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Final Report on BuNGee Antenna

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Executive Summary

This deliverable report deals with the conception and development of the Hub Base Station (HBS) antenna system required for the BuNGee project. The work has been carried out by Cobham Antenna Systems (Microwave Antennas) (CASMA) along with the other partners involved in the overall plan to develop “Beyond Next Generation Mobile Networks”.

Within this report the required characteristics of this multibeam antenna are stated; the procedure used for modelling the individual elements; prototyping the individual elements followed by sub-structures of the whole antenna, and finally building and testing the complete prototype. In conjunction with this work there has been research and development into a practical solution for a 6 way beam former (the Butler matrix) for which test results are shown when connected to the antenna. As each assembly will provide a 90˚ coverage it is envisaged to use four assemblies per HBS to cover a 360˚ area.

The report also refers to the Hub Subscriber Station antenna and the Access Base Station antenna required to fulfil the requirements of the project as a whole.

Contributors

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List of Acronyms

Abbreviation / acronym	Description
ABS	Access Base Station
CASMA	Cobham Antenna Systems (Microwave Antennas)
ETSI	European Telecommunications Standards Institute
HBS	Hub Base Station
HSS	Hub Subscriber Station
VSWR	Voltage Standing Wave Ratio

1. Introduction

This deliverable describes the BuNGee HBS antenna design and beam forming circuitry developed in T2.2, including full directional and polarisation responses for all available beams. The antenna will be used in T4.3 and T4.4, and the results will be used in T4.1. This document can be read in conjunction with Interim Report IR.2.2. "HBS Antenna Characteristics". It has been developed with inputs from other partners in the BuNGee project to whom CASMA has provided simulated and measured results for ray tracing and other modelling purposes. There will be reference also to developing the 3.5 GHz HSS antenna and the 2.4 GHz ABS antenna included in the project.

Note about authors: During the BuNGee project Brian Phillips passed away suddenly. His contribution both to this report and to CASMA's involvement in the BuNGee project have been invaluable and are greatly appreciated.

2. Approach to Design

The HBS antenna described below fulfils the requirement of the BuNGee project to submit a dual-polar multibeam antenna assembly suitable for installation on a Hub Base Station to communicate with Hub Subscriber Stations in the BuNGee platform. As part of the project a multiple beam forming network in the form of a Butler matrix has been specified and will be integrated with the terminations of the antenna radiating element and feed network array.

2.1 HBS Antenna Requirements

This needed identification of the required frequency band, gain and power requirements; the optimum coverage and thus beamwidths, azimuth, elevation patterns and polarisations. The specification, confirmed by the BuNGee members on which the design was based is as follows:

- **Frequency:** 3.4 – 3.6 GHz
- **Gain of each beam of complete array:** 19dBi
- **VSWR:** approx 2:1
- **Polarisation:** Dual-polar (+ and - 45˚ polarisations)
- **Cross Polar:** approx 15dB
- **Sidelobes:** 12dB maximum for each beam in elevation and azimuth
- **Front to Back:** approx 30dB
- **Isolation between beams:** approx 15dB
- **Power requirement of each beam:** 15W
- **Beamwidth of each beam:** 15˚ (azimuth) x 10˚ (elevation); 2˚ elevation downtilt
- **Number of Beams:** 6 beams x 2 overlaid polarisations = 12
- **Azimuth beam angles:** -37.5˚, -22.5˚, -7.5˚, 7.5˚, 22.5˚, 37.5˚, achieved using Butler matrix beamforming technology.
- **Total beam coverage:** 90˚ per antenna; four antennas per HBS achieving 360˚ azimuth coverage
- **Phase deviation between beams:** ± 10˚ max

2.2 Modelling

The modelling of the antenna, conducted using CST software, began by simulating an individual dual polar slant 45˚ element, optimized around 3.5GHz. This progressed to developing a single tier elevation array of 8 elements as well as an 8 element azimuth array to represent the eventual characteristics of each beam.

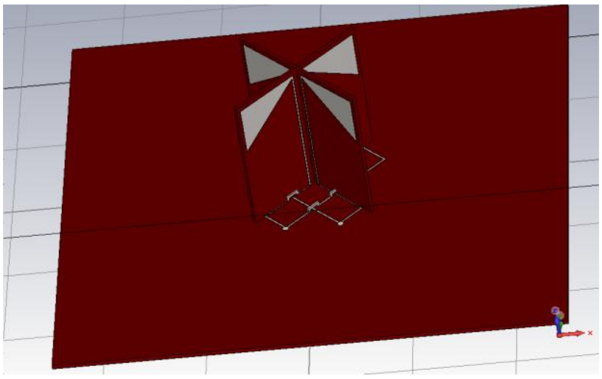

Figure 2-1: Modelled individual dual slant 45˚ element for HBS

The elements were modelled as an interlocking cruciform to achieve the +/- 45˚ dual polarisations on a glass fibre substrate attached to the host pcb; the element sets were spaced λ/2 apart. The modelling of the elevation and azimuth arrays permitted the design of the track layout for optimum phase and isolation balance to conform to the complete array architecture.

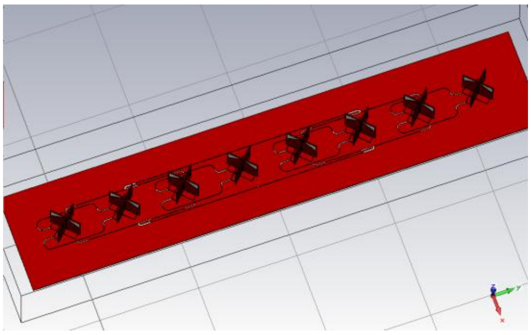

Figure 2-2: Modelled single tier elevation array for HBS

One purpose of using the modeling package was to optimize the feed track lengths and widths since the feeds to one set of dipoles had to cross those for the other. The solution was to model a dual-layer approach using plated-through holes in the host pcb and relieving the ground plane locally to accommodate the secondary layer of track. The tracks using above-board routing then had to be lengthened by the extra amount used by those routed underneath so they were all of equal length to maintain phase balance.

