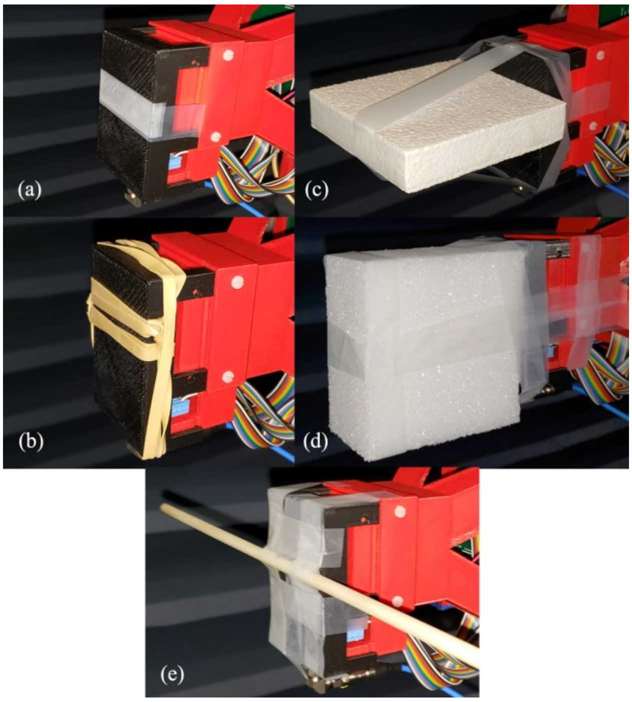

Figure 2. Common "RF transparent" mounting and support materials for wireless testing, including a) cellophane tape, b) rubber bands, c) expanded polystyrene foam, d) extruded polystyrene foam, and e) fiberglass tubing.

This was by no means an exhaustive list of materials, but represents the maximum number of tests performed in the available chamber time, as well as a practical limit to the results that can be presented in one paper. Future work will evaluate additional materials and geometries.

3 Measurement Results

Transmit patterns were measured at the 7.5° resolution specified in TR 38.810, and normalized to the boresight measurement of a single array element, thereby representing approximate array gain in the magnitude plots. To save test time, patterns were only collected in the upper hemisphere, from theta equal 0 to 90° from the normal boresight direction of the array. It is not possible to present all of the available data here, and it is challenging to illustrate all of the differences in individual static 3D plots. For brevity, the vertical 2x8 element arrangement with a single 28 GHz beam at 15° down tilt will be used for most of these plots. Note that the starting orientation of the array was upside down relative to the direction of the beam tilt, so positive elevation values are "down" in the plots. Since spherical plots would hide features like nulls in the patterns, polar temperature/radar plots are used.

Figure 3 provides a comparison of the most significantly changed patterns, which, not surprisingly, are from the largest block of the "near air" dielectric, extruded polystyrene, and the small but dense fiberglass tube. The large polystyrene block has a lensing effect, focusing the energy in the main lobe onto a smaller area, while the fiberglass tube tends to scatter much of the energy from the main lobe into side lobes.

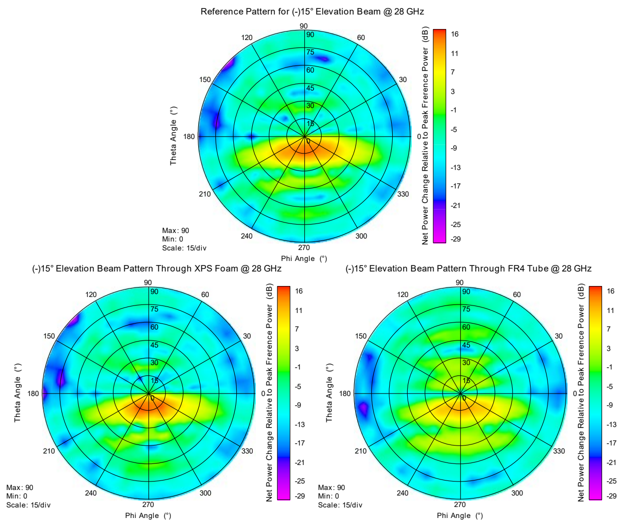

Figure 3. Comparison of XPS block (left) and FR4 Tube (right) to Reference Pattern (top).

Figure 4 compares the peaks of each material pattern with the reference at each beam elevation setting. As intended, the impact of most of the materials is generally more noticeable in the boresight and positive (downward) elevations due to the geometric location of the materials applied. It's important to note, however, that, regardless of the beam direction, the physical impact of the dielectric on the radiation pattern of each individual array element remains the same. When steering the beam, each element is simply shifted in phase relative to its neighbor, so other than any internal electrical impact that may have on the circuitry due to mutual coupling, the radiation pattern of a given element through the dielectric remains the same for each beam direction. Thus, it is primarily just the relative phase shift of the individual elements as seen through the dielectric that is resulting in the pattern changes illustrated.

