Development of an Analogue Phased Array Beamformer for Wide Ku/K Band Applications

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Abstract

This paper presents the design and measurement of a wide 16-22 GHz scalable multi-beam phased array analogue beam former. As the current trend of new chipsets which contain ever more RF circuitry continues, the techniques and principles required to use them also become more challenging. This paper looks at the design criteria required to pack huge amounts of RF circuits together and ensure compliance to beam former theory. The use of automated test and measurement is discussed and how the calibration challenges of such a system can be overcome. The paper uses results and experience which came from the development of EECLs scalable multi-beam, 16/64/256 antenna array.

Introduction

5G communications is certainly a hot topic now. Companies are scrambling to develop technology to address the challenges posed. With 6G on its way, the 5G revolution is still in its infancy and the new networks being launched today do not offer the full benefits that the hype has claimed. The technology to truly deliver what has been promised is yet to be designed. The 5G revolution is also helping to fuel a satellite revolution, companies such as OneWeb and SpaceX are racing to build high speed internet from space systems to remotely serve the 5G infrastructure and deliver other fascinating applications. For the whole system to work it requires better and better Beam Former Systems and Phased Array Antennas. This is the technology at its core. EECL has previously conducted consultancy and design support for OneWeb (Airbus) and was responsible for part of the payload delivery. We have seen first-hand the limits of current antenna technology.

EECL was commissioned to design an analogue beam former in order to work with and test 3D printed antenna arrays. Consideration for space use was important and with EECL having a lot of experience in that area we were perfectly placed. In order to determine the performance of such antennas, beam forming hardware is required that performs better than the antenna itself. It is not possible to decouple underperforming antennas from underperforming RF circuitry and therefore some special was required beyond that currently available. Ultra-high isolation is required between channels to be able to achieve deep nulls for specific applications. With 30dB of attenuation range and lots of gain in beam formers (64 * 20dB gain amplifiers) – around 90dB antenna to antenna / beam to beam isolation is required in order to absolutely decouple the effect of one antenna altering another antenna. If this happens the calibration of a system is practically impossible.

To give an idea of how the architecture of a beam former changes with beams/element count, the current holy grail of beam formers would be a system capable of around 8 beams and 256 elements. This would require a whopping 16,500 RF interconnects between subsystems and for a space system would probably cost more than £1m. EECL decided to build a small module which can handle 2 beams and output 16 antenna elements. These modules would then be easily connected to increase to something like 2 beams and 64 elements and possibly even higher - only limited by budget.

One of the major real technical challenges with creating a high-end beam former is in the splitting of the radio signal multiple times without compromising its "quality". Then handling all these splits without them talking to one another. The frequency range that EECL needed to target is high and in the 17-22 GHz part of the radio spectrum to cover the satellite downlink bands. This represents many challenges, signals in this band carry an awful lot of data and are extremely wide in bandwidth (300 MHz typical). The signal must be split whilst maintaining an equal phase over the split and keep amplitude levels over this bandwidth to 1% variance. Having so many splits of the signal in a small package carries high risk of them interfering with each other. Signals at this frequency can jump across gaps as large as 1 inch.

This split also needs to happen for each beam to be transmitted. Each split arm then needs to then be phase and gain controlled before being amplified. Then each split needs to be combined with the split from the other beams. The total flatness over the frequency band needs to stay in at 1%. The entire system will get very warm due to the amount of control, power and amplification. The system must be controlled and calibrated over its operating temperature range and must function from -20C to +65C.

Integrated SiGe chipsets are appearing from a variety of suppliers. These are exciting as they offer the ability to put a large amount of RF circuits into a small space and at a reasonably low cost. Currently a 4x4 chip is considered high end. However, currently these chipsets only offer certain frequency ranges and the performance is not exceptional. Additionally suppliers are charging a premium for them. The use of these chipsets for this application was looked at but the performance and frequency band combination were just not available. Even if it was, then space qualification would not exist. To obtain an ideal performance on the beam former within the tight timescales allowed a discrete system was designed.

The following paper describes such a system and presents some real results taken from a patch array panel. 3D printed antenna results cannot be presented here. EECL took the whole system from concept to final delivery in just 4 months. The first prototype produced functioned as desired and required no modifications what so ever.

Quick Beam-Forming Recap

In a phased array each antenna radiates as per its standard radiation pattern. Providing that these are far enough apart to not distort one another, a beam can be directed in any chosen direction by adjusting the phase of each radiated element such that they combine exactly and maximise the directed energy in that direction. Mathematics dictates that the element spacing can change how the energy not phased together in the main beam interacts. These are called the sidelobes and different techniques can control them. For a uniform amplitude array, we expect typical sidelobes of around 14dB. Using a Dolph-Chebyshev taper this can be reduced to more than 25dB. The spacing of the antenna elements is crucial because when forming beams at low angles we get a copy of the beam appearing called a grating lobe. This is proportional to the antenna element spacing. Usually a spacing of 0.5 wavelengths is a good compromise. Reducing sidelobe levels using a taper will reduce efficiency since the energy directed into the main beam is reduced.