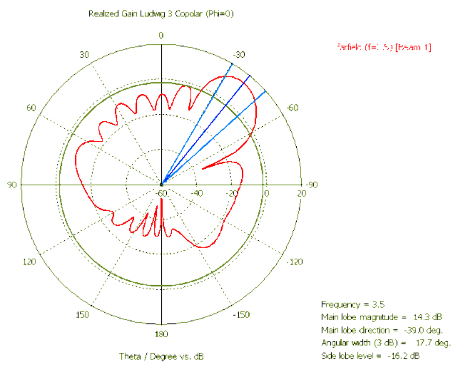

Figure 2-3: Simulated beam pattern for single azimuth array @ -37.5˚

Once the basic antenna was modelled it was possible to simulate elevation and azimuth patterns. A sample polar plot (above) of the azimuth beam which was angled at 37.5˚ demonstrates a beamwidth of 17.7˚, a close approximation to the 15˚ specified.

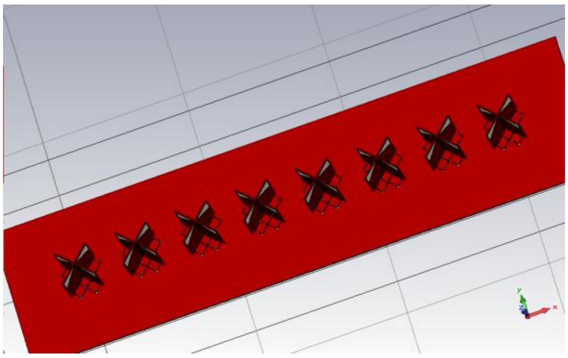

Figure 2-4: Modeled single tier azimuth array for HBS

3. Creation of Prototype

Having simulated the elevation and azimuth arrays to a good approximation it was then possible to start designing a working prototype based on the outputs from the model. First of all, as in the simulations a single cross polar element was made, followed by single tier elevation and azimuth arrays before proceeding with the complete 8 x 8 element topography.

3.1 Evaluating the Building Blocks

For the single element antenna the previously modelled dipoles the glass fibre substrate was specified and prototypes etched. These were soldered to a small host pcb to evaluate the routing of the feed tracks. Initial S11 tests showed that the dimensions of the dipoles needed to be slightly enlarged to resonate at the centre frequency of 3.5 GHz. The model of the dipole element pair were iterated accordingly then etched and tested again to record S11 return loss and S12 isolation measurements. As these measured results considerably exceeded the specification targets of 2:1 and 15dB respectively (see below) it allowed progression to the next stage – the creation of the azimuth and elevation tiers.

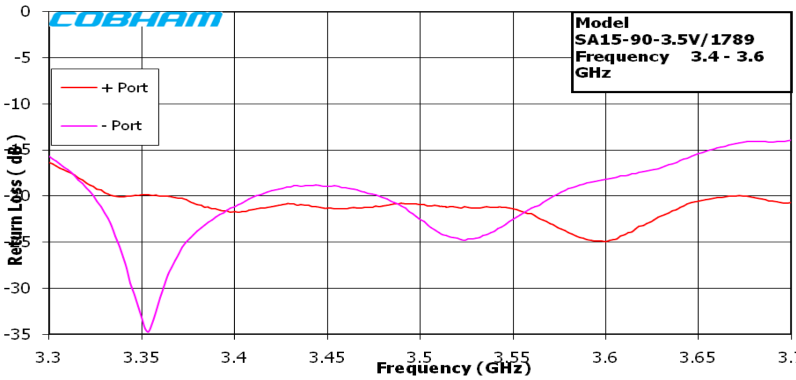

Figure 3-1: Actual S11 measurements for +45˚ and -45˚ port on single element pair

+ to -

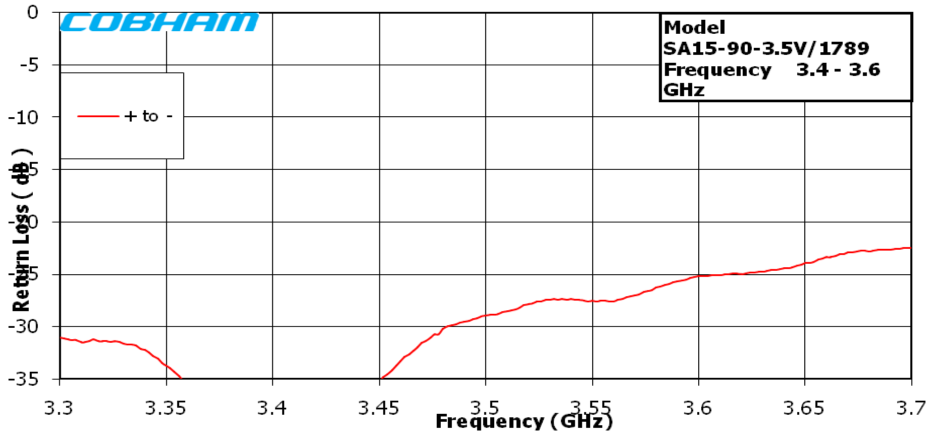

Figure 3-2: Actual S12 measurements for +45˚ and -45˚ ports on single element pair,

3.2 Developing the Array

Having defined the single element cross-dipole pair of elements as a functioning unit, the next task was to create the high gain “single” Sector antenna using the element pair and the feed network from the modelling in section 2.2. From the model it was determined that 8 elements high with 0.7λ spacing in elevation would provide the required pattern and gain. The feed-tracks have to provide the correct phase and amplitude to each pair by differential power splits and line lengths to meet the elevation sidelobe level and electrical down-tilt. They also have to be tightly aligned to the dipole element pairs to ensure that coupling to adjacent “sector” antennas in the array is minimised and isolation is maintained, when they are mounted λ/2 apart in azimuth.

