Multiband Low-Profile Antenna for Remote Antenna Unit Pico Cell Applications

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Multiband Low-Profile Antenna for Remote Antenna Unit Pico Cell Applications

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Abstract- **The design of a compact, low-profile antenna constructed from five wire-patch elements is investigated. For a fibre-radio system a critical design parameter is the isolation between two WLAN elements. It is shown the structure can be optimised to provide in excess of 25 dB isolation. Good agreement between experiment and modelling is demonstrated including these mutual coupling effects.**

Index Terms – **Stacked Microstrip Antennas, Multiple Band Antennas, Mobile Antennas.**

I. INTRODUCTION

For increased coverage of cellular and wireless networks within heavily populated areas, picocells operating on a plurality of systems are required. This places additional constraints on the system designer. One solution to routing a number of wireless systems through a building is to use radio-over-fibre systems [1, 2]. Here a central control station acts as an interface between several pico-cells and the external wireless infrastructure by translating and routing the wireless signals over a fibre-optic network to Remote Antenna Units (RAU) – so called Distributed Antenna Systems (DAS). These RAUs require an antenna that can function in a number of different bands. Usually this is accomplished by employing a broad-band element [3, 4], or a multi-resonant element [5]. For a DAU isolation between up-link and down-link paths is required. For systems using FDD this can be provided using diplexers but where FDD is not available, such as in WLAN application, two separate elements must be used and attention must be paid to the coupling between the elements [6].

It may be preferable to provide an individual antenna feed for the different wireless bands. Not only does this increase isolation giving greater flexibility of the overall system but also allows control of the individual antenna pattern in each band. To meet this requirement a multi-element antenna is needed. Here we describe the design of such an antenna suitable for a ceiling mounted application providing services for the wireless communication frequency bands used in Europe as listed in Table 1. The design is based upon the integration of a number of individual elements with a key design challenge being to limit any antenna performance degradation caused by mutual coupling effects.

For a ceiling mount unit the antenna height should be minimised, while conversely the footprint could be unrestricted. Use of monopole structures could lead to reasonably small heights (~30mm) for the higher bands [7] but would require much longer elements for the lower frequency. For instance a Discone covering all bands would need to be typically 50 mm high. The height of a monopole element can be reduced using PIFA type designs but these invariably lead to a non-toroidal pattern [5], and can be bandwidth limited. Initial investigations placing a number of mono-polar elements in close proximity also showed that interactions between elements could cause significant nulls in the radiation patterns. An alternative 'planar' antenna approach was sought with a design goal of a 20 mm height that would also alleviate the mutual interaction issues.

The obvious antenna element for the ceiling mount application is the patch antenna. For example this approach has been used recently for a WLAN only antenna in [8]. Fundamental TM11 mode patch antennas exhibit a beam focused normal to the surface and therefore are unsuitable for a ceiling mount pico-cell antenna. However a circular patch can be excited in the TM01 mode to give a monopole-like radiation pattern. This requires the diameter of the patch to be approximately twice that at the fundamental mode. For example an air-spaced TM01 circular patch antenna operating in the GSM 900 band would have a diameter of 400mm. While this may be possible for a ceiling mount unit it is quite bulky and an improvement was sought. A number of authors have investigated the effects of shorting pins on patch antennas. For instance these have been used to improve the bandwidth of a TM11 patch [9]. However it has been shown that if the patch is fed in the centre and the height is increased two pins can alter the current flow and cause a TM01 resonance, instead of a TM11 [10, 11]. The bandwidth can be increased further by using ‘plates’ instead of wires for the shorting post [12]. Further reduction in the patch height can be obtained by using 4 pins placed symmetrically to suppress the TM11 mode [13].

II. ANTENNA DESIGN

It was assumed that diplexers could be used to combine the up-link and down-link signals for the mobile phone signals allowing a common antenna element to be used for each of these bands. However two separate WLAN antennas were still required. The multi-antenna unit was therefore to provide 5 individual elements. We propose an antenna solution meeting this requirement based upon a stacked patch antenna configuration as shown in Fig. 1. A ‘sensible’ footprint of 300 x 300 mm square was assumed to allow ease of integration behind a typical ceiling tile of a suspended ceiling as found in the modern office. Using the pin-loading techniques described in [13] a patch antenna can be designed that is half the diameter of the unloaded TM01 patch. This gives a diameter of approximately 200mm for operation in the GSM band which lies well within our design goal of 300 mm footprint. This diameter is for an air-spaced plate. The size could be reduced further by using a dielectric but this would increase cost and may introduce dielectric losses that can be significant for patch antennas depending upon the quality of the substrate used and the frequency of operation. For a single band operation at 900 MHz it was found that the patch height could be reduced to 10 mm and provide sufficient bandwidth.

Additional elements needed for the L-band systems (DCS, 3G and two WLAN) were provided by stacking air-spaced pin-patch elements [11] on top of the GSM 900 pin-patch as shown in Fig.1. The GSM plate (Diameter D1) is used as the ground plane for the L-Band elements. The smaller L-Band disk elements, denoted by their diameters D2 - D5, therefore formed a two-layer structure above the GSM plate. The L-Band elements were excited by embedding a coaxial feed within the shorting posts for the GSM antenna. In Fig.1 a cross-section view through the centre shows the coaxial lines for D4 and D5 in the lower half, H1, with the pin-plate structure in the upper half, H2. Note the GSM feed in the centre is a capacitive plate structure (the dashed outline in the top view). The feed positions for the four L-Band elements were therefore fixed by the position of the GSM shorting posts. For size reduction pin-loaded patches were used. A plate height of 10mm was again used. As the patches are electrically thicker only two pins are needed to suppress the TM11 mode. Increasing the height also reduces the required patch diameter, allowing the four L-Band elements to be easily arranged on the top of the GSM plate.

