Evaluating the effect of antenna tilt and rotation on antenna performance in an indoor environment.

Geoffrey Hilton, Evangelos Mellios, Di Kong, David Halls and Andrew Nix

Centre for Communications Research, University of Bristol
Merchant Venturer's Building, Woodland Road, Bristol, UK
geoff.hilton@bristol.ac.uk

***Abstract*— In this paper the relative performances of antenna elements are assessed by combining the measured full (3D) far-field radiation patterns of each with measured angle of arrival data for a laboratory/office space. Three element types (Cavity-backed Slot, Printed Inverted-F and Dielectric Resonator) at two positions on a small mobile terminal are considered, and the terminal is tilted and rotated in order to determine the variation in performance that is obtained for three transmitter locations. Results are presented as cumulative distribution functions of directivity relative to a benchmark Hertzian dipole for operation at 5.2GHz. A variation in signal strength of greater than 30dB was observed due to both the directivity of the elements and their polarisation alignment with the vertical transmitting source.**

I. Introduction

In the analysis of antenna performance, it is important that there is a complete knowledge of the antenna's far-field radiation pattern in terms of magnitude, phase and polarisation for all angles. This is especially important when dealing with the way the user operates a terminal. For instance, the way a mobile handset is tilted and rotated within the environment in the course of normal operation. Furthermore, in order to attempt to analyse the performance in a multipath environment, the signal angles of arrival/departure (AoA/AoD) also have to be known in terms of magnitude and phase for vertical and horizontal polarised components. While it may be considered that phase is less important than the magnitude, it is important in ascertaining whether a signal is, say, linearly or circularly polarised and whether incident signals are in phase or out of phase – in both instances these will result in considerable variations in received signal strength.

There are a variety of methods of analysing the performance of antennas in multipath environments such as Mean Effective Gain (MEG), Total Radiated Power (TRP) and Total Isotropic Sensitivity (TIS) [1]-[5]. While 3D pattern measurements are required for full analysis, Over The Air testing (OTA) by subjecting the antenna under test (AUT) to simulate multipath fading using a number of radiating sources surrounding the AUT [6], [7] or inside a reverberation chamber [8], [9] have also been used to yield comparative performance figures for antennas.

In this paper 3D antenna radiation patterns and AoA data for a typical laboratory/office environment are combined to evaluate the performance of various antennas at 5.2GHz. Both sets of data are measured and both contain magnitude, phase and polarisation information for all angles. The main aim is to show the variation in performance of a number of antenna types mounted on a terminal reminiscent of a small handheld unit while the terminal is tilted and rotated, Figure 1. Three types of antenna (Printed Inverted-F, Dielectric Resonator and Printed Cavity-backed Slot) are mounted in two positions (vertical and horizontal arrangements) for the tests - for the Slot and Dielectric Resonator (DRA) elements this was on the top and on the side as indicate in Figure 1, while for the Printed Inverted-F elements (IFA) these were contained on a single PCB. The pattern data used here is a subset of data from measurements by Pal et al [10] in which 4 elements were mounted on the terminal of dimensions 11cm high by 6cm wide by 1.4cm thick. While the original work considered a MIMO scheme, this analysis assumes SISO operation. The pattern data does not include the effects of body shadowing, as used for instance in [11], and further measurements will be undertaken to ascertain the how shadowing affects overall system performance. All results presented here are benchmarked against a theoretical (ideal) Hertzian dipole.

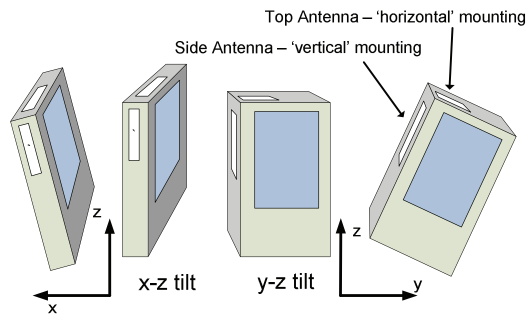

Fig. 1. Antenna element positions on terminal and elevation tilts.

