DEMONSTRATOR PLATFORM FOR ANTENNA ARRAY CALIBRATION

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Abstract-**This paper presents a hardware platform for antenna array calibration research in tower top electronics. The platform has eight phase and amplitude controlled transmit channels and a novel antenna coupler array structure which provides non-radiative calibration capability. The phase and amplitude of each channel can be varied between 0 and 360° and over 25dB respectively under full software control. The platform has been used to test and develop array calibration routines which achieve amplitude variances of less than 1dB and phase variances of less than 5° measured between eight channels at the antenna connections.**

I. INTRODUCTION

In order to achieve accurate beamforming it is essential that the elements of an array are amplitude and phase matched or that the differences are known, in addition these relationships must be maintained in demanding environmental conditions such as a tower top over long periods of time. Traditionally this has been achieved through the use of tight tolerance components, phase matched cables and the use of factory measured calibration tables, however this is an expensive approach and offers little adaptation to the ambient environmental conditions.

Amplitude and phase errors between array elements distort the antenna radiation pattern in terms of beam pointing direction, sidelobe level, half power beamwidth and null depth [1] . The extent of the distortion has been well covered in antenna array literature [2], [3], [4].

There are several approaches to array calibration including tight tolerance design with factory determined calibration tables, calibration using internal and external radiating sources and non-radiative dynamic calibration [5]. The third approach was chosen as it does not require external radiators, high tolerance cables and components or extensive array modelling. In addition dynamic calibration allows continuous monitoring of the array status for network management purposes; this is a critical requirement for all cellular and wireless network operators.

Desirable features of any research platform are: that it be simple to use, that the controlling software be easy to modify and that the hardware be easily expandable, for example, through the addition of more array elements. In hardware, this was achieved through the use of off-the-shelf phase and amplitude adjustment components configured in a modular easily expandable fashion. As regards software it was decided to use Labview to control the system, implement the calibration algorithms and collect measurements. Labview is a graphical programming language aimed and test and control applications, it is easy to implement graphical user interfaces and can call both C and Matlab functions [6].

II. PLATFORM ARCHITECTURE

Effective non-radiative array calibration relies on the ability to measure the transmit or receive signals as close to their antennas as possible and to compare the measured signals with reference signals to ascertain the phase and amplitude relationship between the elements. The reference signal(s) can be the actual transmit signal in the case of live calibration or a pilot signal in the case of off-line calibration. A block diagram of a distributed transceiver array with integrated calibration/reference blocks is shown in Figure 1. This system consists of interconnected transceivers and calibration blocks where the calibration blocks provide at least one and in most cases multiple calibration paths to each transceiver, in addition every transceiver calibration path is linked to every other path through the tessellated transceiver and calibration block structure. This multiplicity and interdependence of calibration paths for each transceiver facilitates the development of powerful calibration algorithms [7].

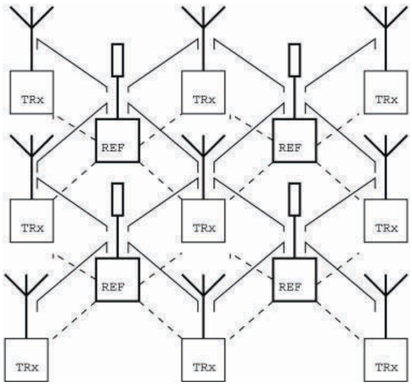

Figure 1: Distributed Transceiver System, with built in Calibration Infrastructure

A block diagram of the platform is depicted in Figure 2. The heart of the demonstrator is a 2x4 antenna coupler array; this novel design consists of an array of couplers where each coupler output provides coupling from the four surrounding transceiver through paths; a more detailed description of this coupler array and its operation is provided in [8] and [10]. In the case of transmission, the coupler outputs provide attenuated versions of the forward TX signals present at the through path inputs. The loss and phase shift between the through path input and output is small, less than 1dB and the phase variation across all through paths is less than 2°. The coupler array variations can be included as a calibration offset table in the calibration algorithms.