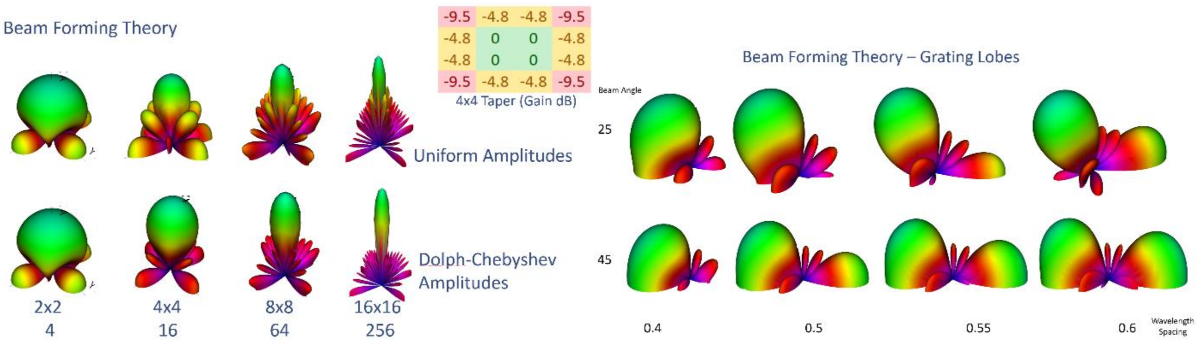

Fig: Beamformer Theory

Patch Antenna Array Design

Since the end use antenna was for a commercially sensitive 3D printed horn, no details on this can be discussed here, a phased array panel was designed to obtain a baseline for the performance and this forms the basis of the rest of the paper. This panel was created using standard techniques with special care taken on the feed arrangement in order to minimise parasitics and obtain exactly equal performance between all 16 elements. The image below shows the designed panel and measured performance of all 16 elements.