The 8 element elevation array was constructed and tested in CASMA’s anechoic chamber, iterated and re-measured to confirm the expected azimuth and elevation beamwidths, gain and electrical downtilt. The measured results at the centre frequency are shown below.

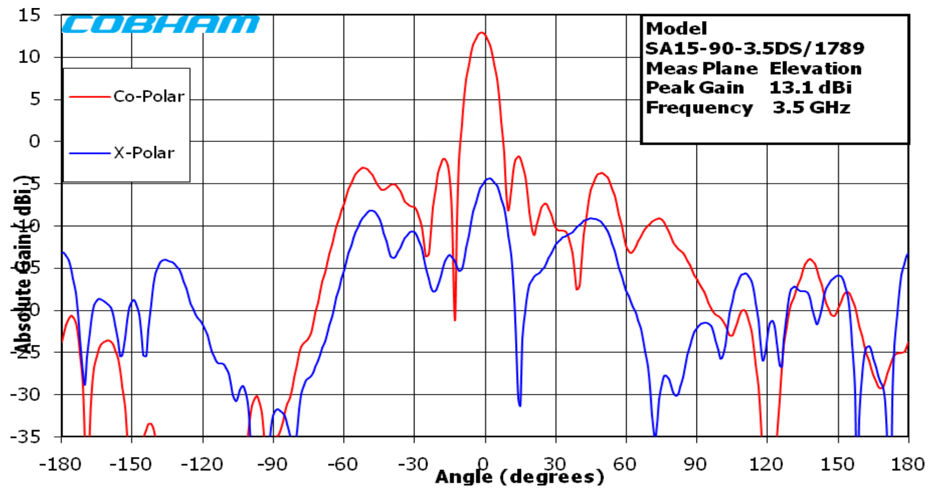

Figure 3-3: Measured elevation pattern for 8 element single tier array +45˚ port showing required 2˚ downtilt and 9.8˚ beamwidth at mid-band. The -45˚ port showed similar characteristics, and close approximation to simulated patterns

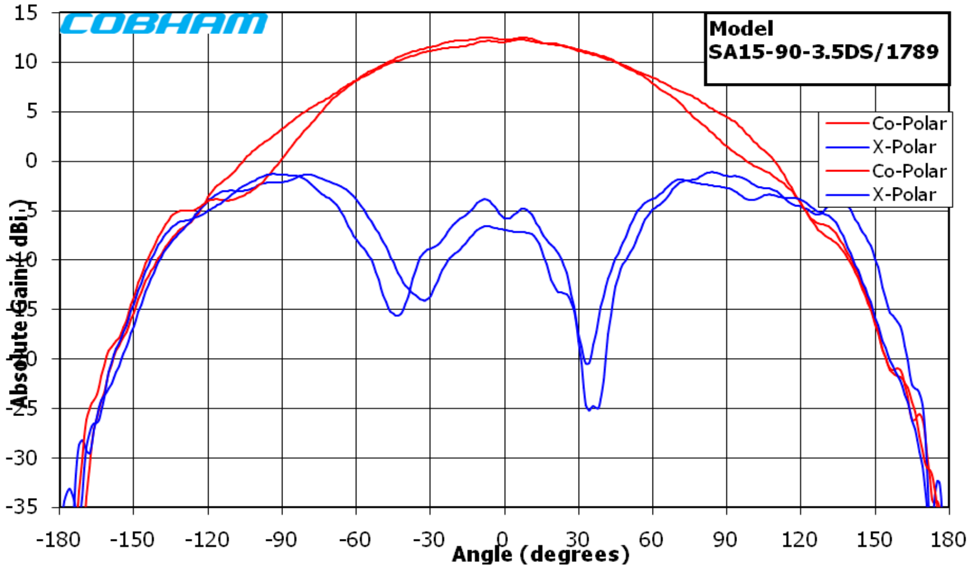

Figure 3-4: Measured azimuth patterns for 8 element single tier array showing +45˚ and -45˚ polarisations overlaid at mid-band. They show that the two polarisations overlap very well over the centre 90˚ over which the 6 narrow beams will be arrayed

The 8 element single tier azimuth array was also developed based on the cross-polar element and spacing from the model. In parallel a multiple beam former was specified which would be able to feed the 8 dual-polar sector antenna elements to create the six, high gain, narrow azimuth beam (15˚**)** patterns across a 90˚ arc in azimuth. This could be achieved using a Butler matrix configuration which would provide the (15˚ wide) beam centres at +/- 37.5˚, +/- 22.5˚ and +/- 7.5˚. The "handover" between beams would occur at the Half Power points thus providing continuity of coverage across the 90˚ arc. In the meantime CASMA was offered the loan of a commercial multiple (8 way) beam former and set of phase-matched cables. This was assembled and used in conjunction with the azimuth array to provide an initial set of patterns which verified that the configuration would meet the primary aims.