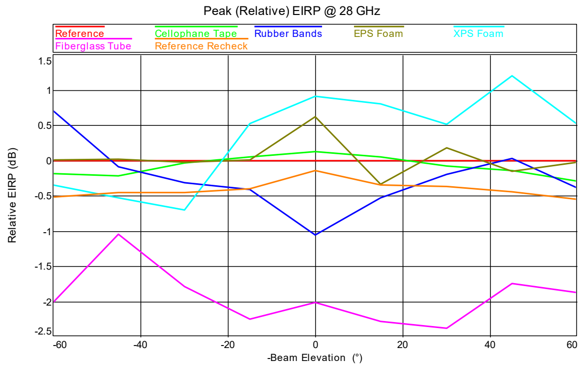

Figure 4. Comparison of peak point in each pattern relative to the peak of the reference pattern.

Figure 5 shows the average power integrated from the measured half surface of each pattern. Most of these remain near the reference, while the fiberglass tube shows a notable loss across each angle, indicating that the energy from the main lobe wasn't just scattered into side lobes, but a significant amount was actually lost in the material. Thus, it would appear that FR4 does not have a very low loss tangent at mmWave frequencies. Note of course that all of these curves change significantly as a function of frequency, since the phase relationships of the various components are affected differently as they propagate through the material. In other words, the electrical length of the dielectric material is changing as a function of frequency. Note too that a re-check of the reference pattern at the end of several weeks of testing shows about half of a dB of drift between the two patterns. This can be considered as an estimate of the stability/repeatability of all of the measurements, so it is not possible to make a definitive statement on the loss of the materials that cluster within half a dB of the original reference. However, it does appear likely that the rubber bands have a rather significant loss to have the visible impact from such a small amount of

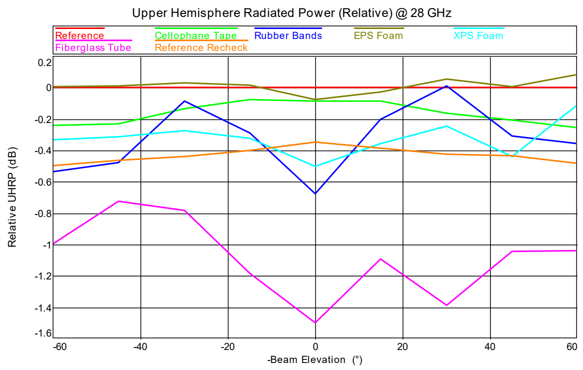

Figure 5. Comparison of the average power in each pattern relative to the reference pattern.

material. Conversely, while the large XPS block probably illustrates some loss, compared to the amount of material present (or at least the size of the block) the impact is negligible.

These figures are representative of the impact of support structure on the TR 38.810 beam peak search, where at each point in a spherical pattern, the DUT will be made to adapt to the best pattern for a given direction, and then either the EIRP or receiver sensitivity will be measured in that position. This implies that the result in that position represents the best that the device can do in that direction. Of course, if the support structure is acting as a lens and either increasing the performance in the tested direction, or possibly producing a null where one does not normally exist, then the result will be wrong. Note too that in this scenario, the beam selection and the beam measurement are in the same direction, so the impact of the support should be similar in both cases. The data presented in Figure 4, then, provides the peak of the entire pattern for each beam direction, so the actual peak direction may be different in each measurement. In other words, it compares peak to peak for the same array pattern setting, regardless of where the peak occurred. Figure 6, instead, shows the result when the same impaired patterns are used to extract the values corresponding to each peak direction in the reference patterns for each beam elevation. That is, it illustrates how the reference point changes when measured through the given dielectric. It's apparent that the delta in performance is generally larger when comparing the same data point between each pattern.

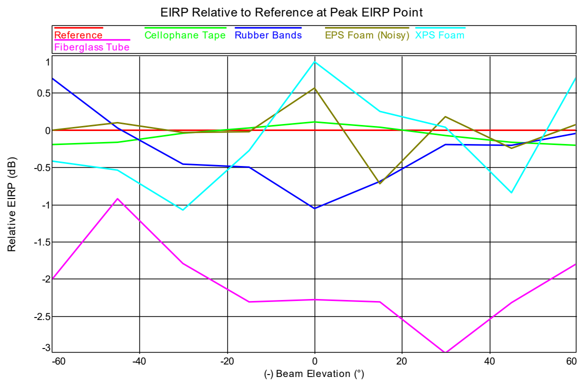

Figure 6. Change to the peak EIRP point in the reference pattern due to the presence of each dielectric material.