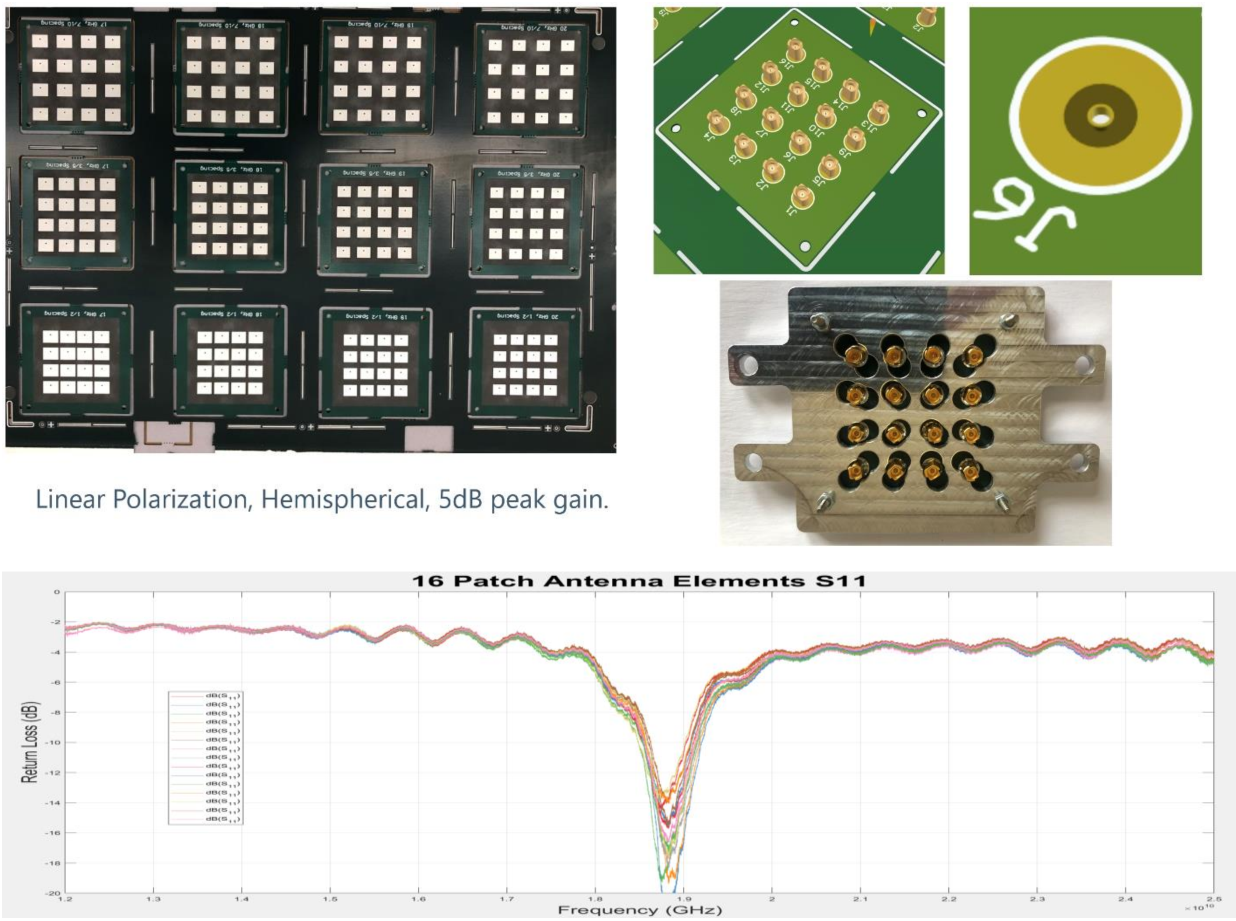

Figure 1: Patch Antenna Configuration and Results

Analog Beam Former Design

The beam former block diagram is shown below. The system is a 2 beam, 16 element card. Novel techniques were employed to design small, low loss, repeatable splitters which are flat to 1dB over 7 GHz of bandwidth. The system takes 2 individual RF inputs, splits them 16 times and then gain and phase adjusts each channel. They are then cross combined to form 16 antenna ports. The combiners and isolation is such that every channel is completely mutually exclusive to one another.

The control system for the board is complex, it requires 226 digital lines, 32 analogue lines and 98 power lines. In order to fit 66 amplifiers, 46 splitters, 32 phase shifters, 32 VV attenuators and 18 high frequency connectors onto the board EECLs proven and complex layer stack was used with a hybrid Rogers/FR4/Rogers board layout. RF was laid out both sides to achieve the cross combine and layout techniques ensure 90dB+ isolation.

The board was sandwiched between 2 metal plates which form the housing – they contain a special isolation gasket and material to facilitate operation of the combiners which are an EECL proprietary design of 8mm x 5mm x 2mm in volume. The gain stages and attenuators are well controlled with the metalwork to allow them to function flat over huge bandwidths – especially at highest attenuation.

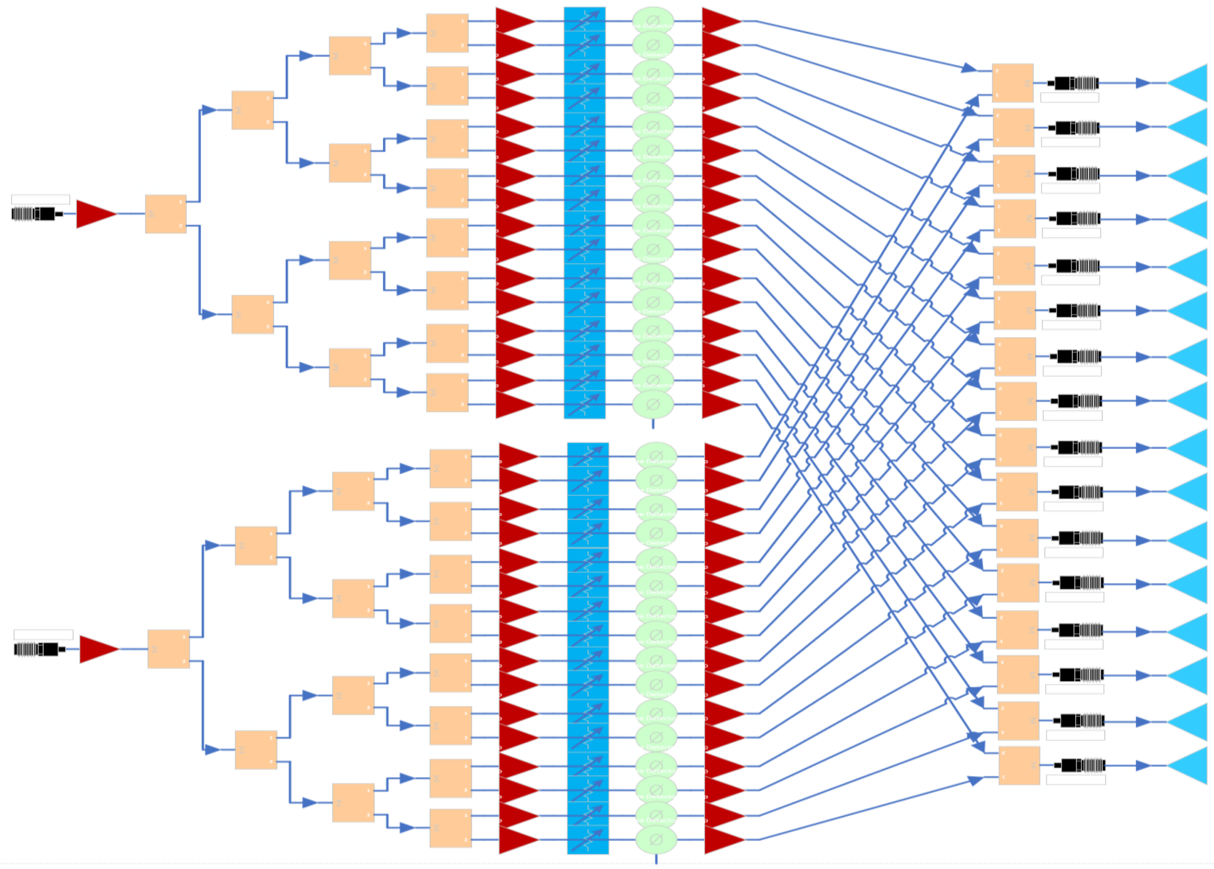

Figure 2: BFN Block Diagram

The diagram shown describes how the RF connects. For this system multiple amplifiers were used before and after the phase shifter to isolate the splitters and provide a constant match. Also the high power amplifier is on the output and the first one is merely a low power LNA to allow the system to keep its noise figure when the following phase shifter and VVA are very lossy.