Details of the final design are given in Fig. 1. The GSM900 feed used a 1.3 mm diameter pin at the centre while the four shorting ‘pins’ were actually 12mm square blocks with the L-Band coaxial feeds running though their centres. The L-Band elements used a 5 mm diameter feed pin at the centre with two 1 mm diameter shorting pins placed either side. These shorting pins were surrounded by 5 mm diameter PTFE bushes for additional mechanical support. The ground planes and patches were formed using a metallic plate of 1 mm thicknesses.

It was found that a common design could be used for all the L–Band patches with the resonant frequency of each element achieved by tuning only the respective top plate diameter. Although our construction used individual metallic plates, a production design may use construction similar to [8] whereby the L-Band top patches are etched onto a thin substrate which is possible if a common patch height is used. This is illustrated in Fig. 2. A single L-band 2-pin loaded patch antenna was modelled by CST MWS. As the plate diameter is increased the bandwidth and centre frequency decrease – determined from the 10 dB input return loss points. Not shown on Fig. 2 was the change of impedance at resonance. At larger radii the impedance is closer to 50 Ω but with the narrower bandwidth – i.e. a sharper resonance. Conversely reducing the radius further does not lead to a wider bandwidth as eventually the minimum return loss is less than 10 dB. From Fig. 2 it can be seen that for a 10 mm height patch the bandwidth requirements of DCS (9.5%), UMTS (12.2%) and WLAN (3.4%) could be met. Including the plate thicknesses, the overall height of the unit is 23mm – close to the target of 20mm. Using common height and pin diameters for all the L-Band antennas allows use of common parts to ease manufacture.

The final antenna combines five individual elements providing one GSM 900, one DCS 1800, one 3G (UMTS) and two WLAN antennas. The GSM, DCS and 3G antennas each cover both the uplink and downlink bands. These can be separated by use of commercially available diplexers such as the Murata DFYH series of dielectric diplexers. These have some insertion loss (<2 dB) but fit easily within the footprint. The antenna design is very efficient (no dielectric losses) so allowance for diplexer losses can be made by the system designer. In this way individual antenna feeds can be provided for each band for both uplink and down-link. The overall size of 23 mm height and 210 mm diameter for our design antenna compares favourably against the design of [13] (height 32 mm diameter 120) but this is only a single feed point GSM /DCS antenna.

III. MUTUAL COUPLING EFFECTS BETWEEN ELEMENTS

A critical design parameter is that of mutual coupling between the antennas. Placing the L-Band elements on top of the GSM patch and using feedthroughs in the GSM shorting posts provides good isolation between this band and the L-Band elements. Initially the L-Band elements were placed close to the edge of the GSM disc to tune the GSM patch antenna – the shorting posts should be placed as close to the edge as possible to provide a 50 Ω impedance of the GSM patch. In practice this required the L-Band antennas to be at an offset of 80 mm for the DCS (S2) and 3G (S3) elements and 85 mm for the WLAN elements (S4 & S5, due to physical size restraints. Although the L-Band elements are at the maximum separation so mutual coupling might be assumed minimal, it was found that the L-Band elements suffered a strong interaction. This resulted in significant nulls in the azimuth radiation patterns particularly in the DCS and 3G bands as can be seen in Fig. 3.

As the antenna structures had been designed and tuned using the commercial CAD package CST Microwave Studio (CST), predictions were made with CST that showed close agreement to the measured radiation pattern for the combined structure (Fig. 3). As such we were able to use the model to identify the source of these nulls. It was found that removing the 3G antenna provided nearly 100% improvement in the DCS antenna pattern. The GSM antenna has a second order mode around 1800MHz but this has little influence on the DCS antenna. Further investigation showed that a standing wave was being set up between the 3G and DCS antennas due to their spacing (160 mm) being approximately an integral number of λ/2. Moving the antennas closer together (S2 = S3 = 60 mm), such that the spacing is an odd integral number of λ/4 at 1800 MHz, gave a significant improvement in the polar diagram as shown in Fig. 3. Similarly the WLAN antennas were also moved to λ/2 spacing.

Further to the effects of mutual coupling on the radiation pattern a key issue in the design of this multi-element antenna is the isolation between the WLAN antennas. While this is determined for the GSM, DCS and 3G antennas by diplexers the WLAN antennas rely upon the spatial separation and polar diagram. For the element chosen the radiation pattern is essentially omni-directional in the azimuth plane to suit the pico-cell application meaning the isolation must be determined by other means. The isolation between the two WLAN antennas was again investigated using CST. In Fig. 4a the isolation is plotted as a function of separation at the band centre frequency (2.45 GHz). It is seen that a minimum of -26 dB occurs when S4 and S5 are 72 mm apart. However it was noted that further improvements could be made by making the offset of each antenna different and also by varying the position of the DCS and 3G elements. CST indicated an isolation in excess of 30 dB across the WLAN band could be found by optimising the position of all 4 L-Band antennas. However, the DCS and 3G antennas needed to remain in position to maintain their radiation patterns. A final solution was found by fixing one WLAN antenna and varying the other as shown by the dashed curve of Fig 4a. For offsets of S4 = 68mm and S5 = 76mm an isolation of -28 dB could be obtained. These values were applied to the design in Fig. 1. The final isolation between the WLAN antennas across the band is plotted in Fig. 4b. A nominal 'specification' mask is included in Fig. 4b, whereby the isolation should be greater than 20dB in the WLAN band [6]. The measured result is slightly poorer than the prediction but is still in excess of 25 dB across the band.

Changing the L-Band antenna positions meant that the GSM shorting post positions had also changed as these provide the L-Band antenna feeds. This detunes the GSM antenna significantly. However, this was readily re-matched as illustrated in Fig. 5. The antenna impedance is lowered to around 30 Ω in series with an inductive reactance (shorting post inductances). This can be matched using a capacitive step-up transformer as shown in Fig. 5(a). In practice the capacitors are realised using a distributed structure as detailed in Fig. 5(b) employing coupling plates at the top and bottom of the GSM feed pin (expanded view of feed from Fig. 1). These were constructed by etching small square patches on double-sided 1.6 mm FR4 PCB, with a ground plane on the underside. This is clamped onto the metallic plates. In this way the spacing between the plates is determined by the PCB thickness and avoids any problems caused by any air-gap between the PCB and the metallic plate. Any additional inductance caused by the feed pin between the capacitive plates can be tuned out empirically by adjusted the capacitive patch dimensions.