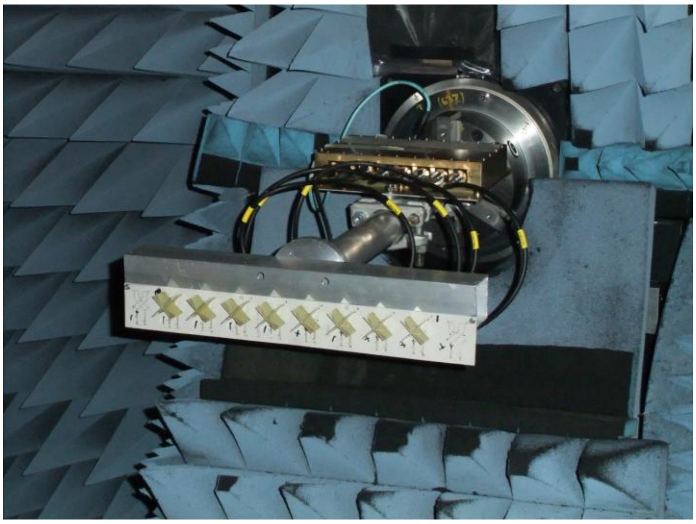

Figure 3-5: The single tier azimuth array and loaned beam former in the test chamber

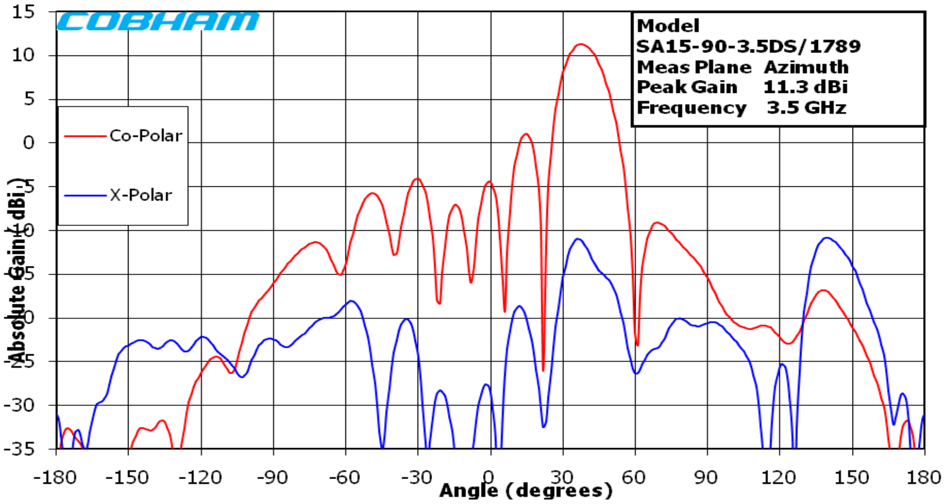

Figure 3-6: Measured mid-band azimuth pattern for 8 element single tier array -45˚ polarized Port 1 showing 37.5˚ beam steer when connected to a Butler matrix. The beamwidth measured 15.8˚ in this example

3.3 The Butler Matrix

The specification for the 8 x 8 Butler Matrix was part of the initial modelling phase and was iterated when the dipole pair was fully defined. The electrical properties have already been referred to and the physical dimensions were such that a pair, one for each polarisation, could be attached to the back of the housing containing the full 8 x 8 dual-polar element antenna and connected with short, phase-matched cables. The required Butler matrix dimensions could be achieved using stripline technology and proprietary crossover circuitry.

An early iteration Butler matrix was produced and the parameters measured. The results listed in the table below show phase difference between input ports 3L, 2L and 3R; A1 to A8 are outputs to the antenna ports, each with a phase shift ranging progressively from 0˚ - 270˚ between successive inputs. Of the 8 input ports the outermost two are terminated with 50Ω loads so that only the inner six are used, representing the 6 beams at between -37.5˚ and +37.5˚ azimuth pointing angles.

Insertion loss and amplitude variations are also shown in the table; it is clear that by using a passive device such as the Butler matrix that the antenna output will experience some loss in overall gain.

Table 3-1: Specification table for prototype Butler matrix showing input ports 3L, 2R & 3R

	3L										
		A1	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**	**A8**		
Phase˚	Spec		-112.5	-225	-337.5	-90	-202.5	-315	-67.5		
	Measured		-118.9	141.7	27	-80.9	160	53.5	-61.1		
Insertion Loss dB	Worst	-10.83	-11	-10.75	-10.75	-11	-11.2	-11.4	-11.45	Min	-11.45
	Best	-10.35	-10.65	-10.55	-10.56	-10.56	-10.6	-10.74	-10.85	Max	-10.35
										Nominal all	-10.9
Amp Deviation dB	Nominal	-10.59	-10.825	-10.65	-10.66	-10.78	-10.9	-11.07	-11.15	**Output +/-**	0.55
	Deviation +/-	0.24	0.175	0.1	0.095	0.22	0.3	0.33	0.3		
	2R										
		A1	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**	**A8**		
Phase˚	Spec		67.5	135	202.5	270	337.5	45	112.5		
	Measured		59.1	130.2	-167	-97.6	-27.3	37.8	103.8		
Insertion Loss dB	Worst	-11.2	-10.98	-10.83	-10.91	-10.7	-12.22	-10.75	-11.89	Min	-12.22
	Best	-11	-10.67	-10.48	-10.49	-10.36	-11.23	-10.58	-10.76	Max	-10.36
										Nominal all	-11.29
Amp Deviation dB	Nominal	-11.1	-10.825	-10.66	-10.7	-10.53	-11.73	-10.67	-11.33	**Output +/-**	0.93
	Deviation +/-	0.1	0.155	0.175	0.21	0.17	0.495	0.085	0.565		
	3R										
		A1	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**	**A8**		
Phase˚	Spec		112.5	225	337.5	90	202.5	315	67.5		
	Measured		118.8	-129.9	-20.2	92.3	-152.2	-37.6	12.7		
Insertion Loss dB	Worst	-11.66	-11.15	-11.16	-10.6	-11.22	-10.9	-10.85	-11.3	Min	-11.66
	Best	-11.22	-10.63	-10.89	-10.52	-10.9	-10.58	-10.52	-10.83	Max	-10.52
										Nominal all	-11.09
Amp Deviation dB	Nominal	-11.44	-10.89	-11.03	-10.56	-11.06	-10.74	-10.69	-11.07	**Output +/-**	0.57
	Deviation +/-	0.22	0.26	0.135	0.04	0.16	0.16	0.165	0.235		