External control and power was provided by an external PCB, for a real space application this can not fly and therefore would be replaced by a spacecraft interface. This board allowed USB control of the BFN and brought some sensible protocols to the huge number of interface lines. The RF board parts are fully compliant for operation in low earth orbit with regards to typical radiation levels of 10Krad.

The final stage amplifiers used here are each moderately powerful at +23dBm output power. When arranged together in phase using 16 elements the beam power is increased beyond the single amplifier power. The more elements that a beam former uses the more directional a beam becomes. Although this is not providing antenna gain the typical sense it is due to a larger number of antennas radiating in phase. As element count increases, for a given link budget the power output of each antenna can be reduced. Larger arrays can therefore use less powerful SSPA – in fact LNAs, on the output stage for a given link budget. This has the added benefit of spreading the heat and making thermodynamics easier to manage. However, total efficiency may be reduced.   Some very large arrays with hundreds of elements only use LNAs on the output stage, but due to the number of them high output powers can be achieved.

The produced circuit board is shown with housing. Some of the internals on the metalwork have been removed and are not shown for intellectual property reasons.

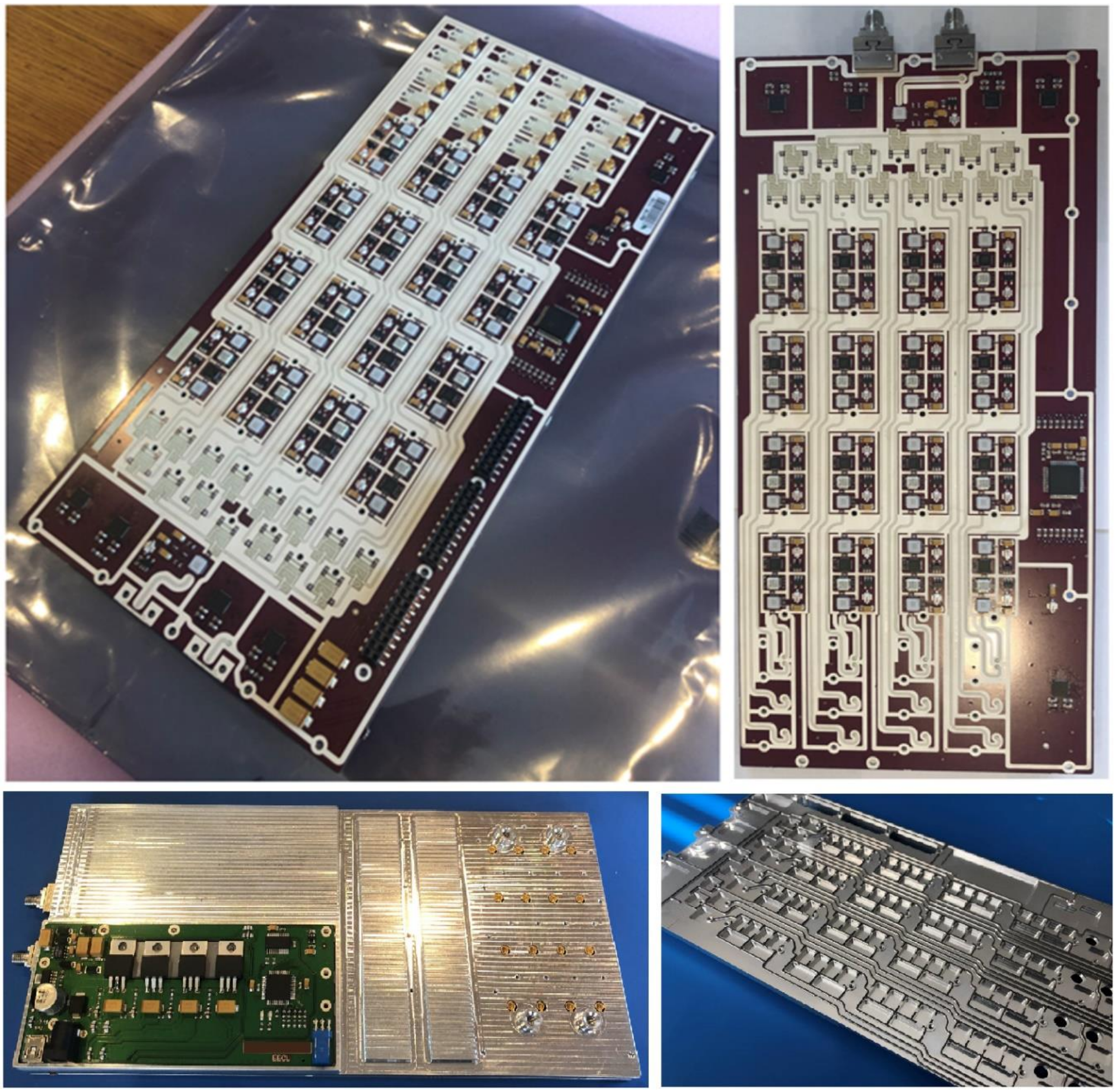

Figure 3: Produced BFN Hardware

Analog Beam Former VNA Results