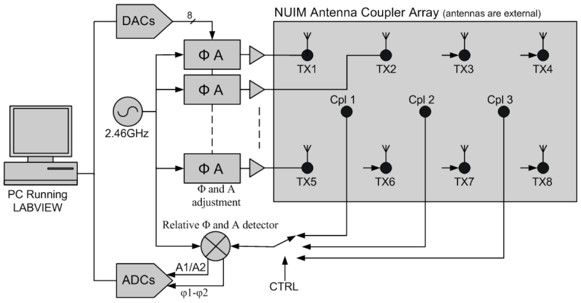

Figure 2: Block diagram of calibration and beamforming platform

The coupler outputs are connected through an RF switch to the vector voltmeter module which compares the coupled signal with a reference signal and produces DC outputs corresponding to the phase and amplitude difference between its inputs. The detector module is comprised of two Analog Devices AD8302 RF Gain and Phase Detector IC's configured to give I and Q outputs (cos φ & sin φ), from which it possible to generate a linear monotonic output for all angles between 0 and 360°.

$$I = A.\ \cos\varphi$$
$$Q = A.\ \sin\varphi$$

$$\begin{array}{lll}
\varphi\ = \tan^{-1}(Q/I) & & (1) \\
\varphi` = \varphi & \text{for } I > 0,\ Q > 0 & (1.1) \\
\varphi` = \varphi + 180° & \text{for } I < 0,\ Q > 0 & (1.2) \\
\varphi` = \varphi + 180° & \text{for } I < 0,\ Q < 0 & (1.3) \\
\varphi` = \varphi + 360° & \text{for } I > 0,\ Q < 0 & (1.4)
\end{array}$$

The phase shift is described by equation (1) however this produces discontinuities at 90° and 270° so the response is modified according to equations (1.1 - 1.4). As regards relative amplitude, the AD8302 produces a linear output voltage for amplitude difference from -60dBm to 0dBm.

The phase and amplitude adjustment modules, one for each array element, allow the phase and amplitude of the RF signal to be varied from 0 to 398° and -7 to -32dB with respect to (wrt) the input by applying DC voltages to the phase and amplitude control inputs. The modules comprise continuously variable voltage controlled phase shifters (Mini-circuits JSPHS-2484) and a variable attenuator (Mini-circuits RVA-3000). These components are mounted on a printed circuit board with some control voltage level adjustment circuitry and the ensemble placed in a shielding can to minimise electromagnetic interference between array channels. Figure 3 shows a photograph of the phase and amplitude adjustment modules. An external amplifier was added in series with the phase and amplitude adjustment modules to compensate for their insertion loss and to ensure that the signal fed back to the phase and amplitude detector module would be at the input mid-range point.

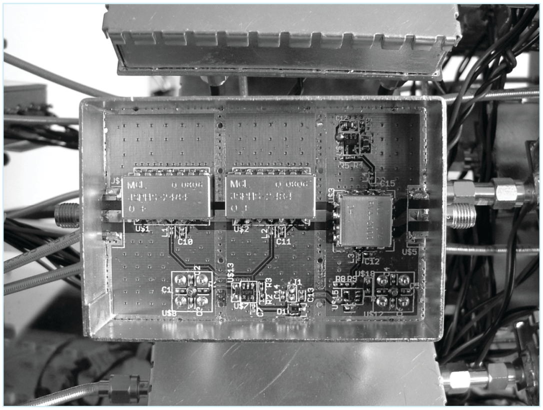

Figure 3: Phase and amplitude adjustment module

The control voltages for the phase and amplitude adjustment modules are generated by a National Instruments multi-channel 13 bit digital to analogue (DAC) card (NI PCI 6723); similarly the outputs of the vector voltmeter are digitised using a NI 16 bit analogue to digital (ADC) card (NI PCI 6251). The control of the ADC's and DAC's as well as the implementation of the control loop and the calibration algorithms were all done through Labview.

III. PLATFORM MEASUREMENTS

In the previous section the operation of the phase and amplitude adjustment and vector voltmeter modules was explained. In this section, measurements from these modules which are the core components of the platform are presented and discussed.

The phase and amplitude adjustment module was tested using a vector network analyser. By sweeping the module control voltages, the phase and amplitude of the RF signal at the output were plotted against the RF signal at the input, this is shown in figures 4 and 5. All RF measurements were taken at 2.46GHz. The amplitude response is very non-linear but nonetheless monotonic. The phase response covers 398° and has some non-linearity at low voltages but again is monotonic. Non-linearity in the module's responses is not critical as phase and amplitude are set within a control loop which uses the vector voltmeter response to set reference points.

