

Multi-Input Multi-Beam Beamformer For Focal Plane Array

M.Tech final year STP report Submitted By
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NCRA • TIFR

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August 2015-July 2016

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Abstract

Surveying and imaging speed of radio telescope depends on the number of beams creating the field of view and their position with respect to each other .The traditional telescope used either single dipole or horn antenna as a feed system. In focal plane array dense antenna array with large number of element used as feed system. These elements create multiple beams by collecting and manipulating entire electric field in focal plane.

FPA is provide dish with wide field of view for retrofit existing large radio telescope .we describe a prototype design for four elements of focal plane array two coherent-beam beamformer. This prototype implemented on ROACH one (reconfigurable open architecture computing hardware) board using CASPER(collaboration for astronomy signal processing and electronics research) environment.Tested it with noise source (Lab test),GMRT antennas and Focal Plane Array setup.Beam staring also done by applying complex weight.

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Chapter 1

Introduction

1.1 Introduction to GMRT

The Giant Metrewave Radio Telescope (GMRT), located near Pune in India, is the worlds largest array of radio telescopes at meter wavelengths. It is operated by the National Centre for Radio Astrophysics, a part of the Tata Institute of Fundamental Research, Mumbai. The GMRT contains 30 fully steerable telescopes, each 45 meters in diameter with the reflector made of wire rope stretched between metal struts in a parabolic configuration. This configuration works fine as the telescope operates at long wavelengths (21 cm and above)[1].



Figure 1.1: Antennas at Khodad pointed towards a source[1]

Every antenna has four different receivers mounted at the focus. Each individual receiver

assembly can rotate, enabling the user to select any of them for the observation. GMRT antennas operate in five frequency bands, centered at 153, 233, 327, 610, and 1420 MHz. Out of the 30 telescopes at GMRT, twelve telescopes are randomly arranged in the central square of 1 km by 1 km in size. Images of radio sources. Rest eighteen telescopes are arranged in three arms of a nearly “Y” shaped array each having a length of 14 km from the array center. Therefore GMRT can act as an interferometer which uses a technique known as aperture synthesis to make.

The maximum baseline in the array gives the telescope an angular resolution (the smallest angular scale that can be distinguished) of about 1 arc-second, at the frequency of neutral hydrogen provide seamless coverage from 100 MHz to 1600MHz in addition to upgrades to the mechanical and servo control systems to the antenna and an improved high speed telemetry system for controlling the antennas remotely .

This needs a major upgrade to the backend electronics, the backend upgrade are currently being developed on GPU cluster. As part of the upgrade, increase the bandwidth of the GMRT from 32 MHz to about 400 MHz and also upgraded the digital backend from GSB (GMRT software Backend) to FPGA and GPU based backend(GWB).

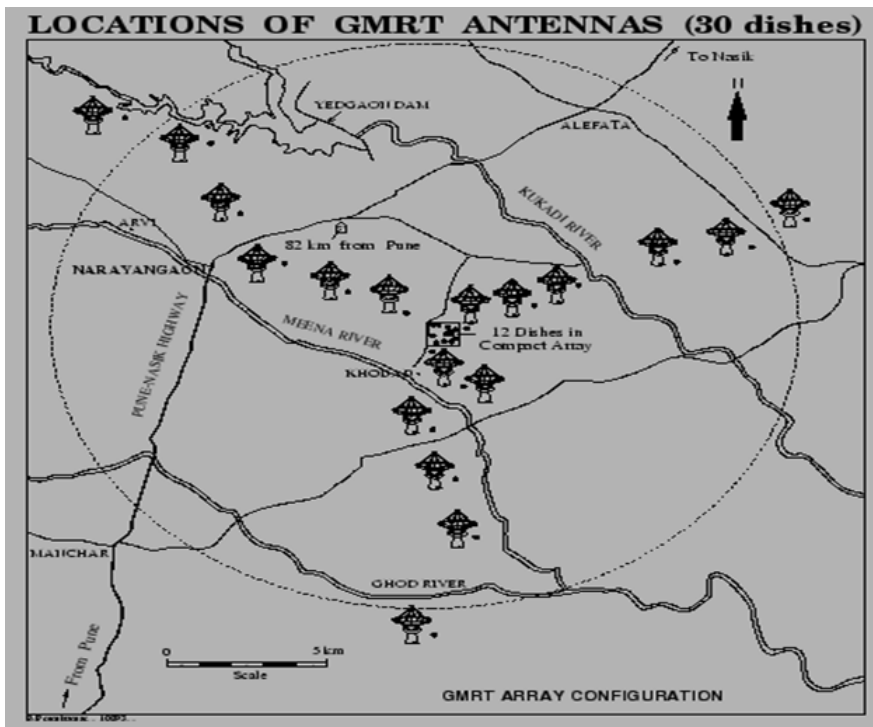


Figure 1.2: Location of 30 Antennas in a Y shaped configuration[2]

1.2 Receiver chain

Antenna feed: Signals coming from sky are in the form of EM waves, it converted in to electric form by using antenna(feed).Present GMRT system contain five frequency bands (153, 233, 327, 610, 1420 MHz) and four feeds[2].

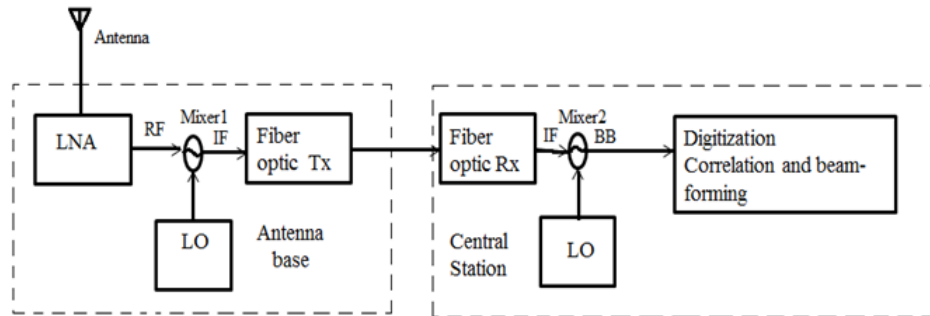


Figure 1.3: Receiver chain

LNA(low noise amplifier): Signals from sky are very weak therefor RF amplification needed.

Frequency mixer1 and 2 :RF signal converted into the IF using frequency mixer1 i.e 130MHz and 175MHz two polarizations at the base of antenna and IF frequency converted in to base band signal using frequency mixer2 at the central station, i.e present system band width is 400MHz and old system bandwidth was 32MHz.