The beam former module was tested on the bench as a stand-alone unit. Due to the high number of possible settings, 32 channels with power controls, each with 64 phase bits and 256 attenuation levels automated testing was used to control the BFN and sweep a VNA. Hundreds of combinations of other channels were also tested to check for any potential leakage paths in each node. The results showed what can be considered perfect beam-beam and channel-channel isolation. The wideband plot with some phase and gain steps shown is below and a typical 300MHz channel showing better than 1dB flatness over the band. A single splitter response is also shown for reference.

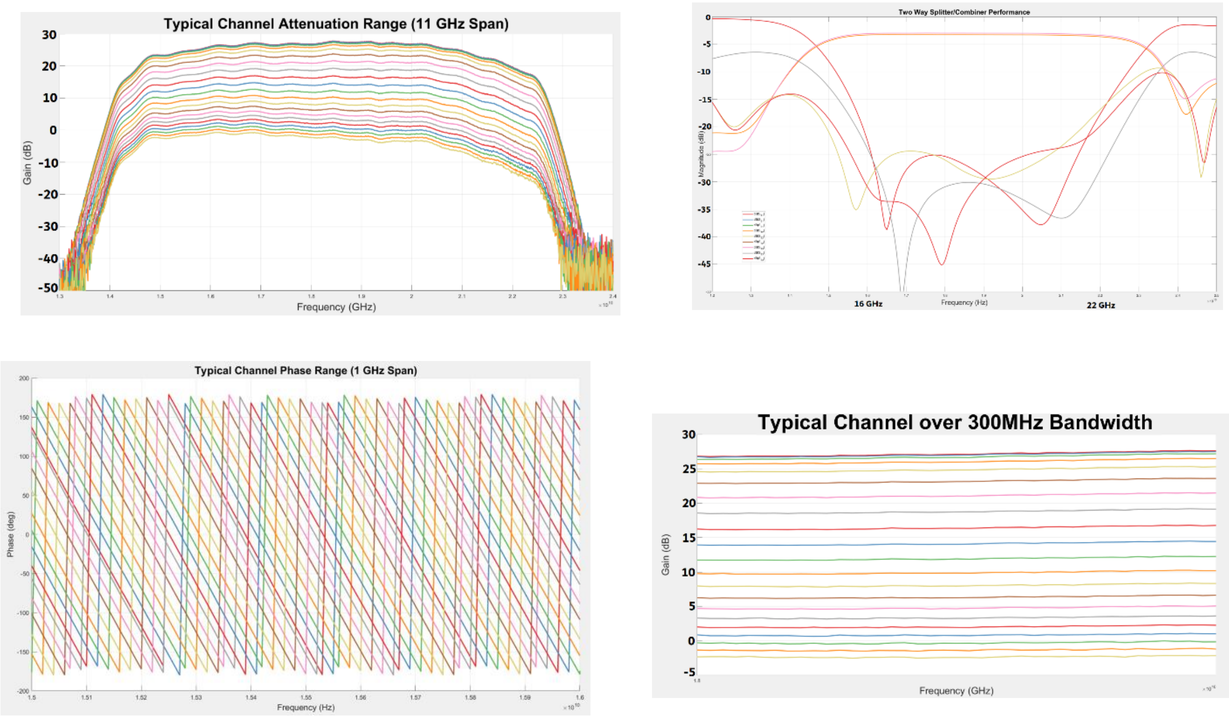

Figure 4: BFN VNA Results

Calibration and Beam Forming Method

In order to allow the beam forming hardware to take the RF input signal and produce the 16 antenna feeds precise control of the phases and amplitudes are required and imperfections in the beam former must be calibrated out. Various things in a real system impact performance: the phase shifter has a different insertion loss for each phase setting, amplifiers are never the same gain, traces between components have different phases and therefore the reflections alter the forward gain. Subtle differences in each path can add up quite a lot and then we have temperature variations to deal with. An image below shows just how much a typical phase shifter varies with phase setting. Care is required during calibration to make sure that a change gain seen during change of phase of one element is truly down to the phase and not just a change in loss through the phase chip. If this is not taken care of the main beam may form perfectly well but the subtle antenna sidelobes will not be as expected.