Add ± 360˚ to the measurement to be specification compliant

3.4 The 8 x 8 Array

The successful results from tests of the single tier, row (azimuth) and column (elevation) arrays led directly to the development and assembly of the 8 x 8 dual polarisation array, combining the features of the individual units. The same dual-layer technique was to be used with the final host pcb with ground plane relief to accommodate the crossover tracks. The whole assembly has been designed to be mounted in an aluminium tray which will also support the two bespoke Butler matrices. The radome which extends the full dimensions of the tray will be glass fibre, supported in the centre by nylon pillars.

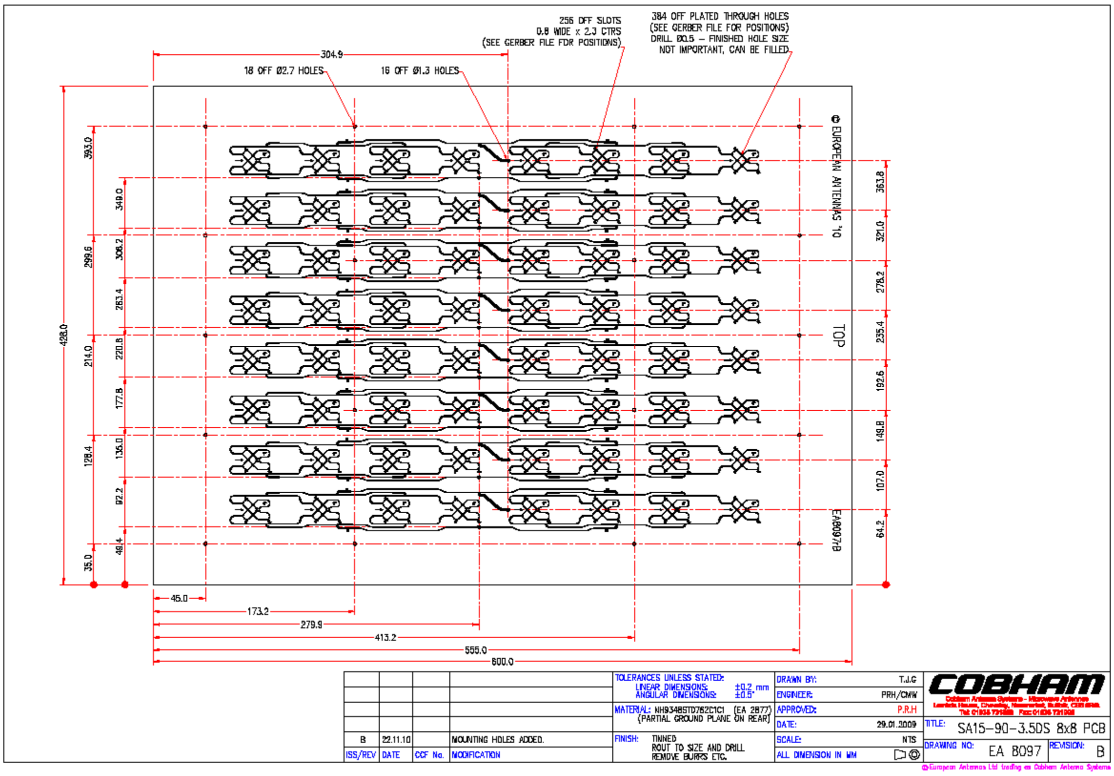

Figure 3-7: Drawing of host 8 x 8 pcb. The dual polar track layout can be clearly seen; the 16 SMA connectors are attached along the centre vertical axis

4. Testing of Prototype

After assembling the full 8 x 8 array a sequence of tests was conducted to evaluate the prototype with the plan that it will become the design for the final product. VSWR and isolation tests showed consistency between ports as well as with simulated results. Pattern measurements in the test range without the housing or radome demonstrated the expected set of six patterns, with narrow beamwidth and increase in the overall gain predicted in the simulation.

4.1 VSWR and Isolation Results

The return loss of all the 16 ports (8 x +45˚ and 8 x -45˚) was measured on the complete antenna (without housing or radome), with the results shown below. The target VSWR of 2:1 (<-9.5 dB) was easily achieved between the limits 3.4 – 3.6 GHz in every case, the poorest being -11.21 dB @ 3.42 GHz. Likewise isolation between each adjacent + and – port was measured and found to easily exceed the target of -15dB; -22dB being the lowest figure, at the top end of the band. There was also reasonable consistency between the characteristics of each port which validated prototyping methods.