Fiber optic transmitter: Electrical signal converted in to the optical signal and transmitted to the central building via optical link.

Fiber optic receiver: At central station again this optical signal converted in to the electrical form.

Digitization, correlation and beam-forming: Baseband signal is analog signal it converted in to digital form, geometric and instrumental delay correction perform. correlator output gives visibility information and beamformer output gives intensity of source.

1.3 Introduction to the project

The project implementing and testing multi-input multi-beam beamformer for focal plane array is part of e-GMRT backend system. It is coherent type beamformer.

Focal plane array feed is a multi-pixel feed .By replacing the single receiver element at the focus of each GMRT parabolic dish with an array of receiver elements at the focal plane of each dish, i.e. a “focal plane array” (FPA) improve the field of view of interferometer. Such an FPA is designed so that each of its elements receives signals from a different direction, and thus sees a different part of the sky. The field of view of each element would be the same as the present GMRT field of view, with a single receiver element. The total field of view of such an FPA

would be the sum of the fields of view of the individual elements as shown in fig



Figure 1.4: Difference between field of view with single receiver feed and Focal plane array feed

Propose system design is prototype of four elements single polarization two coherent beam on single FPGA based ROACH(Reconfigurable Open Architecture Computing Hardware) board. Output of ROACH is coherent sum of all element signal i.e voltage sum. Offline compute intensity . Beam steering also possible by changing the direction of the main lobe of a radiation pattern by changing the relative phases of the signals driving the elements.

1.4 Aims and Objectives

The aim of this project is to design and implement multi-input multi-beam coherent beamformer for focal plane array on single ROACH board (FPGA platform) for 4 antenna elements with single polarization and test the design with sky signal The objectives of the project are:

- 1)Design and implement the coherent beamformer for 4 antenna elements and single polarizations on FPGA platform (ROACH-board).
- 2) Write scripts for the necessary interfacings of the ROACH-board with host PC.
- 3) Simulation and implementation of design on hardware for verifying design logic.

1.5 Layout of thesis

The layout of thesis is organized as, Chapter 1 describes general introduction of GMRT ,project introduction, receiver chain , aim and objectives of proposed work. Chapter 2 includes work carried out in beamforming area at GMRT, history of focal plane array based telescopes and work going on in this field Chapter 3 describes basics concepts of antenna, Beam-forming and Focal plane array(FPA)Chapter 4 describe hardware and software used for proposed system implementation chapter 5 includes some basic simulations related to the coherent/incoherent addition and phase correction using weight multiplication Chapter 6 describes steps follow while implementing four element two beam design, implementation of four element two beam design

and weight multiplication and coherent sum subsystems Chapter 7 represent setup for experimentation .Chapter 8 shows step by step results of proposed system and analysis of it. Chapter 9 contains summary and conclusion of the thesis. It also contains future scope of the system.

Chapter 2

Literature Review

2.1 Following work has carried out in this area at GMRT

First design packet beamformer in 2011 which is an FPGA based digital design that implement the beamforming algorithm for 2 antennas for pulsar studies at GMRT. The PoBe is an add-on to the Pocket correlator (PoCo) which is 2 antenna correlator designs which has been developed a part of the GMRT upgrade. This digital design work for a bandwidth 300MHz on the single FPGA board. This project forms incoherent beam for 2 elements.[3]

The incoherent array beamformer using packetized FX correlator was design and tested in 2013. In this project, incoherent packetized beamformer was design 4 antennas on FPGA platform work with 400 MHz bandwidth. It is eight input, i.e. R and L polarization of 4 antenna incoherent packetized beamformer is implemented on multiple FPGA boards (eight FPGA base ROACH boards)[4].

The coherent phase array beamformer using packetized FX correlator was tested 2014. The sensitivity of the system is improved by factor $N^{1/2}$ (N is number of antennas). This is an four antenna single polarization design.[5] These all FPGA based system used to form single beam in the field of view.

2.2 History

Two type of antenna array have more recently come in to usage in astronomy application, including electrically dense aperture array of low gain direct view to the sky and phase array feed located at reflector focus.

Out of these two technology aperture array (AA) represent cost efficient solution for creating large collecting aperture without shaped reflector. Phase array feed technology represent hybrid solution for combines advantages of traditional reflector antennas like high gain ,low side band level with multi-beam capabilities and wider field of view of phase array.

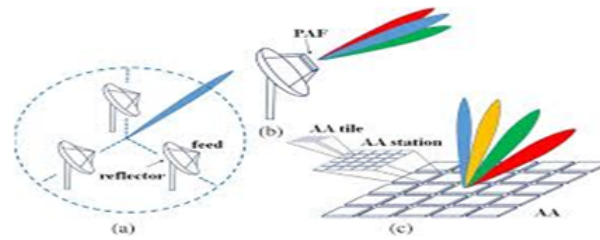


Figure 2.1: Fig7:(a) Conventional sparse aperture synthesis array, (b) phased array feed (PAF), and (c) aperture array (AA)

Many development in aperture array field been driven by the Netherlands institute of radio astronomy(ASTRON).Aperture array build by ASTON include Thousand element array (THEA),low frequency array(LOFAR). Research and development in dense PAF begin at the end of 1990 almost simultaneously united states and Europe. National radio astronomy observatory(NRAO)US team design full sampling array receiver with 19 antenna elements arrange in hexagonal grid with 0.7λ spacing between element with , operated at 1.4 GHz with an uncooled receiver .This FPA system tested with 43m reflector at Green Bank[6].

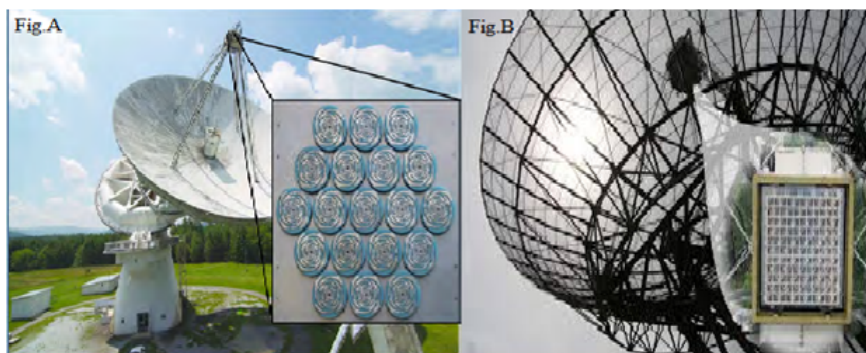


Figure 2.2: Fig 8: FPA feed images A)The first (uncooled) PAF demonstrator developed by NRAO, USA B) The APERTIF PAF installed at the Westerbork Synthesis Radio,Telescope (Westerbork, the Netherlands at ASTRON)

The Netherlands institute for radio astronomy (ASTON) design their first PAF demonstrated with European commotion project focal plane array (FPA).In 2008 ASTRO develop a prototype of first operational PAF system foe weasternbork synthesis radio telescope. Obtain initial results with fully digital beamformer. This PAF has 8×9 dual polarized Vivaldi elements operating in the band 1000-1750MHz.This prototype successfully tested at the end of 2014[2]. In Octo-

ber 5,2012 common wealth scientific and Industrial research organization (CSIRO) in Australia launched telescope with focal plane array feed on 36 12m antennas.