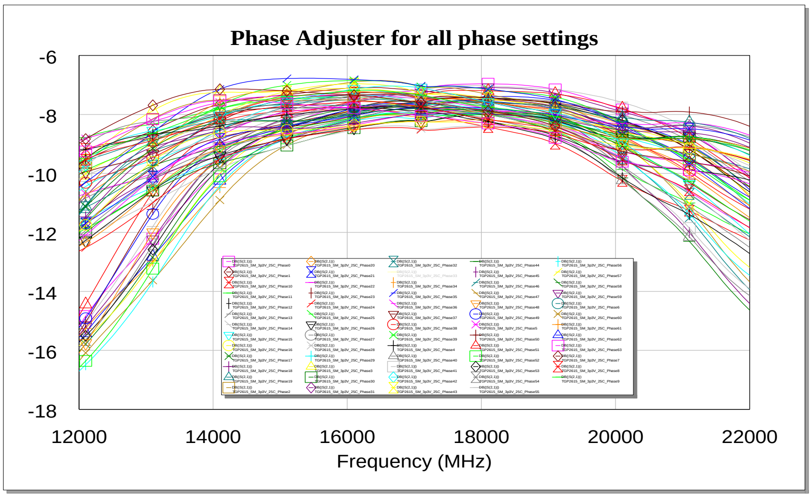

Figure 5: S21 of phase adjuster with phase setting

Methods were developed to allow this precise control to be carried out. The BFN was connected to the array panel and a reference antenna placed exactly in front. Calibration algorithms were developed using Matlab to enable accurate beam configurations to be generated for any direction. However, many things needed to be considered and the calibration needs several manipulations of data. In order to be able to calibrate the BFN properly the absolute gain from the beam input to each output must be known and controllable to the same levels regardless of antenna. Given these differences the peak gain of any one channel can therefore only be equal to the lowest peak gain of all the channels. An attenuator setting was therefore found for each possible phase setting which yielded a maximum possible gain achievable on every single antenna for every single phase setting. This process gives the maximum efficiency and highest dynamic range whilst making sure every setting can be obtained.

Secondly a calibration process is required to profile the attenuator slope from the baseline value to the highest absolute minimum value. This process gives the total system dynamic range and dictates the attenuation range possible by any beam former taper configuration.

After this is carried out a particular gain taper can be introduced to reduce the sidelobes as for example per a Dolph-Chebyshev taper. Beams were then able to be formed by pointing the BFN in the direction that the beam is required and using a third algorithm to adjust the phase states (whilst keeping antenna path gain constant) to find a maximum in the particular direction required. The found settings could then be saved. The temperature of the BFN was recorded that this configuration was valid for. After beam data has been found the data can be used to setup the BFN very quickly.

Full System Antenna Pattern Measurement

The BFN was connected up to the array panel as shown below using phase stable cables. The 3D printed antenna fits using a fixed cable system but in this cable system care needs to be taken to not disturb the phase calibration. Development of the calibration methods and techniques required a lot of time in the anechoic chamber. It may be trivial to form a beam in any particular direction but control of the sidelobes is what makes beam forming tricky. After refinement of the system calibration could be carried out in 10 minutes and need only be done once. Beams could then be formed in any direction needed within about 2 minutes. The system could then recall previous beam states and alter the system about 1000 times per second. The BFN was steady with temperature after about 20 minutes of on time. Variations in temperature were not found to alter beam shape much due to the amplifiers being quite phase stable. Changes in temperature were pretty uniform and therefore the gain across the BFN drifted in the same way for each channel.

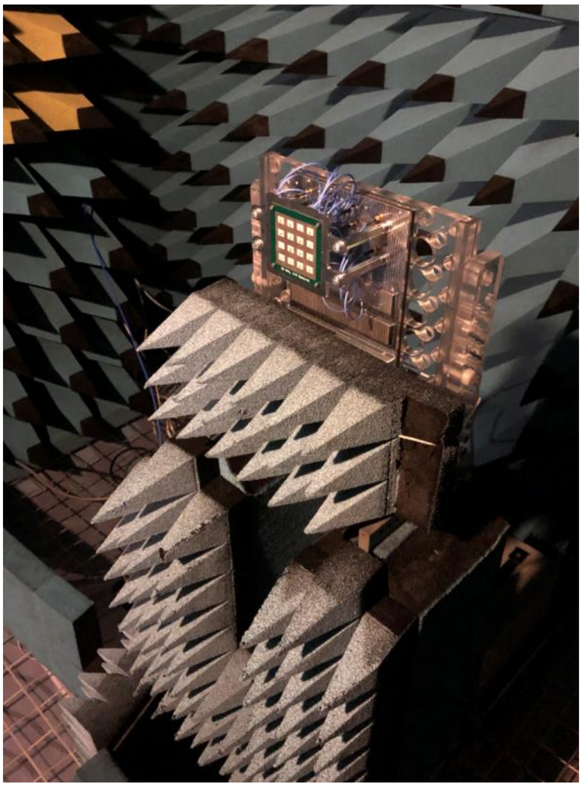

Figure 6: Anechoic Chamber Measurement of BFN

An opportunity to measure at Sheffield Universities Communications group was available using their new 3D EM scanner. The results below show patterns obtained here.