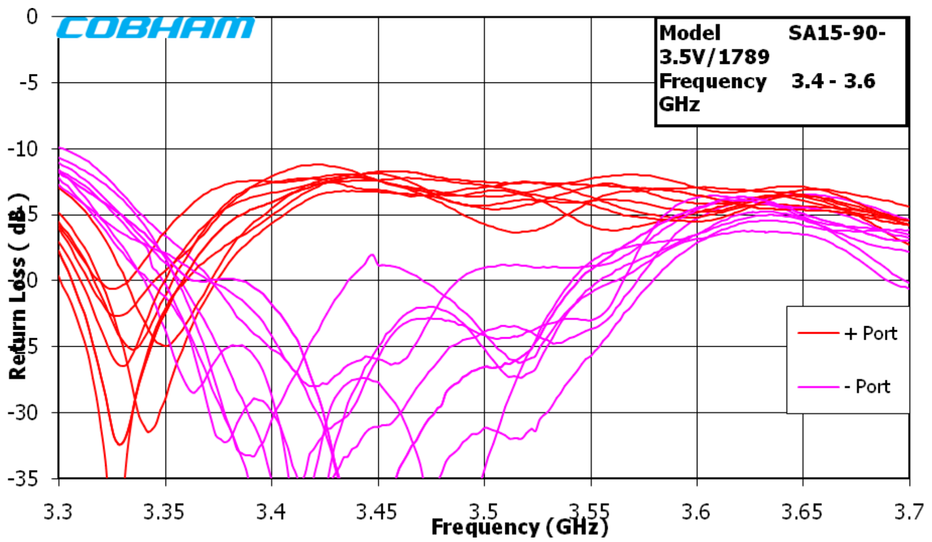

Figure 4-1: Graph showing return loss of +45˚ and -45˚ ports overlaid

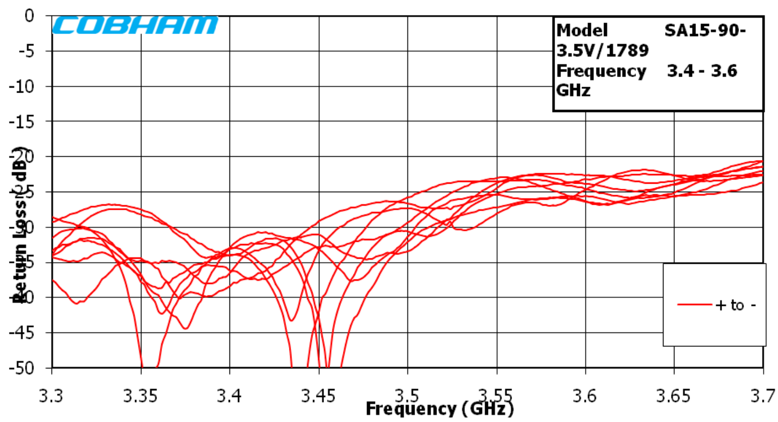

Figure 4-2: Graph showing isolation between adjacent +45˚ and -45˚ ports overlaid

4.2 Range Testing of Complete Array

It was decided to test the 8 x 8 element array, with the loaned multiple beam former. As the beam former did not feature built-in taper this was applied using external attenuators in line with the interconnecting phase-matched cables. Results were reported to the BuNGee consortium.

The overlaid plots below show the performance of the assembly for one polarisation without the attenuators; the gain shown includes losses in the Butler matrix and phase-matched cables. From the graph the handover at the 3dB points can be seen, giving a total beam coverage of 90˚ in azimuth.

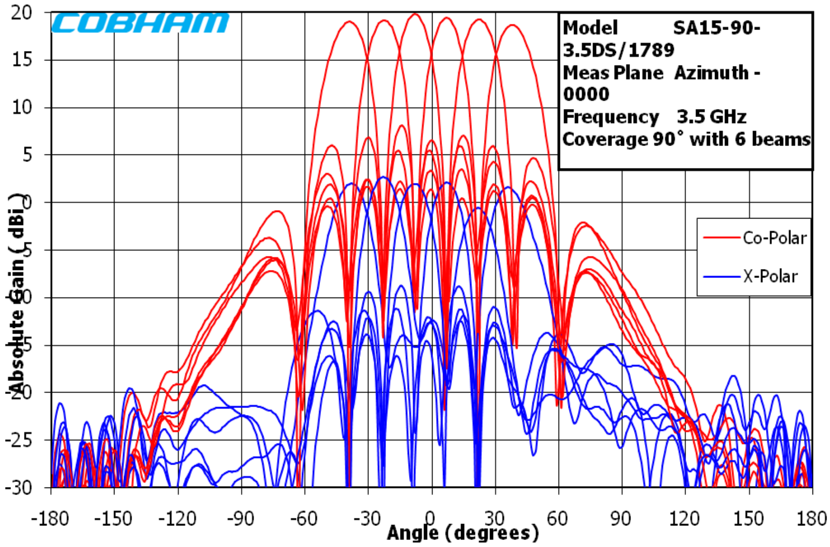

Figure 4-3: Graph showing overlaid beams from -37.5˚ to + 37.5˚ over a 90˚ spread

5. Final construction of assembly

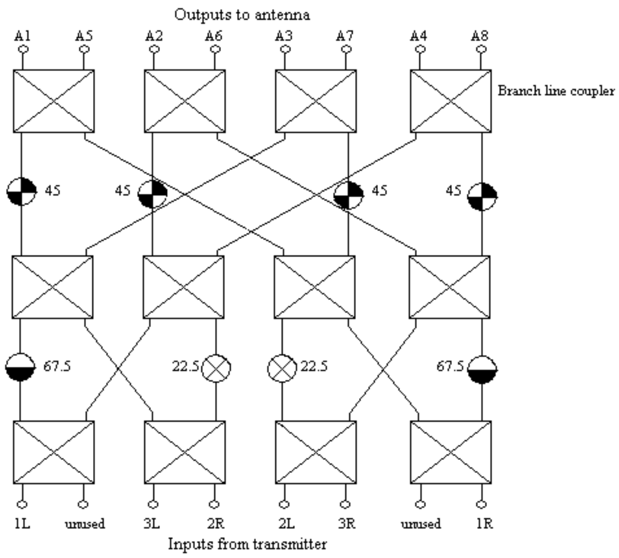

Figure 5-1: A typical Butler matrix schematic showing the 90˚ branch line couplers (rectangles) and interconnections showing phase shift in each combination of connections[1].