IV. MEASURED PERFORMANCE

The return losses for the 5 feed points of the antenna are shown in Fig. 6. Again comparison is made against the model with reasonable agreement. For assessment a 'requirement' mask for an in-band -10 dB return loss has been added, Using a capacitive matching circuit the response of the GSM antenna exceeds this requirement. The model used a rectangular capacitive structure that approximated the experimental antenna that had been finely adjusted, hence the experimental curve shows a better match. Not plotted in Fig. 6, the GSM feed, also exhibits a second resonance around 2 GHz but this does not influence the DCS or 3G antenna performance. The model predicted that the DCS and 3G antennas should meet the requirement, but while the experimental results exhibit similar bandwidths their centre frequencies are approximately 3% lower. This difference is likely due to mechanical tolerances, particularly the feed structures, so a production design would need to make an allowance for this. The 3G antenna has a decreased match but increased bandwidth compared to the DCS antenna, as expected from the parametric study in section 2.0. The WLAN antennas are plotted together (black curves for D4, grey for D5). The model gives reasonable agreement again, although the resonant frequencies are a little lower than predicted. Whilst the bandwidth is relatively wider than for the DCS and 3G antennas, as expected from Fig.2, the match has also improved. From the plots there is evidence of a secondary resonance that may account for this improved match and further evidence for this is seen from the radiation patterns, discussed below.

The measured radiation patterns of each antenna are given in Fig. 7. It was found that the radiation was essentially linearly polarised so the patterns at the band centre and the band edges were plotted, to illustrate the antenna variation with frequency, for the dominant polarisation but only at the band centre for the cross-polarisation. In general all antennas exhibit the desired vertically polarised 'doughnut ring' pattern. The azimuth patterns (actually at 15^o Elevation) are approximately omni-directional with only a few dB ripple that increases with the antenna operating frequency.

The elevation plane cuts show a nominally vertically polarised characteristic with a beam peak around 40^o Elevation. Despite a small ground plane most of the energy is in one half of the sphere, as required by a ceiling mount antenna. As expected there is a deep null on boresight although this is compensated to some extent by the cross-polar radiation. However for a picocell application the range directly under the antenna is at a minimum and therefore this null should be tolerated. The radiation pattern for the 3G antenna is deteriorating at the band edges but this may be simply due to operation away from resonance. However the azimuth gain remains at a similar level allowing use in a pico-cell application.

The WLAN antenna patterns exhibit significant asymmetry between the two elevation planes. In one plane there is the emergence of a double humped lobe whilst in the other plane there is a deep wide null (with high cross-polarisation). This indicates the onset of a higher order mode and may explain the relatively high level of ripple in the azimuth plane and the additional resonances in the return loss plots. This design kept the height and pin spacing of the L-Band elements equal for ease of manufacture but in practice these could also be varied to improve the WLAN antenna characteristic.

V. DISCUSSION

To assess the overall performance of this antenna some simple comparisons were made against three other antennas. A broadband discone of 50mm height for an up link antenna and a group of 4 individual quarter wave straight wire monopoles for the downlink antennas on a 300 mm square ground plane provided a reference. For a more application orientated assessment, comparison was also made against the planar design of [45]. The performance of this new design using the original L-Band antenna spacing has also been included in the comparison.

The polar diagrams of each type of antenna were measured and summary parameters compared. A first metric listed in Table II was the average azimuth antenna gain in the band centre. Here the monopole has the highest gain, with the discone and the proposed stacked patch design being approximately 2 dB lower. These three antennas are clearly linearly polarised. The planar element has the advantage of similar gains for both polarisations but the nominal level is significantly lower than the vertical gain for the other two elements which demonstrates the planar element is the least suited for a ceiling mount application.

The second metric was to consider the ripple on the azimuth polar diagram by expressing this by the standard deviation, σ, of the azimuth curve; the ideal would have a σ of zero. This is summarised in Table III. The discone has the lowest σ around 1 dB (considering the vertical polarisation). The monopoles have a slightly higher σ around 2 dB due to interaction between the different elements. For the stacked patch design σ for the GSM element is very good. However it is seen that σ is very high (5 dB) for the L-Band elements using the original spacings, but reduces to 2 dB with the optimised spacings; similar to the performance of using an array of monopoles. (Note the σ for the cross-polarisation level is naturally higher). The planar element exhibits high gain variation making it less suitable for the present application.

VI. CONCLUSIONS

A multi-feed antenna constructed by integrating five ‘monopolar’ type wire-patch antennas has been designed providing operation in four primary wireless communications bands. Mutual coupling was shown to have significant detrimental effects but with careful design these can be minimised to an acceptable level. The design studied here aimed to keep commonality between components to ease manufacture, particularly for the L-Band antennas. The resulting structure exhibited close to ideal performance with each antenna providing a toroidal shaped beam. It was noted the bandwidth for the 3G antenna was marginal and there was evidence of a higher order mode present with the WLAN antenna. Although these factors are minor it would be possible to tune them out by changing the individual antenna element design but possibly at the loss of commonality of construction. The structure was tuned to provide high isolation (>20 dB) between the WLAN antenna ports as required by a Remote Antenna Unit (RAU) application. Overall the final design has a total height of only 23 mm and each antenna pattern is close to a straight wire monopole making this design ideal for a ceiling mount RAU application.