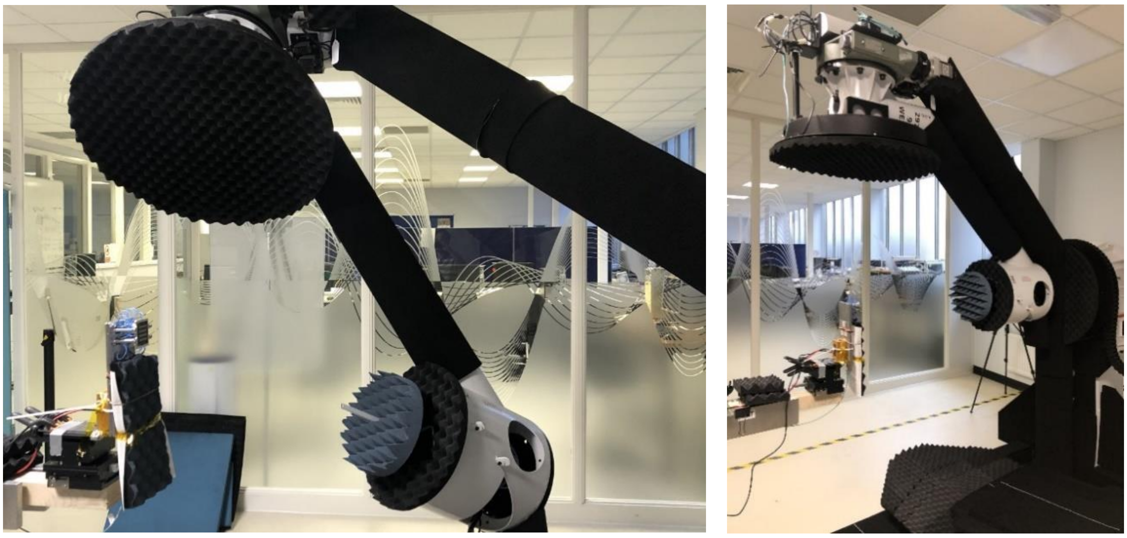

Figure 7: Sheffield Universities 3D EM Scanner – BFN Under Test

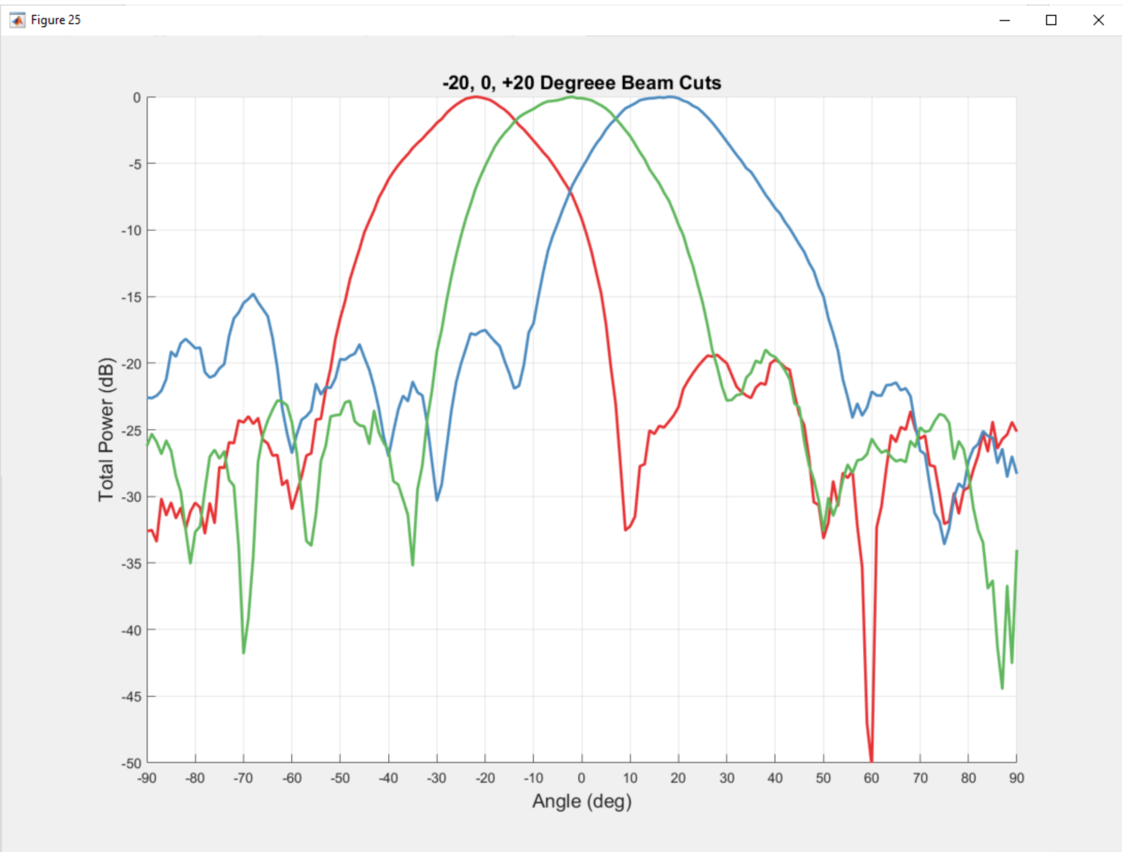

Figure 8: Horizontal Cut of -20, 0 and +20 beams

The BFN was measured for antenna pattern over frequency. This can be used to ascertain beam squint. Beam squint is where non ideal phase shifters do not shift the phase in the same way as frequency changes. Most phase shifters are not true time delay. The plot shown here is for 500MHz of band width on a patch antenna array. The array is narrow band in that the antenna pattern will have some small shift over frequency. However, it can be seen that still over the bandwidth the beam maintains its shape.