For this analysis it has been assumed that the terminal would be tilted in the x-z plane between 0° and 60° in order to see the screen and between 5° and 45° in order to hold near the head, whilst undergoing full 360° degree rotation in azimuth. Angular resolution is 10° for all rotations and equal weighting has been assumed for all potential orientations. The result of this is that cumulative distribution functions (cdf) are produced showing comparative antenna performances for different environments and importantly the affect of polarisation misalignment on the antenna performance.

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II. Angle of Arrival Measurements

Figure 2 shows the plan of the laboratory and adjacent office space with 11 transmitter locations indicated. Of interest in this paper are location 6 (in laboratory and in direct line of sight), location 10 (in kitchen area with no visible line of sight) and location 11 (an anechoic chamber with one door left open for illuminating the laboratory space). The receive antenna was a dual polarised Flann DP240 horn mounted on a positioner that performed full azimuthal scans of all elevations for vertical and horizontal polarisations, while the transmitter was a vertical monopole on a 60cm diameter circular ground plane - the measurements presented here are only for vertical transmit polarisation at 5.2GHz. Both transmit and receive antennas were at a height of 1.4m above the floor and connected to an Anrisu 37397C VNA.

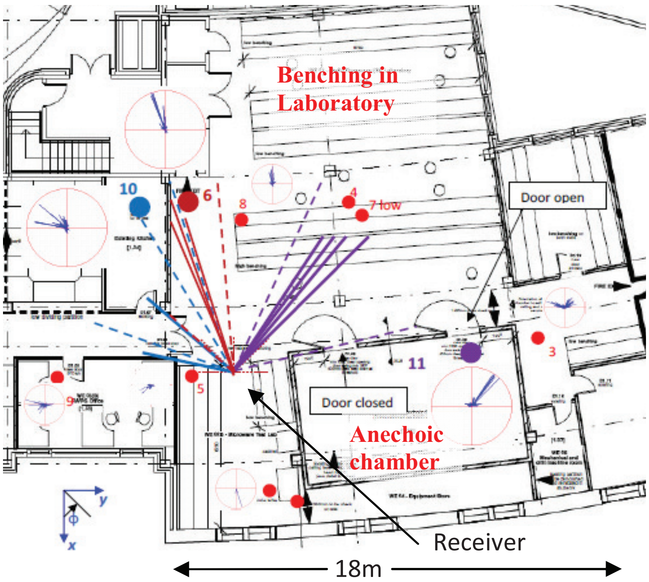
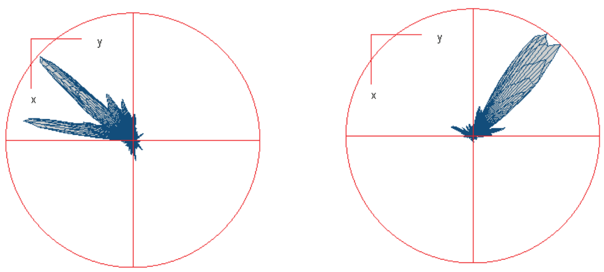


Fig 2. Locations of transmitters and receiver in the laboratory and office.