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TABLE I
EUROPEAN WIRELESS BANDS

System	Frequency (MHz)
GSM	890-960
DCS-1800	1710 – 1880
3G (UMTS)	1920-2170
WLAN (ISM band)	2400-2483.5

TABLE II
COMPARISON OF AZIMUTH AVERAGE GAIN (DBI) FOR DIFFERENT TYPES OF ANTENNA

Antenna Type	GSM		DCS		3G		WLAN	
Polarisation	Vert	Hor	Vert	Hor	Vert	Hor	Vert	Hor
Stacked patch; 80/85mm spacing	-3.6	-16.7	-2.7	-14.4	-2.7	-11.1	-2.7	-14.3
Stacked patch; 60/76mm spacing	-3.4	-15.6	-3.9	-13.1	-2.1	-15.4	-4.8	-14.2
Monopole	0.2	-7.6	-0.4	-11.3	-0.3	-11.7	-2.3	-14.3
Discone	-2.3	-8.2	-1.8	-13.6	-1.2	-13.0	-3.1	-17.9
Planar multiband element [5]	-11.6	-9.9	-13.3	-10.6	-11.7	-8.2	-14.8	-11.1

TABLE III
COMPARISON OF AZIMUTH GAIN VARIATION (DBI) FOR DIFFERENT TYPES OF ANTENNA (STANDARD DEVIATION OF ANTENNA GAIN IN AZIMUTH PLANE)

Antenna Type	GSM		DCS		3G		WLAN	
Polarisation	Vert	Hor	Vert	Hor	Vert	Hor	Vert	Hor
Stacked patch; 80/85mm spacing	0.9	6.4	4.2	6.4	5.8	5.5	2.4	5.3
Stacked patch; 60/76mm spacing	0.8	6.1	1.7	5.7	2.0	4.6	2.3	5.8
Monopole	1.2	4.1	2.0	4.1	2.5	6.5	2.1	5.4
Discone	1.4	5.5	1.2	4.2	0.8	4.8	1.2	6.9
Planar multiband element [5]	5.4	6.5	5.0	5.7	5.9	6.3	7.3	6.6

FIGURES

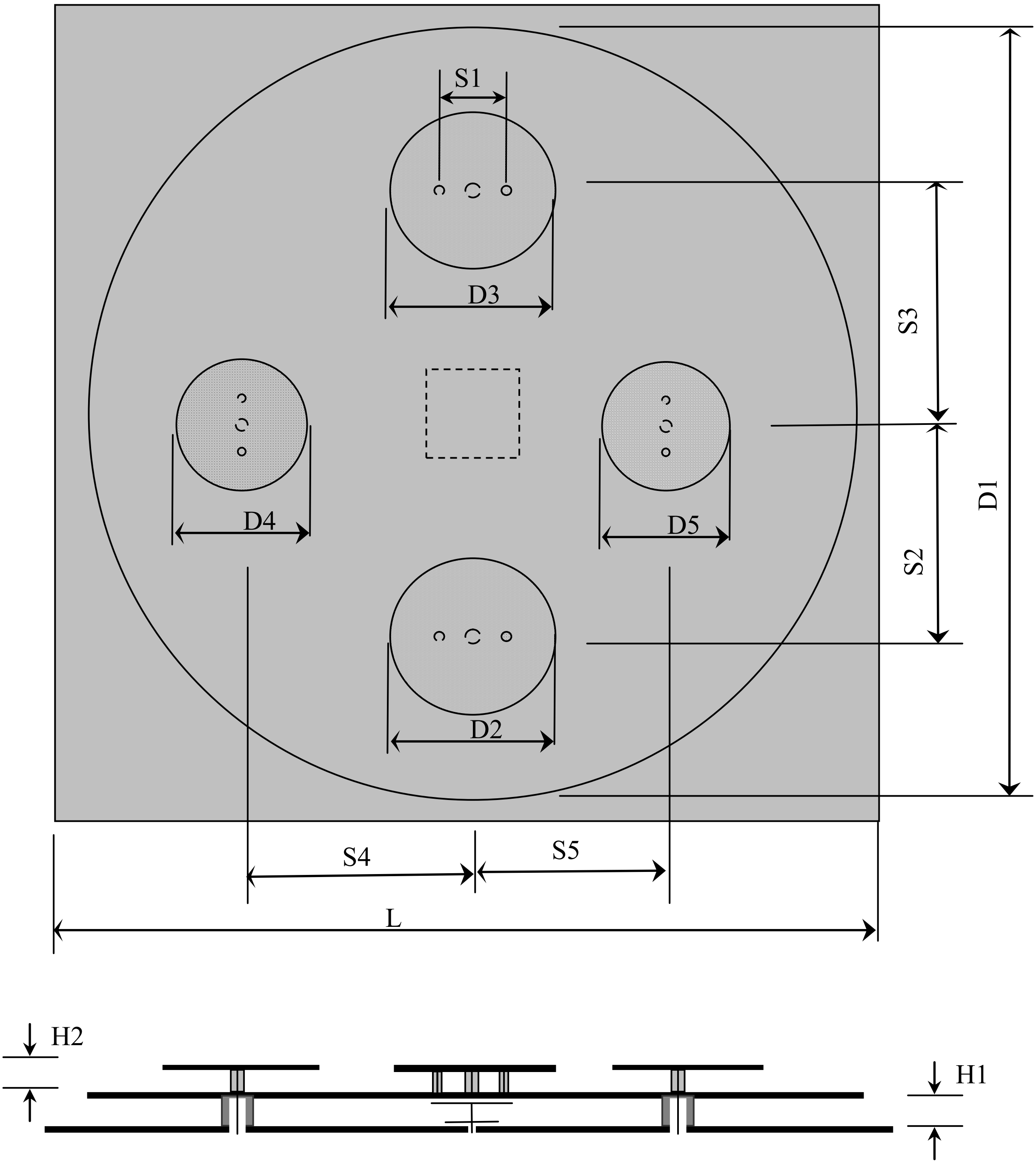


Fig. 1: Design details

L = 300 mm, H1 = 10 mm, H2 = 10mm, S1 = 20 mm, S2 =60 mm, S3 = 60 mm, S4 =68mm, S5 = 76 mm, D1 (GSM) =210mm, D2 (DCS) = 40 mm, D3 (3G) = 34.6 mm, D4 = D5 = 29.5 mm (WLAN)