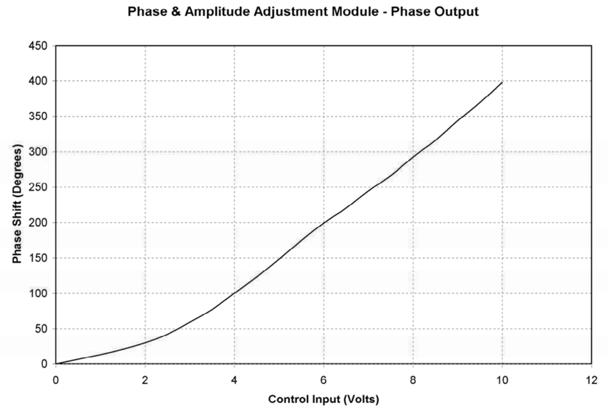

Figure 4: Phase and Amplitude Adjustment Module - Phase Output

The phase and amplitude adjustment module was reused to generate phase and amplitude differences between the RF inputs of the vector voltmeter module. The module DC output levels were recorded over the full platform phase and amplitude range between its RF inputs.

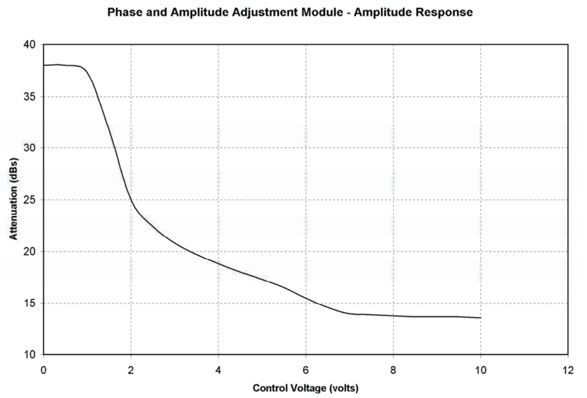

Figure 5: Phase and Amplitude Adjustment Module – Amplitude Output

Figures 6 shows the vector voltmeter phase output against phase input; the phase output is calculated from the I and Q outputs as described in the previous section. The response covers 360° before wrapping back to 0°, there is some non linearity but this could easily be adjusted for with a look up table. The relative amplitude plot in figure 7 shows a range of 25dBs for the platform; this is much greater than the expected amplitude mismatches in a beamformer.

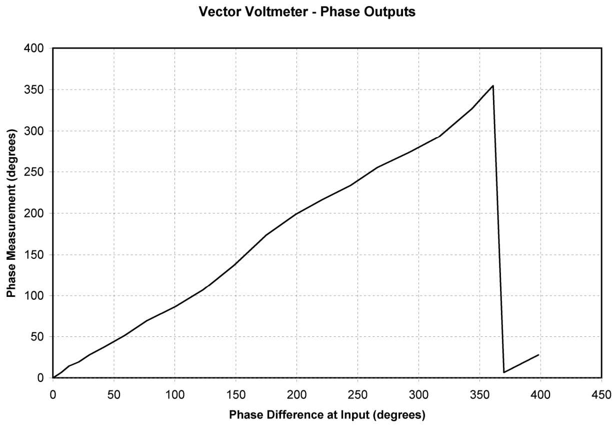

Figure 6: Vector Voltmeter - Phase Output

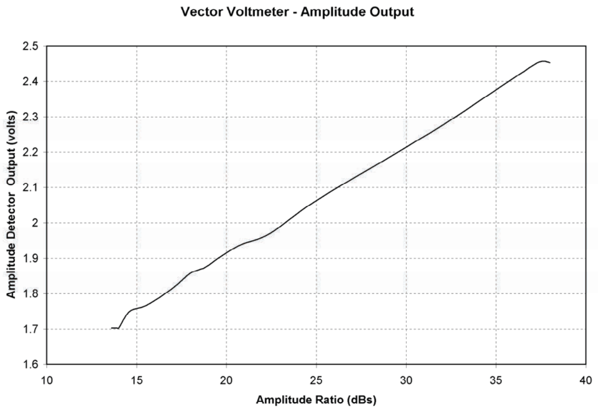

Figure 7: Vector Voltmeter - Amplitude Output

IV. CALIBRATION ALGORITHM DEMONSTRATION

The initial application for the platform was to test calibration algorithms developed at the Institute. The calibration algorithms work by defining a single antenna element as a reference and calibrating all other antennas relative to that reference by following a particular route through the elements of the array. The choice of reference element and the path chosen determines the efficacy of the algorithm in terms of accuracy and speed. The results of testing on different algorithms have been presented in [9]. In this paper the measurements from testing one of these algorithms will be presented as an illustration of the capabilities of the platform.