2.3 Present work

ASTRON (Netherlands Institute for Radio Astronomy) is working towards the Square Kilometre Array (SKA). Objective behind this project is to increase the field of view of the Westerbork Synthesis Radio Telescope (WSRT) with a factor 25. This remarkable performance gain is achieved by placing a receiver array in the focus of each parabolic dish of the WSRT, instead of the single receiver. Focal plane array as installed in 6 of 12 telescopes in 2015. In 2016 the other 6 of 12 telescopes will be equipped with an FPA.[7]

Table 2.1: Key aspects existing FPA system on radio telescopes[8]

Institute	Telescope	Reflector diameter	Frequency	Bandwidth	Steerable Beams	Nr. Beams
JBO	Lovell	70m	4-8	2	Yes	3-9
INAF	SRT	64m	4-8	2	Yes	2
CSIRO	Parks	70m	4-8	2	No	3-8(64)
ASTRON	WESA	14 x 25m	0.6-1.7	0.3	No	25-64
CSIRO	xNTD	20x15m	0.8-1.7	0.4	No	20-50

Chapter 3

Theoretical Concepts

3.1 Beamforming

Beamforming is a signal processing technique used in sensor arrays for directional signal transmission or reception. Simple beam-forming structure based on linear array, where M sensor sample the wave field spatially.

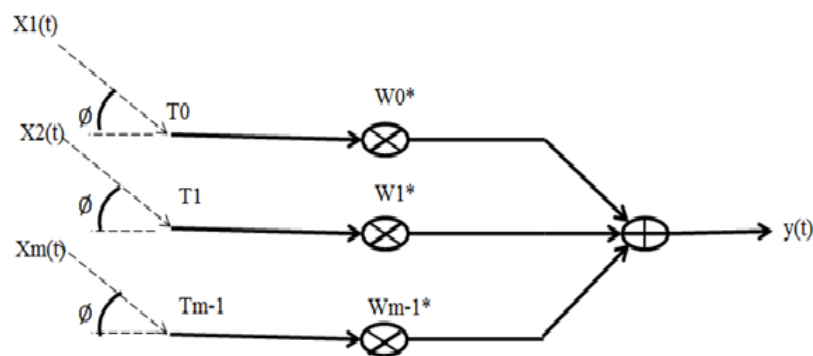


Figure 3.1: linear array beam-former

The output $y(t)$ at time t is given by an instantaneous linear combination of these sample $X_m(t)$ $m=0,1,2,\dots,M-1$

$$y(t) = \sum_{m=0}^{M-1} [X_m(t)W_m^*] \quad (3.1)$$

where $*$ complex conjugate

Proposed system multi-beam beamforming for focal plane array used narrowband beamforming. Narrowband beamforming means bandwidth of impinging signal should narrow enough to make

signal received by opposite end of the array are still correlated with each other. For example analyses the array response to an impinging complex plane wave $e^{-j\omega t}$ with an angular frequency ω and direction of arrival(DOA) angle θ . Phase at first sensor is zero and phase at Mth element is

$$X_m(t) = e^{-j\omega(t-Tm)} = W_d^H(\omega, \theta)$$

Weight vector W hold the M complex conjugate of sensor.

$$W = [w_0 w_1 w_2 \dots \dots \dots W_{M-1}]^T$$

Vector $d(\omega, \theta)$

$$d(\omega, \theta) = [1 e^{-j\omega T} \dots \dots \dots e^{-j\omega T(M-1)}]^T$$

3.1.1 Coherent and incoherent Beamforming:

This is achieved by combining elements in the array in such a way that signals at particular angles experience constructive interference while others experience destructive interference. In beamformer, the antennae signals can be added coherently or incoherently[2].

Incoherent Beamforming(IA):In incoherent beamformer, the voltage signals are firstly converted into power spectra. Then the power signals from the N dishes are combined to give the single incoherent beam. As the power spectra of the signals are added, the phase information is lost and no need of phase corrections.

- 1) \sqrt{N} improvement in sensitivity.
- 2) Beamwidth of single antenna.
- 3) Application in large scale pulsar search
- 4) The mathematical representation of the incoherent beamformer:

$$B_I = \sum_{i=1}^N V_i^2 \tag{3.2}$$

Coherent beamformer(PA): Voltage signals from the N dishes are combined to give the single coherent beam. As the voltages are added, it should be in phase with each other to get the resultant coherent signal referred as beam.

- 1) N times improvement in sensitivity.
- 2) Beamwidth becomes narrower than the single antenna by nearly 1/N times.
- 3) Application in studies individual known pulsars with its polarimetry studies.
- 4)The mathematical representation of the coherent beamformer

$$B_c = \left\{ \sum_{i=1}^N V_i \right\}^2 \tag{3.3}$$

3.2 Focal Plane Arrays :

Focal plane arrays are arrays of receivers placed at the focus of a radio-telescope. Traditional radio-telescopes have only one receiver at the focus of the telescope, but radio-telescopes are now starting to be equipped with focal plane arrays.

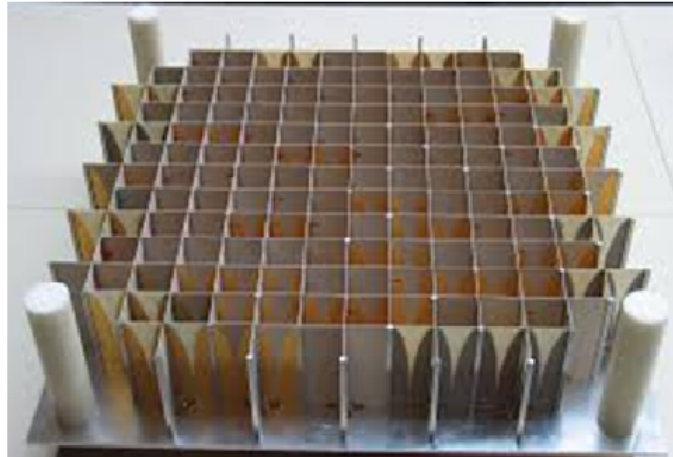


Figure 3.2: Focal plane array feed

3.2.1 Advantage of focal plane array feed over single feed:

Improved Antenna Efficiency: The maximum aperture efficiency of a reflector is achieved when the feed matches the focal plane field generated from an incoming plane wave on the reflector.