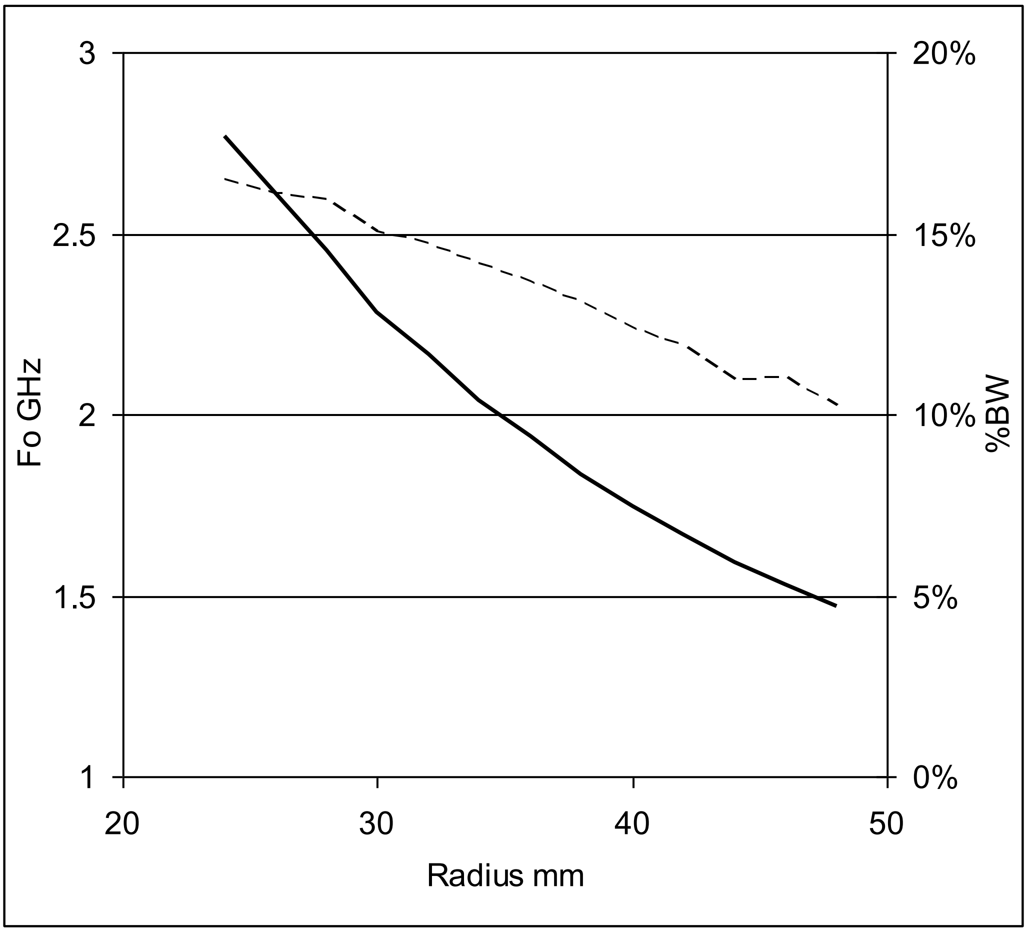


Fig.2: Measured frequency dependence on pin-patch antenna radius in L-Band

Centre Frequency
% Bandwidth (-10 dB Return Loss)