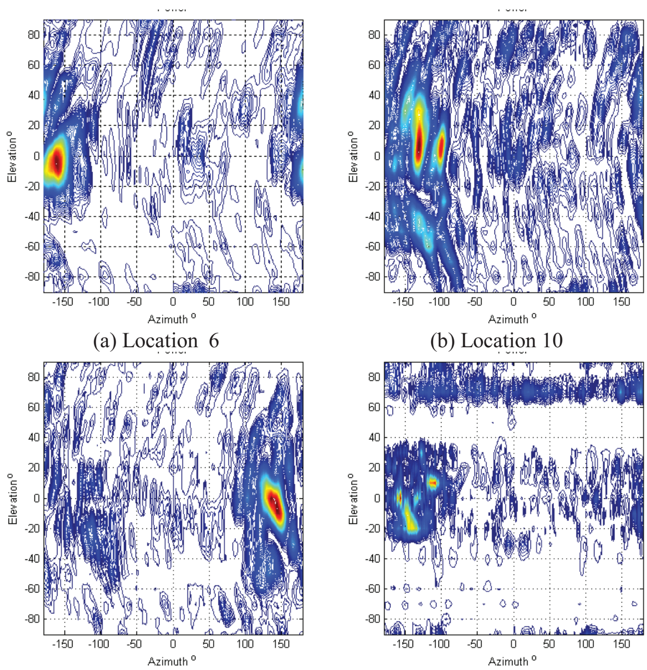
(b) Location 10 (b) Location 11

Fig 3. AoA data projected onto the x-y plane. Linear power plots.

Figure 3 shows the AoA data in polar format for locations 10 and 11 as projected onto the x-y plane, while Figure 4 shows the power spectrum of the full scan for received vertical polarisation (transmit vertical polarisation). Each set of data is normalised to the maximum received signal at each location.

In Figure 3, it can be seen that there are a few of strong peaks with several smaller peaks, while in Figure 4 the red and yellow areas are of main importance with the peaks not occuring at 0° in elevation (hence would have been missed using purely azimuth-scan data). A peak search routine was used to process this data, and after applying a threshold on the data sets, up to 100 AoA paths were used for the subsequent antenna performance tests. The most significant of these paths has been projected onto Figure 2 for locations 6, 10 and 11 and colour coded for each transmitter. The bold lines indicate directions of strong signals, whilst dotted lines are of secondary importance.

As indicated in Figure 2, there were a small number of strong signals for each location resulting from predominantly line of sight (LoS) or diffraction (locations 6 and 10) and reflections (location 11). For instance with location 10 (in blue), there is a signal directly through the wall but the main signal is diffracted from the door openings between laboratory and corridor, while for the transmitter in location 11, there is a concentration towards benching from where the signal is being scattered, while there are weak signals from diffraction around a door and reflection from a support pillar in the centre of the laboratory.



(a) Location 6 (b) Location 10

(c) Location 11 (d) Location 10 (difference)

Relative power levels for transmit vertical and receive vertical.
Red is -1dB and yellow is -3dB.

Fig 4. Angle of arrival data for the transmitter locations.

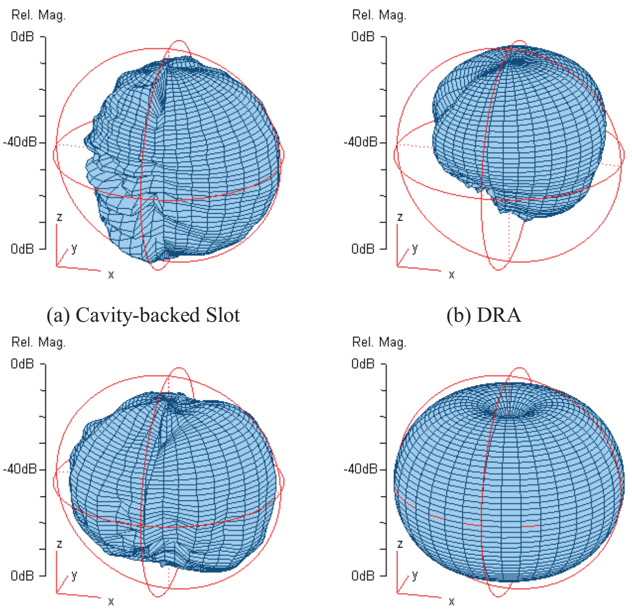
The maximum horizontally received signals were -8.3dB for location 6, -5.3dB for location 10 and -3.5dB for location 11, which indicates a higher degree of scattering from transmitter locations where the dominant signals are reflected.

This AoA data is also a function of the beamshape of the horn antenna (half power beamwidths of 30° and 33° in the principal planes and directivity of 14.5dBi) as this will govern the angular resolution between 'sources' of radiation. Furthermore, the blue ripple in the data is also due partly to the characteristics of the horn antenna away from its main beam rather than reflected signals from within the environment. It may be possible to 'remove' the antenna pattern-dependence using a technique described in [12].