Field of View (FoV): Discrete FPAs can greatly increase the FoV of an antenna system by placing multiple beams on the sky but the FoV is not contiguous and to fully sample the sky four or more interleaved pointings are required[9]. Dense FPAs however can fill in these gaps, providing near constant and smoothly varying efficiency and sensitivity across the FoV .

Interference cancellation: The flexibility that beamforming an FPA allows nulls to be established in directions of an interference[10].

Reconfigurability: Dense FPAs lend themselves to electronic beamforming and so offer the flexibility to adapt the element weighting to changing demands and environments. the weighting can be adjusted to balance them for specific purposes. For example in a radio telescope a balance may be selected between maximizing sensitivity and pattern control or interference mitigation and pattern control.

3.2.2 Challenges:

Beamforming electronics: FPA forms multiple beams and each element of FPA required LNA. In case of digital beamformer receiver, each beam required separate receiver chain. For example we have n reflectors (feeds) and each feed contain m number of elements there for $m \times n$ LNA and receiver chain required.

Power requirements: The large number of receiver chains and processing electronics can have substantial power requirements.

Chapter 4

Hardware And Software For Experimentation

4.1 Software(CASPER)

The Center for Astronomy Signal Processing and Electronics Research (CASPER) is a global collaboration dedicated to streamlining and simplifying the design flow of radio astronomy instrumentation by promoting design reuse through the development of platform-independent, open-source hardware and software.

The CASPER tool flow is better known as the MSSGE (Matlab/Simulink/System Generator/EDK) or bee xps tool flow. It is the platform for FPGA-based CASPER development and is the interface between several design and implementation environments. Casper design environment in GMRT that is used during the course of this project use following version of different utility. Matlab R2008a or R2008b (v7.7.0)

- Simulink R2008b (v7.2)
- Xilinx System Generator v10.1.3.1386
- Xilinx EDK v11.5
- Xilinx ISE v11.5
- MSSGE libraries

The aim is to couple the real-time streaming performance of application-specific hardware with the design simplicity of general-purpose software. By providing parameterized, platform independent "gateway" libraries that run on reconfigurable, modular hardware building blocks, we abstract away low-level implementation details and allow astronomers to rapidly design and deploy new instruments. CASPER instruments use reconfigurable open-source hardware built around Xilinx FPGAs. The GMRT uses Virtex 5 SXT95 based standalone FPGA processing board also called ROACH(Reconfigurable Open Architecture Computing Hardware). The

ROACH board also has the following features.[11]

- 1) A separate PowerPC runs Linux and is used to control the board
- 2) CX4/XAUI/10GbE Networks Interfacing Cards
- 3) ADC2x1000-8: Dual 8-bit, 1000Msps (or single 8-bit 1000Msps)

Design Flow in MSSGE tool flow:

- 1) Create a Simulink model.
- 2) Compile with BEE XPS.
- 3) Program your board.
- 4) Test

4.2 Hardware(ROACH board

Reconfigurable Open Architecture Computing Hardware is a standalone FPGA processing board. It is a Virtex5-based upgrade to current CASPER hardware. The ROACH architecture can be broken down into 3 major and relatively independent subsystems. A ROACH board consists primarily of the FPGA subsystem, the PowerPC subsystem, and the monitor/management subsystem[11].

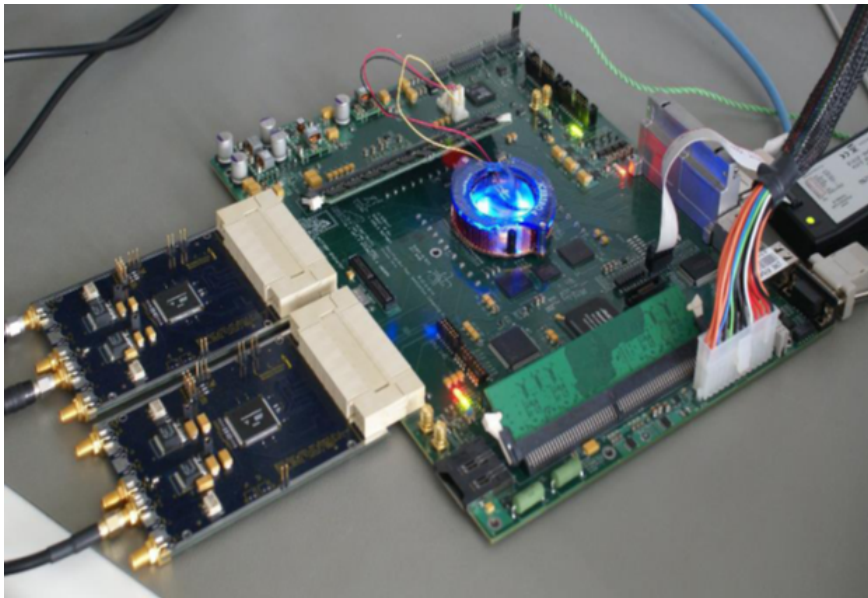


Figure 4.1: Virtex 5 ROACH board

4.2.1 Mangement Subsystem

The MonMan subsystem of the ROACH board provides remote power control and system status monitoring. It can shut down power to the board in the event of a power supply being out of range.