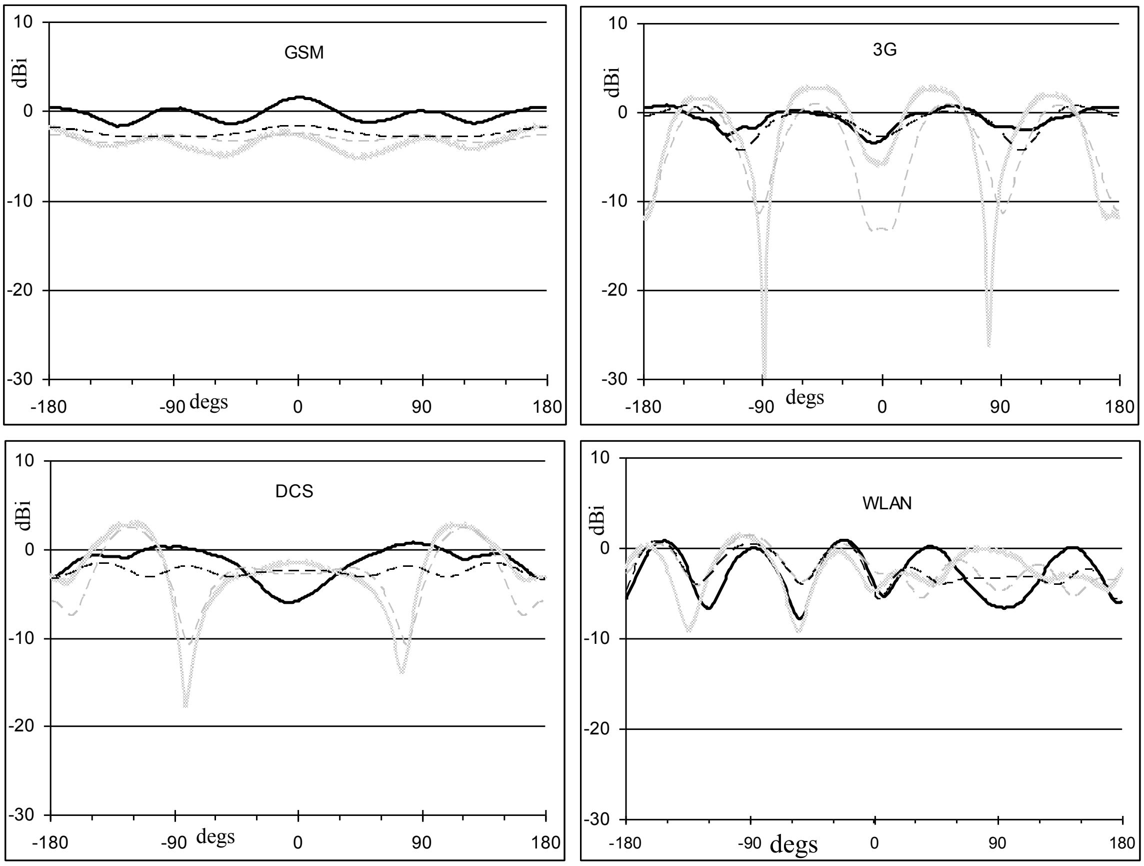
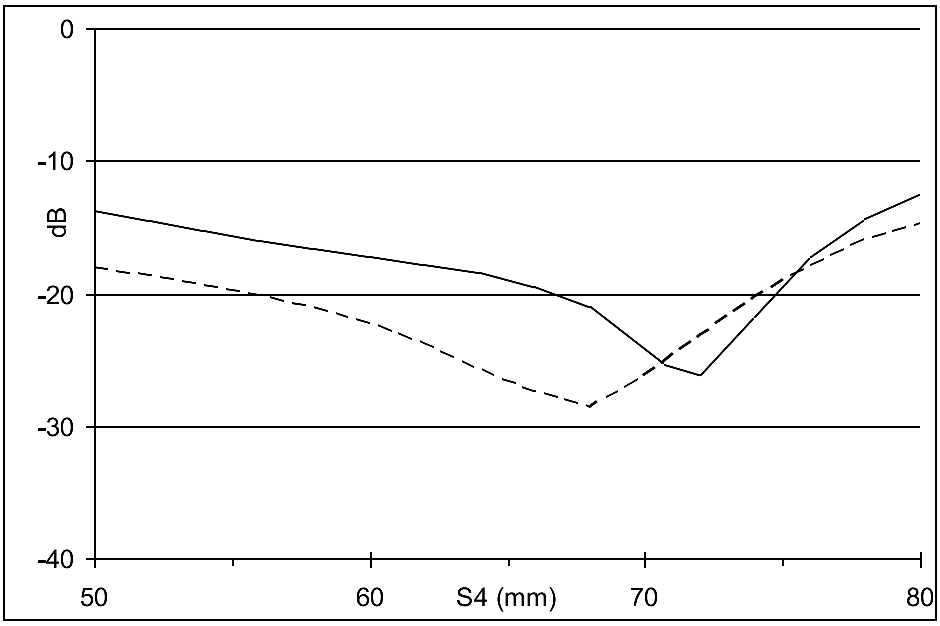
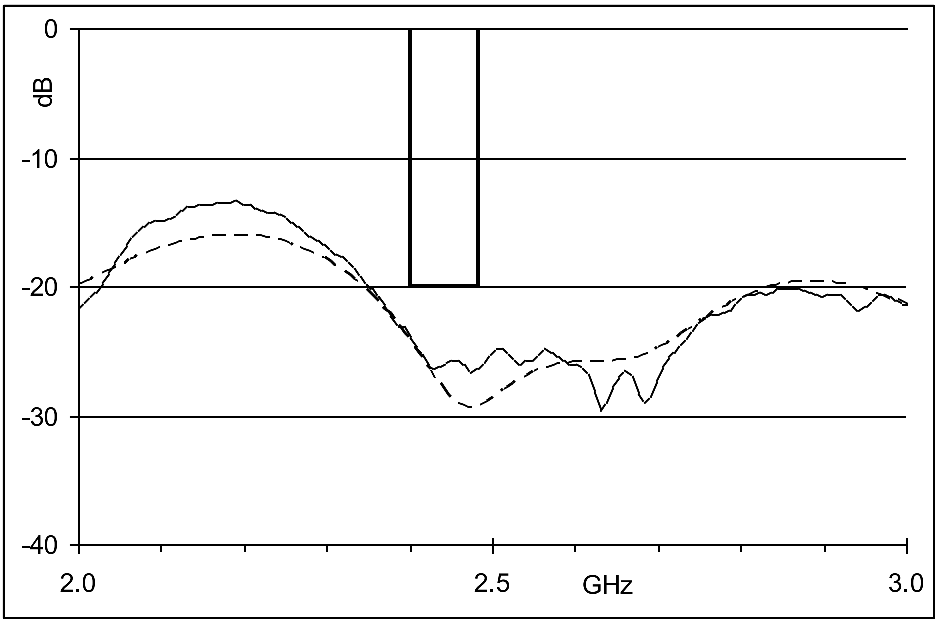


Fig. 3: Effect of Antennas spacing upon the Azimuth Radiation Pattern

Compare model to measurement
S2=S3=80, S4=S5=85mm
S2=S3=60, S4=S5=76mm
solid – measurement dash – CST Predictions

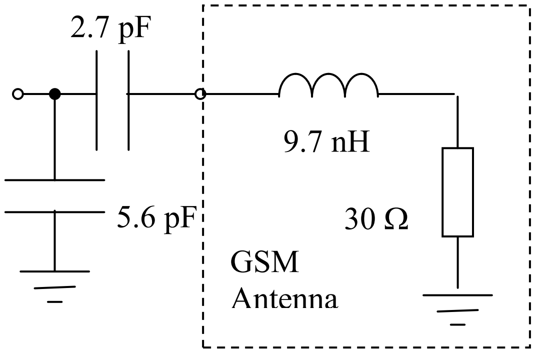


(a) Variation of Isolation at 2.45 GHz with Antenna spacing
——— Vary both S4 & S5 - - - - - - Vary S4 (S5 = 76mm)