Having proven the HBS antenna assembly design, attention turned to producing bespoke Butler matrices and then the final housing and Butler matrix enclosure. Each Butler matrix needed to be optimised for a centre frequency of 3.5 GHz and be compact enough to fit in the proposed enclosure. The standard matrix design of 8 inputs and 8 outputs was adapted so that only 6 inputs are used, i.e. the remaining two are permanently terminated.

[1] Note that only 6 of the 8 inputs are used with the HBS antenna, the remaining ports being terminated

Figure 5-2: Illustration of the final housing and enclosure showing the two stacked Butler matrix assemblies and interconnections to the antenna using phase matched cables

The antenna housing, consisting of an aluminium tray and glass fibre radome provides anchorage points for the external housing which encloses the Butler matrices, interconnecting phase matched cables and right angled SMA connectors. The assembly, covered with an iridescent coating and paint is protected against weather and can be mounted on a pole using a standard CASMA mounting kit on the back of the enclosure. Connector access is via the underside of the assembly through an opening in the enclosure.

6. Final testing of assembly

In this final form it was again tested in CASMA's anechoic chamber to provide radiation patterns as well as spherical data for UCL's ray tracing programme using the bespoke Butler matrices with 3 levels of amplitude taper. The tests used 0 dB for minimum taper; 0,0,2,5 dB for an intermediate level and 0,1,3,5 dB for maximum recommended taper consistent with sufficient main beam gain. The attenuators were fitted between the output of the Butler matrices and the inputs to the antenna. (0 dB attenuators were fitted in order to maintain phase fidelity in each input not otherwise attenuated). As can be seen in the Figures 6-1 to 6-3 the sidelobe level drops with increasing amplitude taper relative to the main beam in the azimuth plane without affecting the elevation pattern save for a corresponding reduction in peak gain.

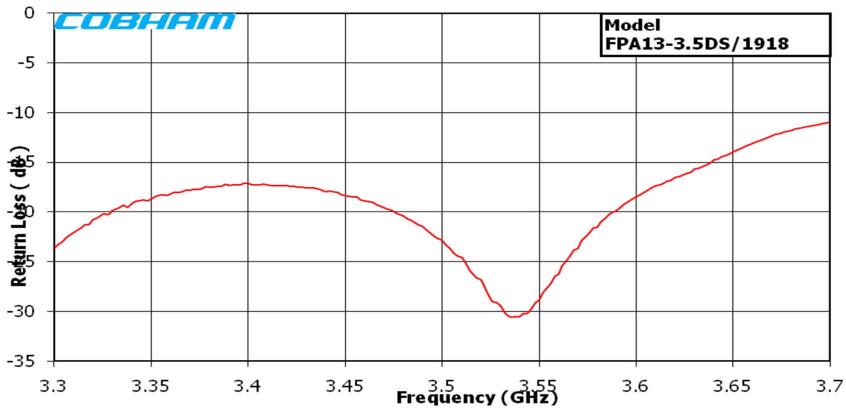

Figure 6-1: Typical return loss plot of the HSS antenna (-45˚ port shown)

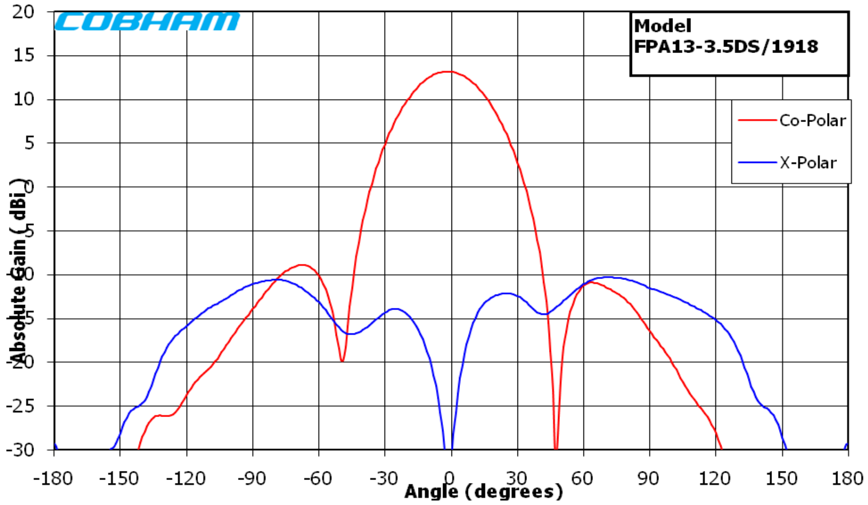

Figure 6-2: Typical radiation pattern of the HSS antenna. This is the +45˚ azimuth beam at 3.5 GHz; peak gain is 13.2 dBi. Using diamond formation elements reduces sidelobe level

Figure 6-3: Final version of the HSS antenna using "N" type connectors on an aluminium backplate with iridescent coating and vacuum formed radome

6.1 ABS Antenna Requirements

The Access Base Station (ABS) antenna is required to operate at 2.4 – 2.6 GHz as a dual polar, slant 45˚ 17 dBi unit. For the purposes of the BuNGee tests a stock CASMA V & H antenna was adapted to suit and mounted in diamond formation for radiation pattern tests. It consists of a 4 x 4 element and parasite design similar to that of the HSS unit carried in a machined aluminium, iridescent coated housing and glass fibre radome.