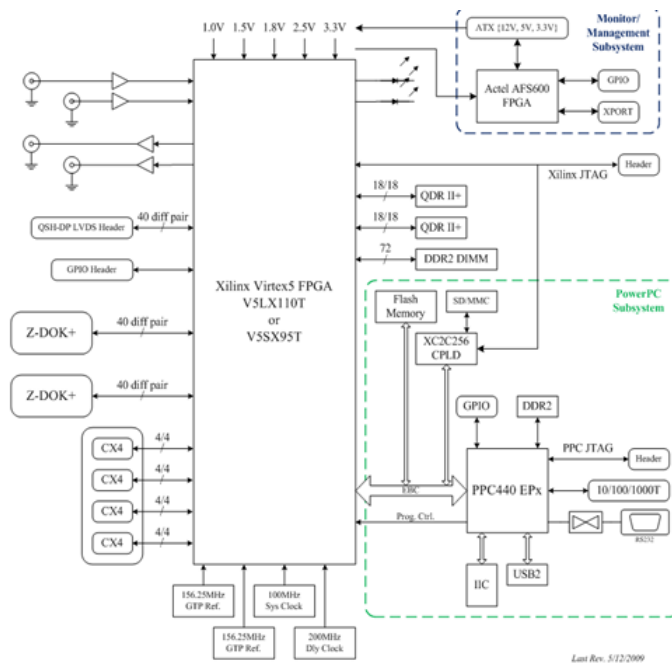


Figure 4.2: ROACH one architecture

4.2.2 PowerPC Subsystem

The PowerPC subsystem is intended to be the primary command/control mechanism for the ROACH board, along with moderate-bandwidth data I/O with the Xilinx FPGA. Its primary component is the AMCC PowerPC 440EPx embedded processor (U1). The PowerPC's functions are supported by DDR2 DRAM (J8), a Spansion 16x32M flash memory (U42), and a National DP83865 10/100/1000 Ethernet PHY (U58). An Xilinx XC2C256 CPLD (U54) acts as an interface to additional I/O capability for the PowerPC, including a MMC/SD memory card socket (J17).

4.2.3 FPGA Subsystem

ROACH is built around the primary FPGA (U15) for its signal processing capabilities. Either a Xilinx Virtex 5 XC5VLX110T or XC5VSX95T can be populated. The FPGA is connected to a number of peripherals and I/O interfaces; high-bandwidth data I/O is accessible via 2 Tyco Z- DOK+ 40-pair host connectors (P5, P7) and 4 CX4 ports for XAUI/10GbE (P3). Memory is available in both DDR2 DRAM (J15) and QDR II+ SRAM (U17, U63). DOK+ 40-pair host connectors (P5, P7) and 4 CX4 ports for XAUI/10GbE (P3). Memory is available in both DDR2 DRAM (J15) and QDR II+ SRAM (U17, U63).

Virtex-5FPGA Features:

- Input/Output Blocks (SelectIO):
 - i) Programmable single-ended or differential (LVDS) operation
 - ii) Input block with an optional single data rate (SDR) or double data rate (DDR) register
 - iii) Output block with an optional SDR or DDR register
 - iv) Bidirectional block
 - v) Dedicated I/O and regional clocking resources
 - vi) Built-in data serializer/deserializer
- Configurable Logic Blocks (CLBs): A Virtex-5 FPGA CLB resource is made up of two slices. Each slice is equivalent and contains:
 - i) Four function generators
 - ii) Four storage elements
 - iii) Arithmetic logic gates
 - iv) Large multiplexers
 - v) Fast carry look-ahead chain
 - vi) The function generators are configurable as 6-input LUTs or dual-output 5-input LUTs.
 - vii) SLICEMs in some CLBs can be configured to operate as 32-bit shift registers (or 16-bit x 2 shift registers) or as 64-bit distributed RAM.
- Block RAM: The 36 Kbit true dual-port RAM block resources are programmable from 32K x 1 to 512 x 72, in various depth and width configurations. In addition, each 36-Kbit block can also be configured to operate as two, independent 18-Kbit dual-port RAM blocks. Each port is totally synchronous and independent, offering three *read – during – write* modes.
- Global Clocking: The clock management tile (CMTs) and global-clock multiplexer buffers provide a complete solution for designing high-speed clock networks. Each CMT contains two digital clock management (DCMs) and one phase lock loop (PLL). The DCMs and PLLs can be used independently or extensively cascaded. Up to six CMT blocks are available, providing up to eighteen total clock generator elements.
- DSP48E Slices: DSP48E slice resources contain a 25 x 18 two complement multiplier and a 48-bit adder/subtractor/accumulator. Each DSP48E slice also contains extensive cascade capability to efficiently implement high-speed DSP algorithms.

Chapter 5

Simulation

Simulations for understanding basic beamforming concepts like beam steering ,coherent and incoherent addition and phase correction effect on correlator output.

5.1 Phase correction using weight multiplication

Understand the effect of phase correction on the cross correlation phase, generate two random sequences $x_1(n)$ and $x_2(n)$ which are act as an beamformer inputs then using 1024 point FFT convert this time domain signal in to the frequency domain i.e $X_1(\omega)$ and $X_2(\omega)$ which is having 512 spectral channels.

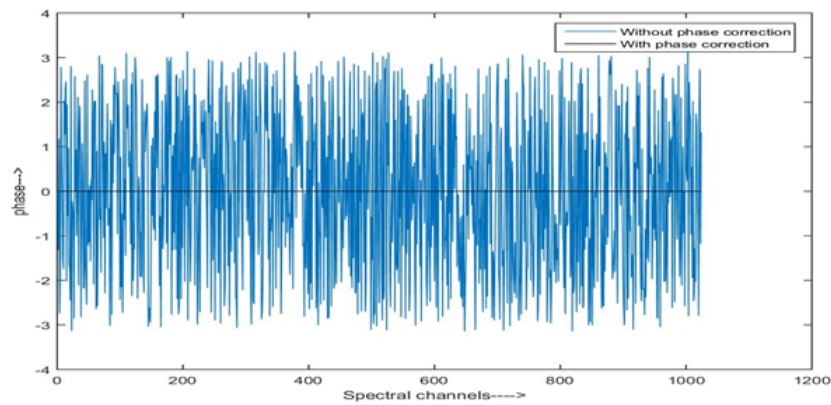


Figure 5.1: cross-correlation phase with phase correction and without phase correction

Take cross-correlation of two signals using FFT property convolution in time domain is equal to multiplication in frequency domain,

$$\text{i.e } x_1(n) * x_2(n) \leftrightarrow X_1(\omega) \cdot X_2(\omega)$$

Then record cross phases .Multiply these cross-phases to the $X1(\omega)$,it means we correct the phase for $X1(\omega)$.Observe cross- phase cancelation at the out put of correlator.

5.2 Coherent and incoherent addition

To understand difference between coherent and incoherent addition in MAT LAB we generate two sine waves with same amplitude ,one with zero phase and anther with 90 degree phase offset .First add two sine waves with same amplitude and zero phase , i.e coherent addition .Then add two signal one with zero phase and another with 90 degree phase offset ,i.e incoherent addition. Amplitude difference between coherent and incoherent addition is $1.414 \sqrt{2}$ as shown in fig.