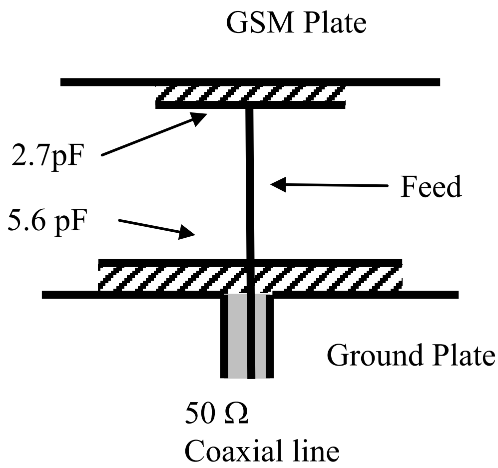


(b) Isolation for offsets of 68mm / 76mm
——— Measurement - - - - - - CST Predictions ━━━ Requirement

Fig. 4: Isolation between the two WLAN antennas



(a) Equivalent circuit of GSM Antenna and matching circuit



(b) Cross Section through GSM Antenna Feed showing realisation of matching circuit

Fig. 5: Details of GSM Matching to compensate for L-Band Feed position detuning

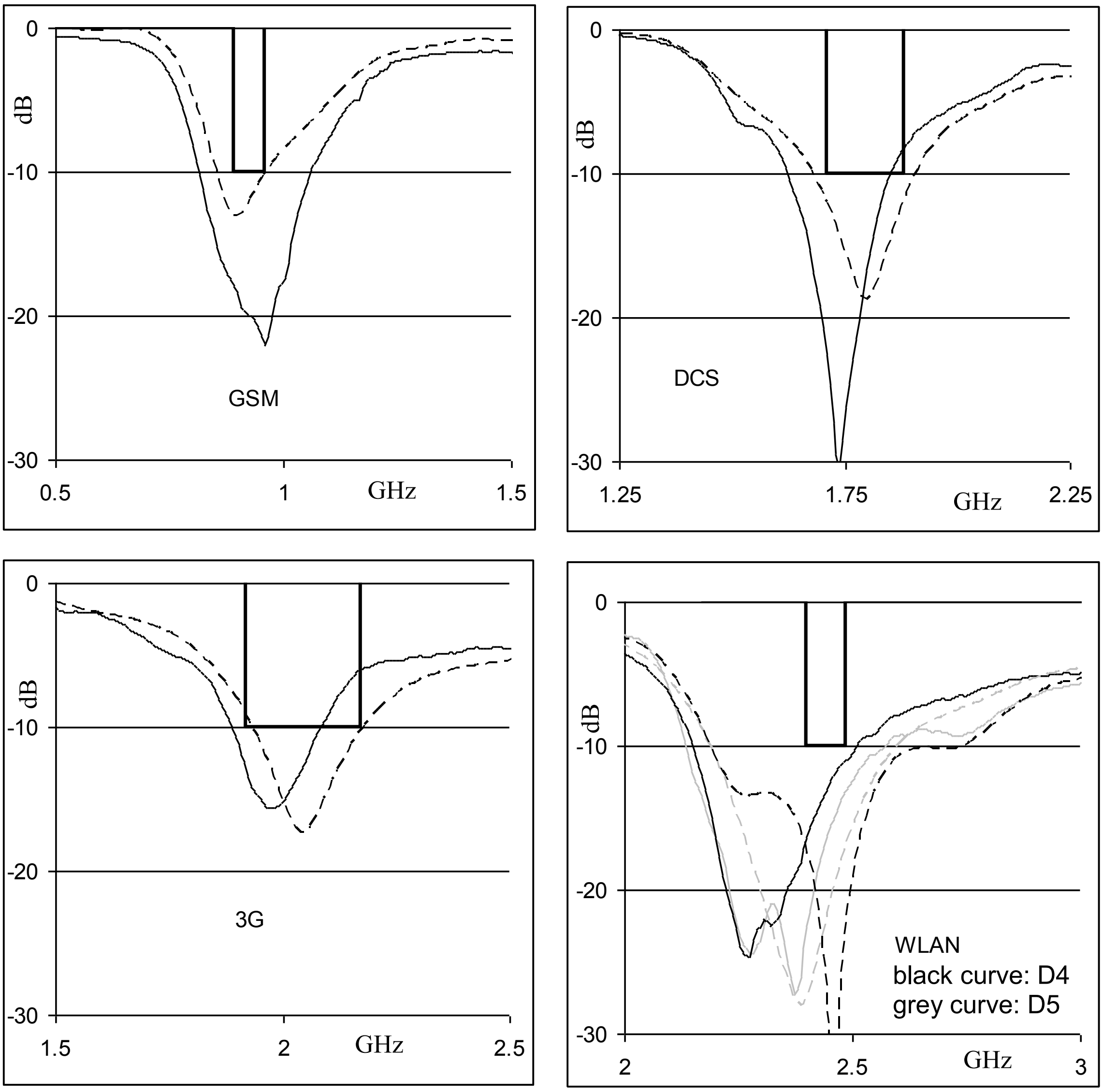
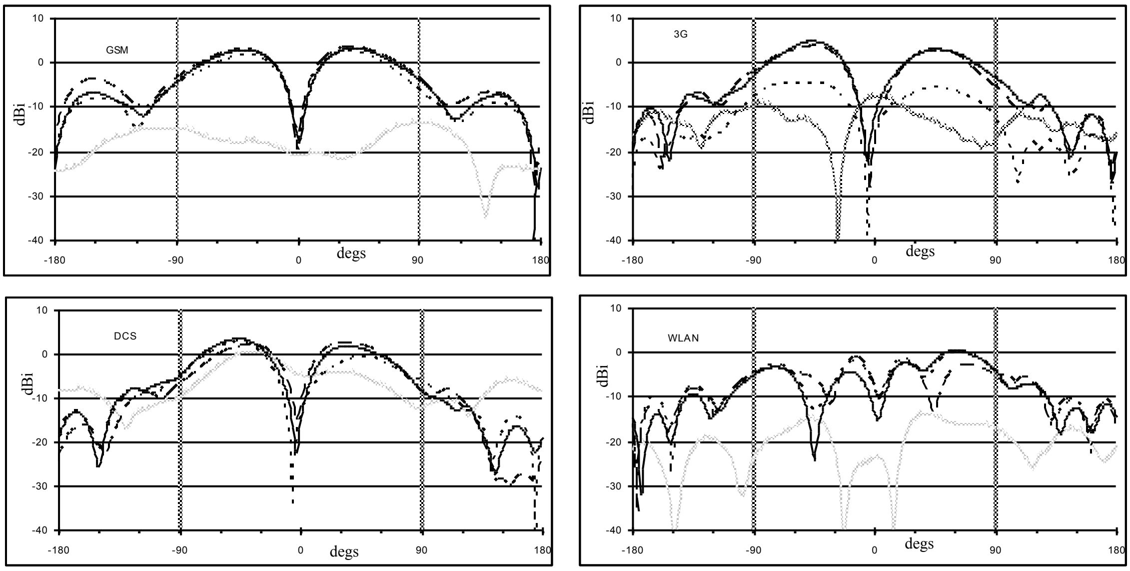
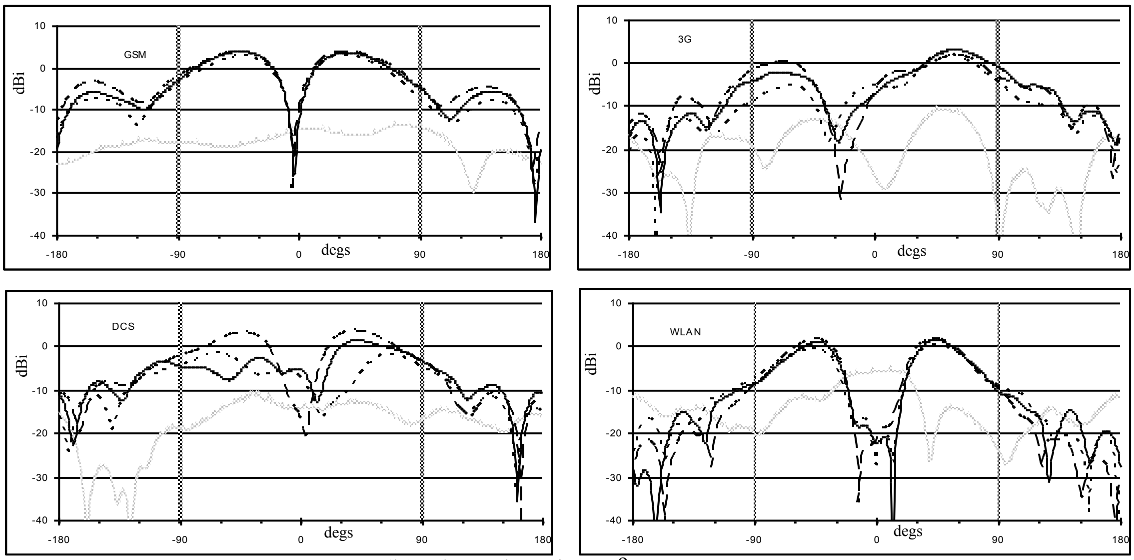