- **Frequency:** 2.4 – 2.6 GHz
- **Gain of each beam:** 17dBi
- **VSWR:** approx 2:1
- **Polarisation:** Dual-polar (+ and - 45˚ polarisations)
- **Cross Polar:** approx 20dB
- **Front to Back:** approx 30dB
- **Isolation between beams:** approx 30dB
- **Power requirement of each beam:** 20W

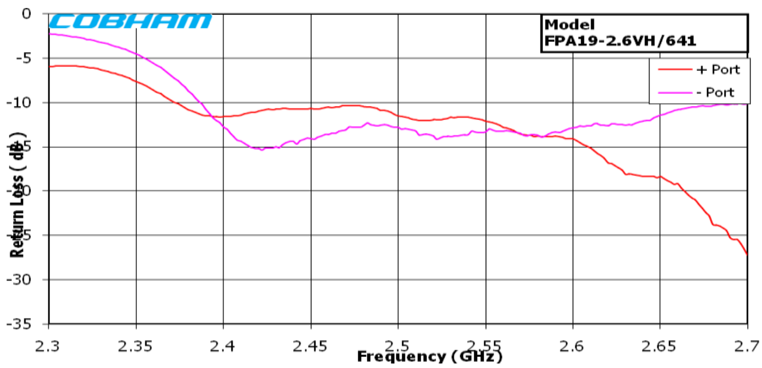

Figure 6-4: Return loss of both +45˚ and -45˚ ports of the ABS antenna, better than 2:1 VSWR (10 dB)

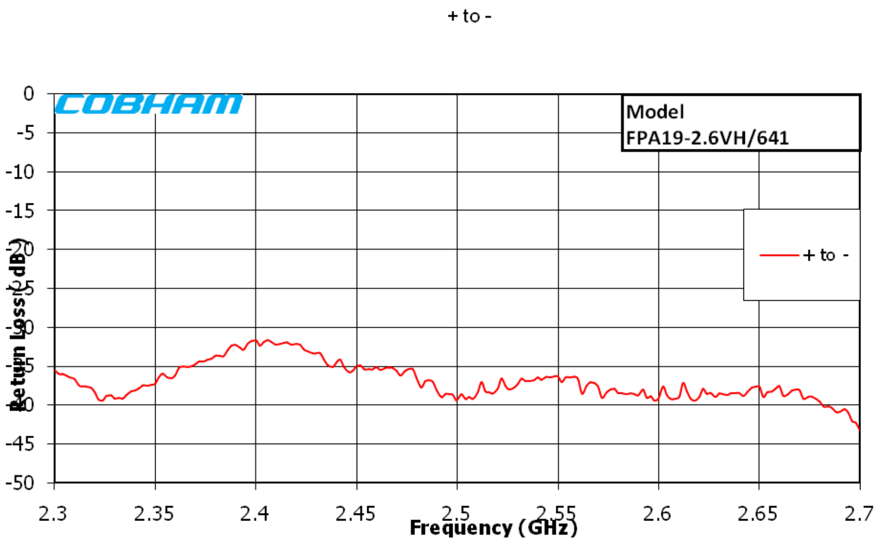

Figure 6-5: Isolation plot of the prototype ABS antenna, better than 30 dB between ports

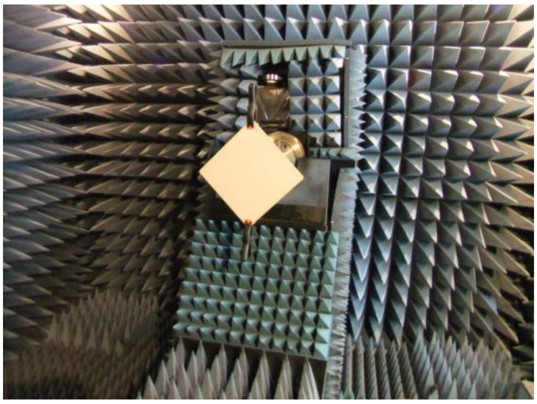

Figure 6-6: The ABS antenna mounted in diamond formation to achieve slant 45˚ patterns in CASMA's test chamber

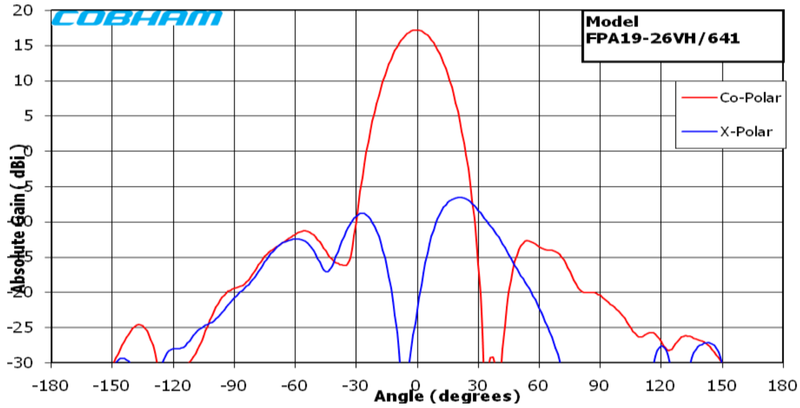

Figure 6-7: Plot of typical radiation pattern of the ABS antenna at 2.5 GHz. Gain is 17.2 dBi

7. Conclusions

CASMA's involvement in BuNGee forms an important part of the whole project. We have successfully modelled and completed a prototype of the HBS antenna; completed work on the dual slant 3.5 GHz HSS antenna and produced a dual slant 2.4 GHz ABS antenna. We have supplied data for safe distance calculations to the consortium, submitted spherical data to UCL for ray tracing and we have endeavoured to cooperate fully as far as possible with other BuNGee partners in advancing their work just as they have helped in the tasks allocated to us. CASMA has been able to complete tasks so far within the expected time frame and within budget.

9. Bibliography

[1] EN302-326-3, section 4.3.3 "Sectored Multibeam Antennas" published by the European Telecommunications Standards Institute 2007

[2] Butler and Lowe, "*Beam-Forming Matrix Simplifies Design of Electronically Scanned Antennas*", quoted on website www.microwaves.101.com