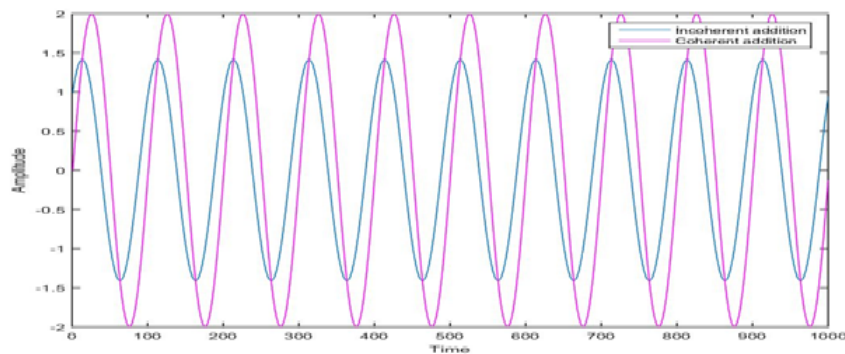


Figure 5.2: Coherent and incoherent addition of two signals

similarly for four signal addition add four signals with one amplitude and zero phase and add four signal first with zero degree phase, second 90degree phase ,third 270 degree phase and forth again with 360 degree phase. Amplitude difference between coherent and incoherent addition is $2 \sqrt{4}$

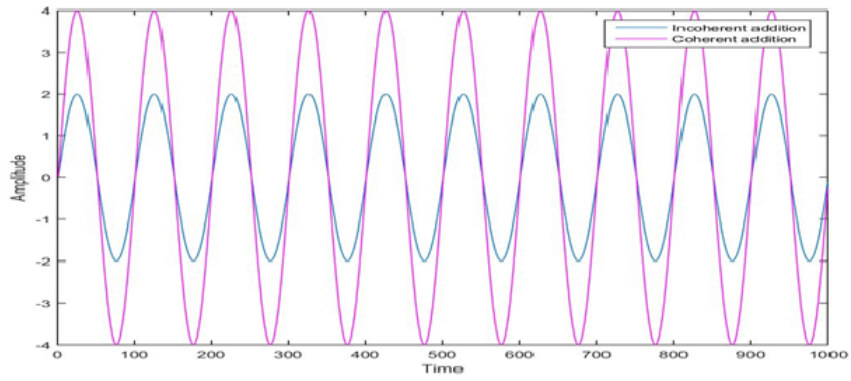


Figure 5.3: Coherent and incoherent addition of four signals

From above two examples difference between coherent and incoherent addition is \sqrt{N} , N is number of signals get added.

Chapter 6

Proposed System

6.1 Steps follow while implementing four antenna two beam design

Two beam four antenna design implemented within following three steps

Step1: single beam without phase multiplication at 1024 FFT points: In this design we remove the integration from beamforming part ,add antenna signals and send this data for post processing through 10Gb link in UDP packet format.In this design we check coherent sum and packet format.

Step2: single beam with phase multiplication at 1024 FFT points : n second step we include weight multiplication block for phase correction and beam starring purpose after FFT block, but this design cannot extended further for two beamformation design due to resource limitation.

Step3: two beam with phase multiplication at 512 FFT points:To avoid memory limitation problem we reduced number of spectral channels .

6.2 ROACH one resource estimation for four input design

In FPGA design, resources used are an important parameter to be considered. This figure below compare the four antenna single beam beamformer 256 spectral channels and four antenna two beams beamformer resources utilized in the ROACH one enviroment.

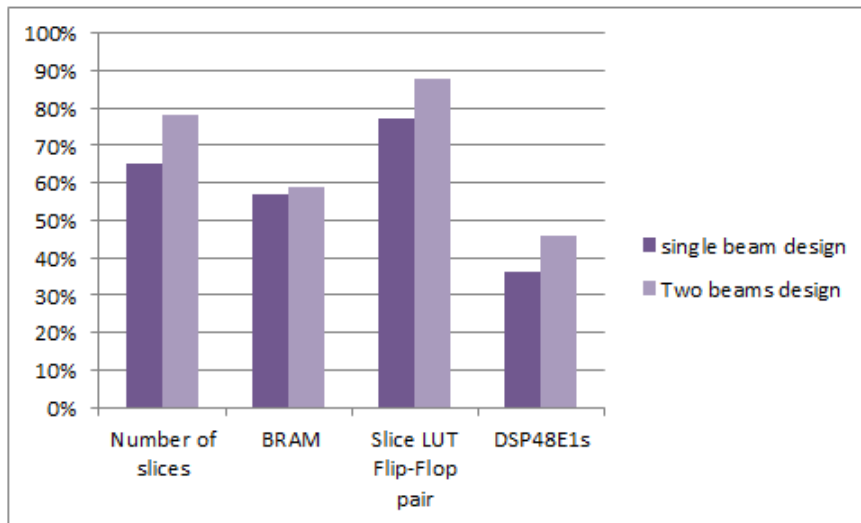


Figure 6.1: Resource estimation for ROACH one design

6.3 Four antenna two beam coherent beam-former specifications

Bandwidth:300MHz
 Number of beams:2
 FFT size =512 point
 Spectral channels:256
 Number of antennas :4
 Polarization :1
 Integration time:1.3msec

6.4 FPA beamformer design Block diagram

ADC:The ADCs interfaced to the ROACH board are ADC2x1000-8. They operate at 600MHz and give an 8 bit output through 4 channels each operating at 150MHz.

PFB: The poly phase filter bank implements a hamming window. The PFB is used to reduce spectral leakage and to increase signal to noise ratio. The data rate at the output will be 4 channels each of 18 bits at 150MHz.

FFT:The FFT block used is FFT Bipler Real 4x (real-sampled bipler FFT). This block computes the real-sampled Fast Fourier Transform using the bipler FFT algorithm to use a complex core to transform two real streams.