Two measurements were recorded (one directly after the other) at all locations in order to show repeatability in terms of phase as well as magnitude. Whilst there was some movement of people in the laboratory and office space during measurements the affect on the measurements can only really be seen by subtracting the two measurements. This is shown in Figure 4(d) for location 10 where the red/yellow areas show movement in the kitchen and corridor outside the laboratory – the plots shown here are relative to the maximum, and the maximum level is actually some 6dB below the maximum level shown in Figure 4(b). Away from this area, there is considerable phase stability for this effectively static environment.

III. Antenna Radiation Pattern Measurements

Far-field radiation patterns for the three types of elements in two positions produced six unique sets of data (complex E-fields for both polarisations for all angles). Figure 5 shows the power patterns for one of each antenna type (together with the benchmarking Hertzian dipole), while Table 1 shows the (maximum) directivity obtained through integration of the Poynting vector for each antenna radiation pattern.



(a) Cavity-backed Slot (b) DRA

(c) IFA (d) Hertzian dipole

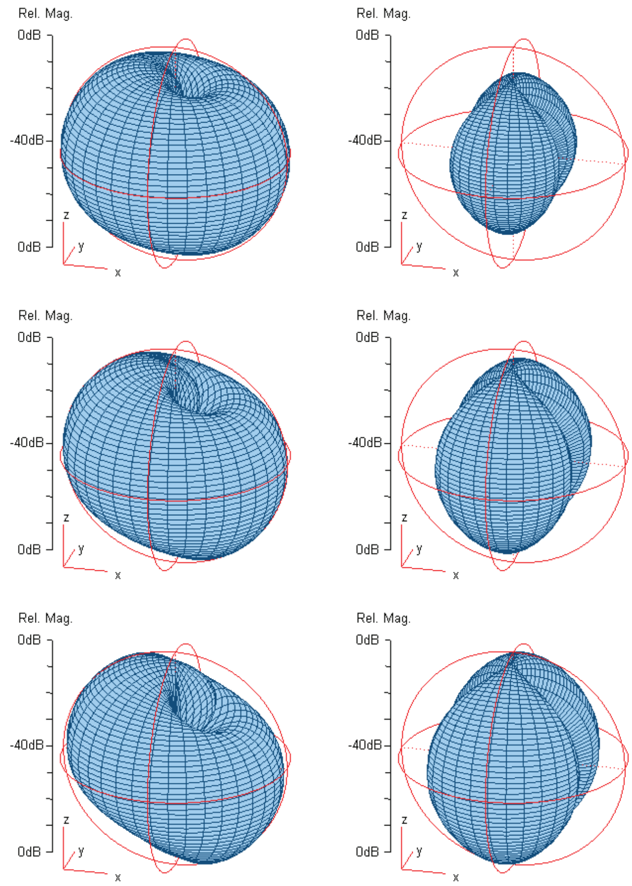
Fig. 5. Far-field radiation patterns for one of each type of antenna (Total power patterns)

TABLE I
MAXIMUM DIRECTIVITY LEVELS FOR THE ELEMENTS

Slot		DRA		IFA		Ideal dipoles	
Top	Side	Top	Side	Top	Side	Jz	Jy
6.8	6.5	7.8	7.2	8.9	5.9	1.8	1.8

Units in dBi

By using three different elements and orthogonally-mounting them, a range of pattern coverage and polarisations were obtained. Even amongst the same element type, the directivity varies due to the mounting arrangement on the terminal with the largest difference by far being with the IFA - these values are all considerably higher than the ideal (Hertzian) dipole being used as a benchmark. The Jz source is aligned along the z-axis, omnidirectional in the azimuth plane, vertically polarised (no horizontal component) and with the pattern as shown in Figure 5(d), while the Jy source is the antenna rotated to align along the y-axis and this splits the polarisation into both vertical and horizontal components.



Vertical polarisation, E_θ, Horizontal polarisation, E_φ
Upper to lower figures: 15° tilt from vertical, 30° tilt & 45° tilt

Fig 6. Effect of tilt on ideal source polarisation components.