Fig. 6: Return loss of Antennas

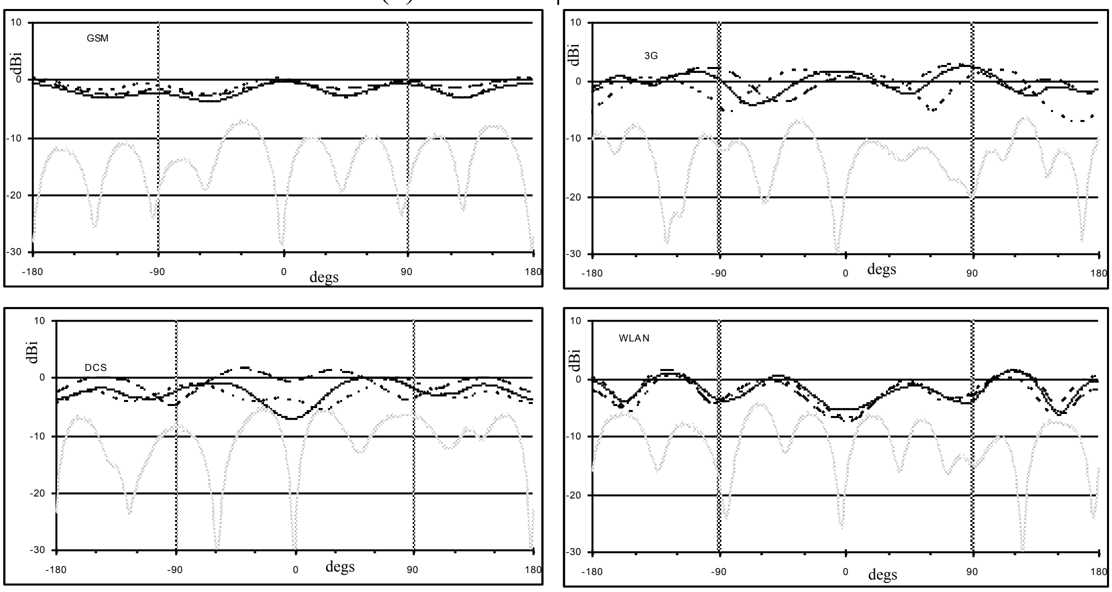
Measurement ------ CST Predictions ▬▬ Requirement



(a) elevation $\phi=0^o$



(b) elevation $\phi=90^o$



(c) Azimuth

Fig. 7 Measured Radiation patterns

Fo   Fo-Bw/2   Fo+Bw/2   Fo Cross-Polar