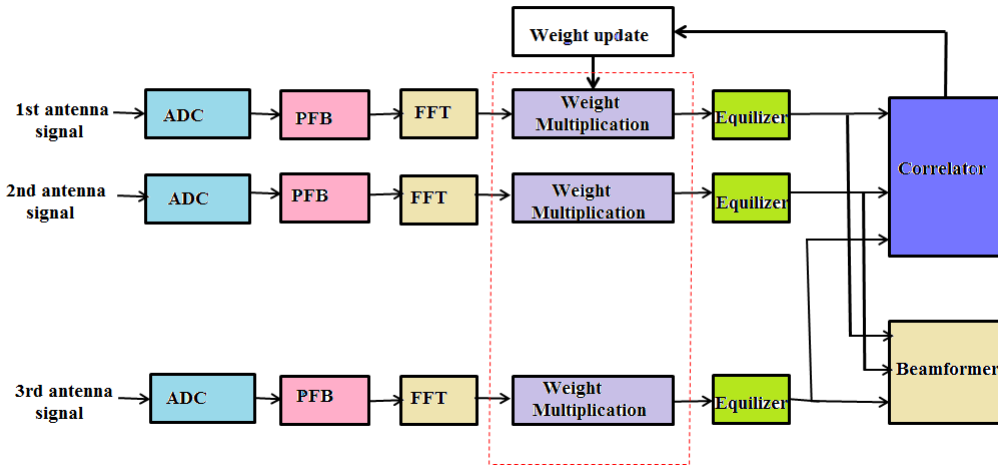


Figure 6.2: Block diagram of Multi-channels Beamforming for Focal Plane Array

The data rate of operation at FFT output is 36 bits each at 300MHz. One of the streams gives even channels while the other gives odd channels. Each channel consists of an 18 bit real part and an 18 bit imaginary part. The channel itself is 36 bits with 17 bit binary point. This can be best explained from the Figure below:

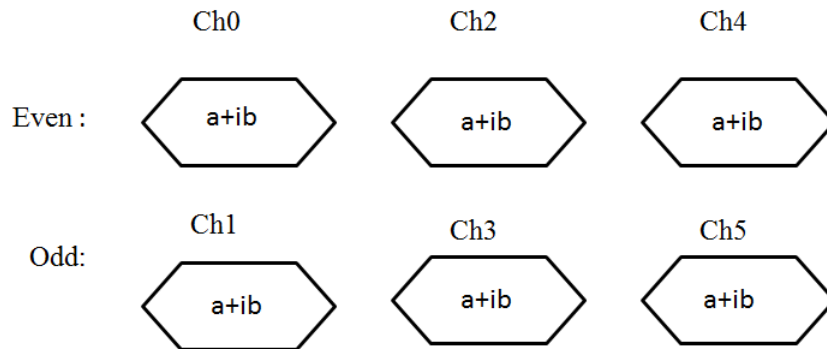


Figure 6.3: FFT Channel Output

Weight multiplication: Proposed system design form multiple beam along different direction by multiplying appropriate weight values to the antenna signals. Weights are in the form of phase, by using look up table it converted in to the complex number. Multiplication of FFT output and weights which is also complex number performs using complex multiplier.

Equalizer block: This block scale down the amplitude of incoming from the channels by a given factor to avoid the over flow during correlation and integration. The scaling factor depends on

the integration time and power level of the signal. This block casts the 36 bits input data into 8 bits data.

Correlation and Integration block: The correlator block in the design performs the product of voltages of two channels. The output of the equalizer is 8 bits. This is fed to an integrator which gives a 32 bit output. The typical integration time is in second. But it can vary in accordance of data rate and noise level. The output is all the self-correlated and cross-correlated pairs. This correlated data is transferred into shared BRAM so that host PC can read correlated data and store it on a disk for further use.

Beamforming: Coherent beam forming is the adding and squaring of voltages from two or more input signals. In this part of design ,addition of antenna signals perform. Post-processing like squaring done in software ,due to this complex addition optimum hardware resource utilization possible.

6.5 Phase multiplication subsystem

Proposed system design form multiple beam along different direction by multiplying appropriate weight values to the antenna signals.

The data is coming in two parallel FFT channels i.e. Even and odd Channel. So, two BRAMs are used to store the phase values for Even and odd respectively, whose depth is half the number of spectral channels(256).These BRAMs will store the phase values for even and odd channels separately which are written in these memory during run time and read the phase value and multiply to each channel . So for the switching this logic in two modes back and forth, a two input multiplexer used for selecting the address line and write enable signal is select control for this multiplexer. When write enable is high, the address line that drives both BRAMs is coming from external peripheral (python script running on host PC) and both the BRAMs are in writing mode. Now we start giving data to BRAM and incrementing the address values accordingly. When writing is over, write enable goes down and mux will switch the address lines.

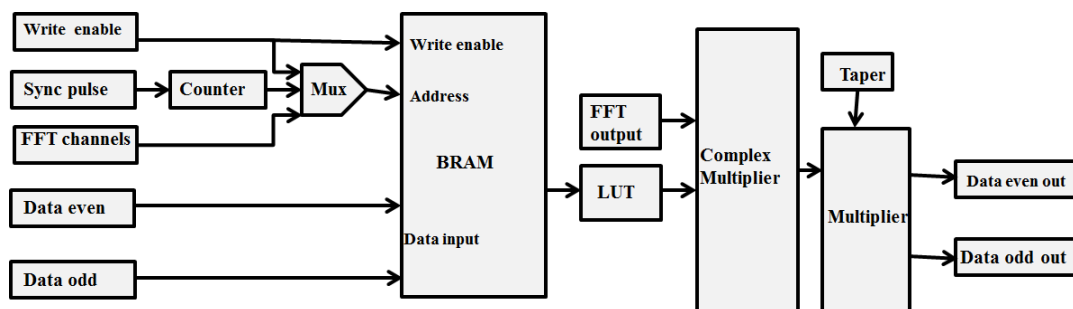


Figure 6.4: BRAM Block overview

Now the address is coming from a counter of bits=FFT channel/2. This counter runs syn-

chronously with the whole design that means the counter output (address) is always equal to channel numbers of data values coming for phase correction.

Following are the parameters for the BRAM used :

a. sync_pulse (reset counter enabled by sync) and **fft_channel** (fft0) are used for addressing the BRAMs. They are multiplexed (Mux) as shown in the figure. **fft_channel** is written through a python script.

b. write_enable enables the write modes of the BRAM and used as a select line for the addressing multiplexer.