In Figure 6, the effect that the tilting of the terminal in the x-z plane has on the polarisation components of the antenna is demonstrated using the ideal (z-directed) Hertzian dipole, shown in Figure 5(d), with the null in the 'co-polar' pattern,

E_θ , rotating to the tilt angle and an increase in the level of 'cross-polarisation', E_φ .

IV. COMBINATION OF AOA AND ANTENNA DATA

For this assessment of antenna performance, the total received power is not required. Instead a comparative measure of the various antenna types and mounting orientation on the terminal was performed. The total (complex) field response of the antenna, g_n, is therefore combined with the corresponding AoA field response, C_n, and polarisation efficiency (mismatch), Γ_n, (based upon [13]) for all angles of arrival, n. The normalisation is with respect to a Hertzian dipole, d_n, whose orientation is set up to correspond to the polarisation of the transmitting source (vertical), Equation 1. Since the antenna 'directivity', $D_{r(norm)}$, is normalised with respect to a dipole it can be expressed in dBd.

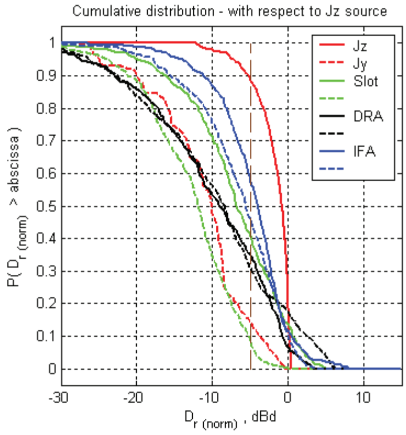
$$D_{r(norm)} = 10\log\left|\frac{\sum_{n=1}^{N} g_n C_n^* \Gamma_n}{\sum_{n=1}^{N} d_n C_n^* \Gamma_n}\right|^2 \text{ dBd} \quad (1)$$

with

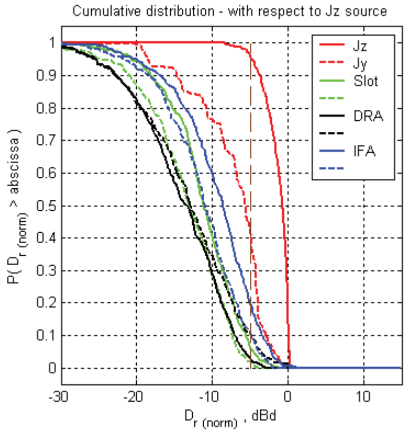
$$|g_n|^2 = D(\theta_n, \phi_n) \quad (2)$$

For each antenna with its tilt and rotation variations, a new value of $D_{r\ (norm)}$ is calculated and the results for the three scenarios are summarised in Figures 7 as cumulative distribution functions (cdf). From these plots, it is possible to judge not only the average performance of an antenna configuration but also to ascertain how its performance may vary between propagation environments. The main observations that can be drawn from these results are:

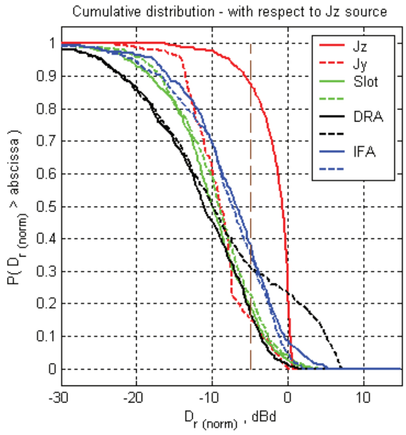
- There is clearly a wide variation of performance with various combinations of element type, position on terminal and environments with over 30dB variation in signal strength. Taking the -5dB level on the horizontal axis and the IFA responses, it can be seen that with the LoS scenario (a) the probability of exceeding this level is 60%, whilst with the diffracted scenario (b) this has fallen to around 20%. Furthermore, the difference in performance between elements is more noticeable with a high LoS content. For instance, in (c) at the 50% probability level, there is 4.5dB variation in signal level, which has rise to 7.5dB with (a).
- The Jz source generally outperforms the practical elements for the majority of the orientations as it is omni-directional in the azimuth plane and hence does not suffer from a large number of orientations where the more directive elements are pointing in the wrong direction. Where the beam is pointing in the correct direction and with the correct (vertical) polarisation, for instance the Side-mounted DRA (shown as black dashed line), then there is a considerable signal advantage as seen in (a) and (c). Hence the roll off in performance for the Jz source is only a factor of the antenna's elevation beamwidth and tilt angle – the wider the beamwidth, the steeper the roll off.