The dual path algorithm is a comparison based calibration algorithm. It selects a reference element in the left hand corner of the array and then performs comparisons with the elements coupled to the reference antenna element; it takes two paths of identical length to each element of the array from the reference antenna.

These two paths are averaged to reduce the effect of coupler errors.

Figure 8 shows a photograph of the calibration algorithm test set-up. The antenna connections on the 2x4 coupler array were connected to the inputs of a high speed digital oscilloscope (Agilent Infinium 5483A DSO 2.5GHz); unused antenna connections were terminated with 50Ω loads. The oscilloscope offers resolutions of better than 1° in phase and better than 0.1dB in amplitude which is sufficient to verify the operation of the platform and algorithm.

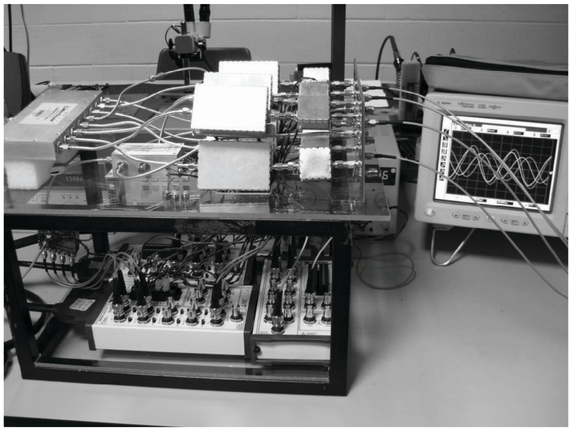

Figure 8: Calibration and beamforming platform with antennas replaced by a high speed digital oscilloscope

To represent an uncalibrated system, each channel was set to a random phase shift and amplitude attenuation by applying control voltages to the phase and amplitude adjustment modules. An oscillogram of the random phase and amplitude relationships on four of the antenna connections is shown in Figure 9. The dual path algorithm was then run in Labview on the platform PC and the phase and amplitude relationships were measured on the oscilloscope; Figure 10 shows an oscillogram of the signals at the antenna connectors after calibration.

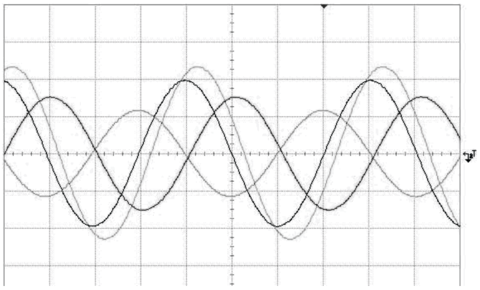

Figure 9: Oscillogram of uncalibrated output signals

From the oscillograms it is clear that after calibration there is no visible phase difference and a small visible amplitude difference between the channels. More precise measurements for each TX output of the array are presented in Table 1

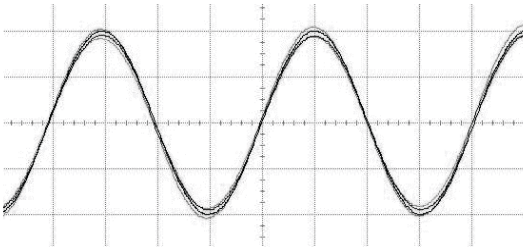

Figure 10: Oscillogram of antenna connections after calibration

Table 1: Transmit phase and amplitude measurements wrt TX1

	TX1	TX2	TX3	TX4	TX5	TX6	TX7	TX8
Phase wrt TX1 (°)	0	1.8	-2.2	-2.2	-1.6	0.18	0.4	-0.4
Amplitude wrt TX1 dB	0	0.11	-0.27	-0.03	-0.49	-0.56	-0.22	-0.3

The results table shows that the maximum phase difference from the reference element (TX1) was 2.2° and between elements was 4°. The maximum amplitude difference between the reference and the other elements was 0.56dB and between all elements was 0.67dB.

V. CONCLUSIONS

This paper presented a test platform for the exploration and development of tower top antenna array calibration algorithms and technology. The platform operates at 2.46GHz and uses off-the-shelf components in a modular easily expandable architecture. The software, Labview, allows easy configuration of the hardware and implementation of calibration algorithms. Platform measurements were presented which showed a phase and amplitude control range of 0 to 360° and 25dB respectively for each array output. Additionally a calibration routine was run on an array with antenna outputs preset to random amplitudes and phases, the routine succeeded in reducing the phase and amplitude difference between outputs to less than 1dB amplitude and 5° phase.

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