While the plots in Figure 3 provide an indication of the differences between the entire pattern, it is very difficult to judge the change between two patterns, especially when the differences are small. However, simply taking the difference between two patterns in dB (i.e. the ratio of linear power) does not provide a reliable method for comparison, since minor changes in the nulls as a beam shifts slightly can easily create 15-20 dB swings and dominate the delta pattern. Instead, we need a way to only look at the changes in the net power near the peak(s) of the pattern that would potentially alter the peak EIRP recorded in the spherical distribution of the beam pointing directions. Thus, we want to look at the difference, not ratio, in linear power. Still, it's preferable to represent the result in dB relative to something; in this case, the peak power in the reference pattern. To that end, the patterns were converted to linear power patterns and then the difference was calculated and converted back to dB by the following formula:

$$\Delta(\theta,\phi) = 10\log(1 + \frac{P(\theta,\phi) - P_{Ref}(\theta,\phi)}{Max(P_{Ref})}) \qquad (1)$$

Thus, only changes in power that are significant relative to the peak power in the pattern are visible on the plots in Figure 7, which show the net impact of each dielectric material on the beam pattern.

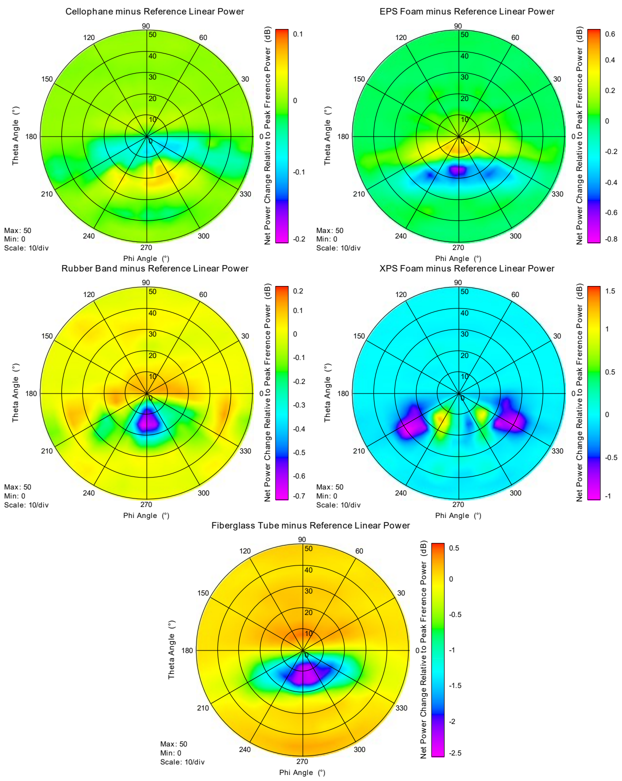

Figure 7. Relative power change due to each of the materials tested (arranged to match Figure 2).

From these we can now make some very definite observations of the impact of each mounting material on the resulting pattern. It is obvious that a few layers of cellophane tape produce a relatively minor (but certainly non-zero!) deviation, with only a few tenths of a dB of change. The impact on this particular pattern is largely just to tilt the main lobe slightly from its original position. Presumably, a higher angular resolution scan would have clearly shown this as a shift in the peak position. Conversely, the rubber bands produce a more significant shift of the main lobe in the opposite direction, with a significant dip in the center of the main lobe and noticeable ripple in the side lobes. The impact of the expanded polystyrene block is primarily just to shift the main beam further towards zero elevation. Very little impact is visible elsewhere in the pattern. On the other hand, the large extruded polystyrene block definitely shows the lensing effect with over a dB of increase near the middle of the main lobe and a corresponding decrease in the beamwidth. Finally, the fiberglass tube is producing over two dB reduction in the power of the main lobe, while generating about half a dB of ripple in the side lobes.

Conclusion

The results here should make it clear that the free-space test condition does not exist for millimeter-wave testing of 5G user equipment where antennas could be located anywhere within the housing of the device. Great care must be taken with support structure and mounting materials to ensure that the actual desired pattern of the DUT is not impacted. Any measurements performed through support structure, regardless of the density or dielectric constant, should be considered suspect and not allowed. Even directions pointing away from the support structure may be influenced by partial penetration and reflection of the main beam or side lobes. While 3GPP has added an option for reorienting the DUT and measuring partial surfaces (e.g. hemispheres) and combining the results, the guidance is limited and no real emphasis has been applied to make this a requirement. The potential to abuse the current requirement by using support structure to actually *improve* the reported device performance should not be overlooked. Even something as seemingly innocuous as cellophane tape or rubber bands used to attach a DUT to a positioning system will have an impact on measured results.

6 Acknowledgements

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7 References

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