(a) Location 6 – mainly LoS



(b) Location 10 – mainly diffracted



(c) Location 11 – mainly reflected

For the Slot, DRA & IFA the solid line is the Top Antenna and the dashed line is the Side Antenna in Figure 1.

Fig 7. Cumulative distributions functions for tilted/rotated antennas with the three transmitter locations.

- Having the 'wrong' polarisation will significantly reduce performance. This can be seen in (a) where the Jy source and the side-mounted slot (dashed green line) are significantly lower than all the others (and 10-15dB below the benchmark) as the majority of the signal comes directly from a vertically-polarised source. However, once there are more multi path components from higher/lower elevations and/or scattering into the horizontal polarisation, (b) and (c), the side-mounted slot is not significantly worse than any other elements.

- Based upon these three transmitter locations, it would appear that overall the IFAs give a generally better performance over the wider range of tilts and rotations of the terminal (plots are to the right in Figure 7), while the DRAs give the poorer performance (plots generally on the left). It can be seen from the radiated power pattern for the IFA, Figure 5(c), that of all elements tested, this most resembles the 'ideal' case, Figure 5(d), along the x-y plane.

V. Conclusions

This paper has taken full measured far-field radiation pattern data for a number of antenna elements and combined this with measured AoA data in azimuth and elevation in order to evaluate the antenna elements when tilted and rotated.

AoA data for a number of transmitter locations within an indoor environment are considered, and these show that with no direct (visible) LoS, the signals reaching the receiver are dominated by a few diffracted paths. Levels of signal (originally vertically polarised) scattered into the horizontal polarisation increased (relative) magnitude from a mainly LoS scenario (-8.3dB) to reflected and no LoS (-3.5dB). Phase stability is also good in this predominantly 'static' environment. Radiation patterns (in terms of magnitude, phase and polarisation for all angles) have been presented for three antenna types (Slot, DRA and IFA) and two orthogonal mounting positions on the terminal, and has shown there is 'significant' variation in polarisation and pattern coverage that results in directivities ranging from 5.9 to 8.8dBi.

While the antennas were rotated 360° in azimuth (x-y plane), the tilting in the x-z and y-z planes were more restricted corresponding to the most usual operation of a handset. Equal weighting was applied to each set of angles, but differential weighting scheme could be used to bias the outcomes to the more common terminal orientations. Variations in received signal strength of greater than 30dB with respect to a Hertzian dipole benchmark were observed due to polarisation misalignment and pattern directivity.

At best the directive antennas only achieved greater than 0dBd levels for 20% of the orientations considered – this was mainly as a result of the rotation in azimuth pointing the directive beam in the wrong direction. In the case of the side-mounted slot, the polarisation was orthogonal to the transmitter polarisation and hence was 10-15dB below the benchmark.

For the transmitter locations, antenna type and terminal mountings considered, the IFA performance was the best on average, though was still lower than the benchmark. Further measurements using a horizontally polarised source will be undertaken to show how the choice of transmit polarisation affects system performance.

It is clear that in order to fully understand the operation of antennas in multipath environment, full pattern and AoA data is required that contains magnitude and phase for both polarisations and for all angles. Thus in the future, polarisation and pattern agile antenna systems can be evaluated in order to determine how best to mount and operate elements in order to compensate for user operation and adapt the system for different multipath environments.

Acknowledgment

The authors wish to thank the Centre for Communication Research, University of Bristol, for the use of the anechoic chamber and extensive laboratory facilities.

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