The sheffiled university system was used to measure the 3D antenna patterns for 2 configurations. Firstly a boresight 0 degree beam with 20dB dolph-chebyshev sideloboes and then a 25 degree beam of the same configuration. The results are shown below. It can be seen that in the 25 degree measurement the grating lobes can be seen ever so slightly appearing on the horizon. The antenna patterns produced are exactly what you would expect for this system and the physics/theory.

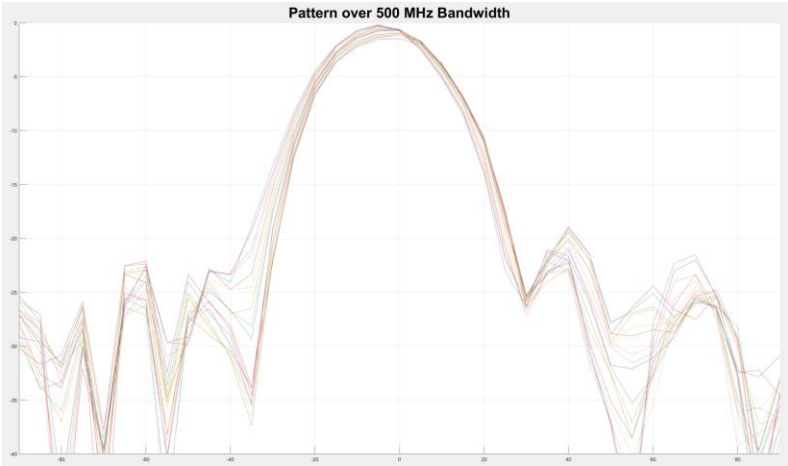

Figure 9: 0 degree beam cuts for 300MHz bandwidth around 19 GHz

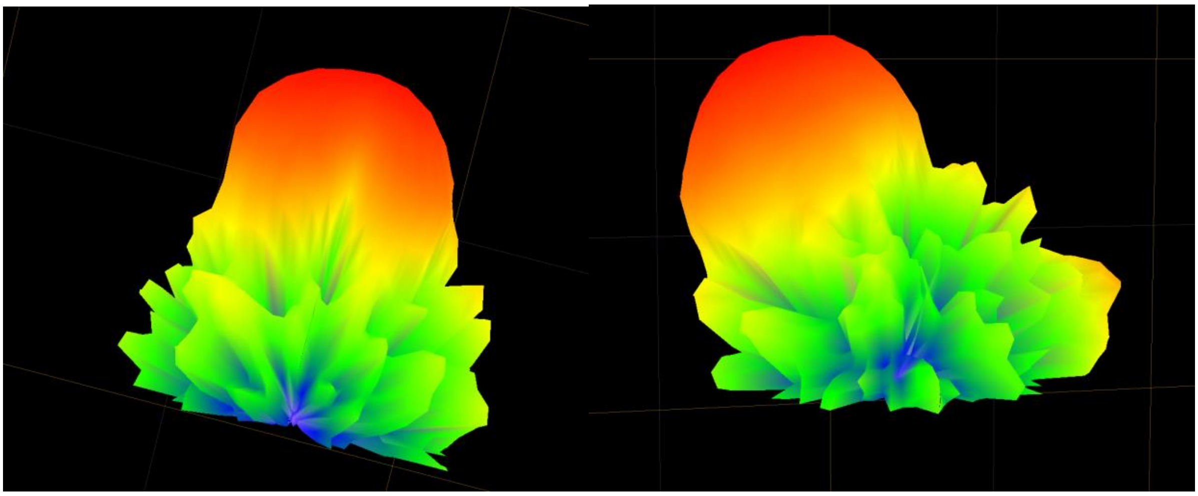

Figure 10: 3D Scans of 0 degree and 25-degree beams

Multi-Beam Tests

The EECL system can direct multiple beams at the same time. The system was configured and calibrated for simulataneous beams directed at 25 and -25 degrees. Different inputs were used from signal sources and a spectrum analyser used to sweep around the far field. It could be seen that each beem was directing its energy from the same antenna in the correct direction. For a multiple beam system to work properly the 2 beam inputs must not be locked together in frequency or phase.

Conclusions

It has been demonstrated here that a phased array system can be designed and shown to operate like an ideal network in a very small footprint. If new more integrated chipsets can be improved, then using good RF design techniques much more complex systems can be constructed and delivered in cheaper and smaller packages. Techniques for calibration have been introduced and a lot has been learnt about how to take such a system forwards towards more beams and more elements EECL is already working on a 256-antenna element system. This project was competed from concept to delivery in 4 months and in those short time scales a lot of value was delivered to the customer.