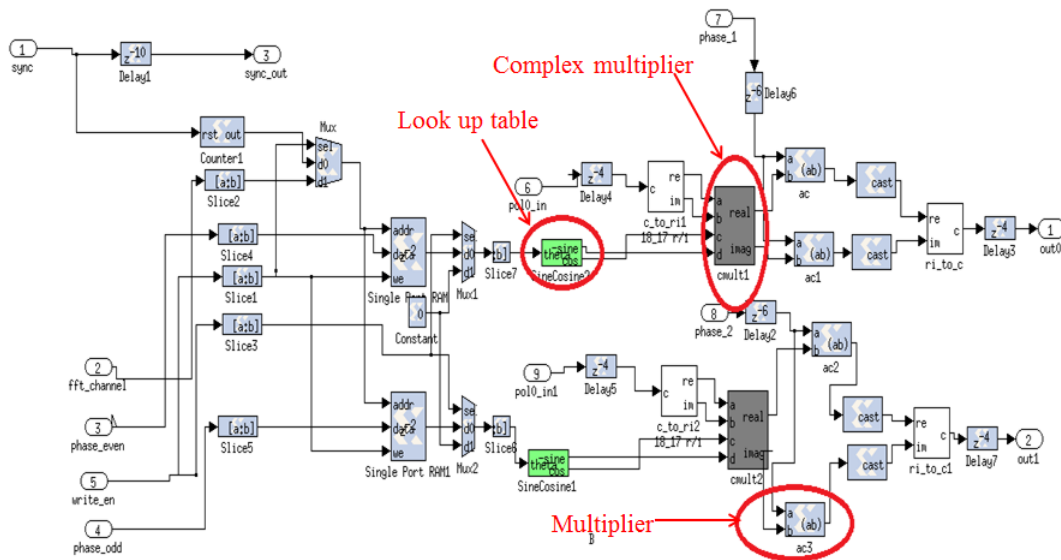


Figure 6.5: weight multiplication block snap short

c. data even and data odd are the Phase Even and Odd values respectively which are written through software registers using the python scripts.

Complex weight contain phase as well as amplitude. Output of complex multiplier is phase multiplied signal, multiplication perform using simple multiplier block as shown in figure 6.4.

6.6 Coherent sum subsystem

The Coherent Beamforming logic equals the Square of Sum of Antenna voltages. Hence, its mathematical representation is as follows:

$$(V_1 + V_2 + V_3 + V_4)$$

Where V_1, V_2, V_3 and V_4 are voltages from antenna one, two, three and four respectively. Output of coherent sum subsystem is real and imaginary part of antenna signals, for example $V_1 = (a_1 + jb_1), V_2 = (a_2 + jb_2), V_3 = (a_3 + jb_3)$ and $V_4 = (a_4 + jb_4)$ are antenna signals.

Real part of coherent sum = $(a_1 + a_2 + a_3 + a_4)$

Imaginary part of coherent sum = $(b_1 + b_2 + b_3 + b_4)$

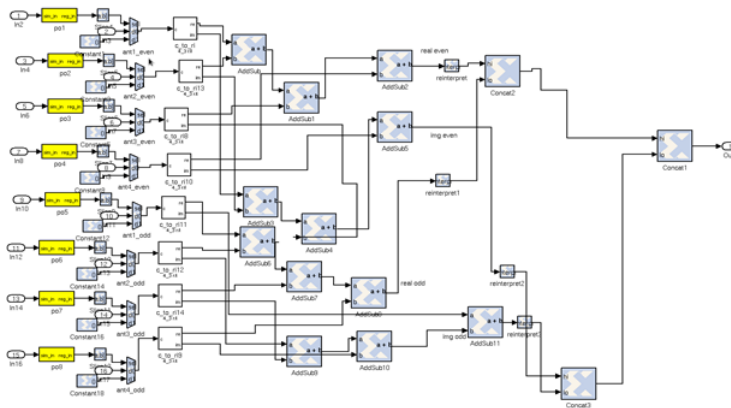


Figure 6.6: Coherent sum snap short

end complex addition of voltages via 10Gb link to the host PC. Post-processing like squaring done in software, due to this complex addition optimum hardware resource utilization possible.

6.7 UDP packet format design and 10Gb packetization

The packetised design for the 10G is a fairly complex system. This section will briefly describe the design. The data is concatenated before packetisation in the form of real and imaginary part of 16 bits each and a other 32 bits padded with zero resulting in 64 bit entity.

The main block responsible for packaging the data is the FIFO. In the most basic sense the FIFO acts as a memory buffer which can read and write simultaneously. It works such that one 64 bit package is written in one clock and is read in the next immediate clock. For the two different, concatenated packages two different FIFOs are used. The 2nd FIFO is delayed by 128 clocks to increase the package depth by 128bytes. This results in the packet configuration as seen in Figure. The packet design will look as follows:

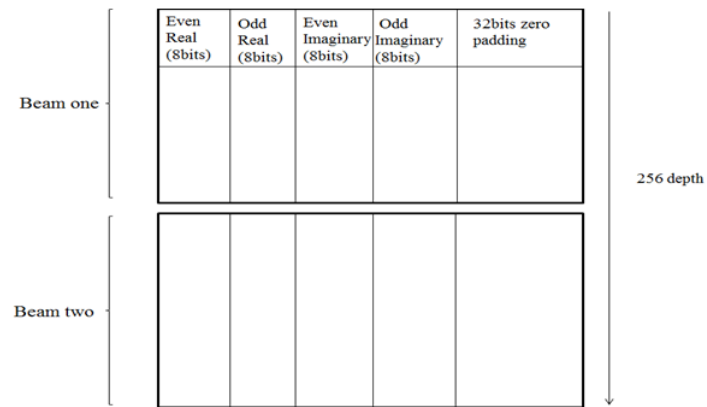


Figure 6.7: UDP Packet format

6.7.1 10Gb Packetization

The 10GbE block requires inputs as tx_data, tx_valid, eof, reset_gbe, tx_destination_ip and tx_destination_port. Out of these eof, tx_valid and tx_data are generated inside the subsystem after coherent sum. For reset_gbe, tx_destination_ip and tx_destination_port, software registers are added to the design. These software registers are configured using python script.

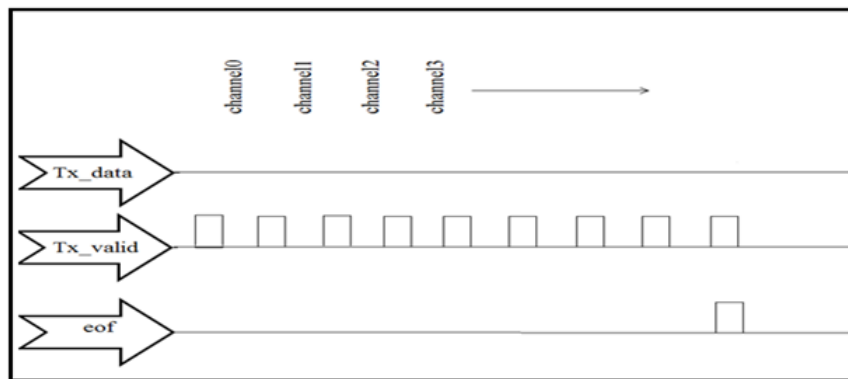


Figure 6.8: Valid signals in 10GbE

The following diagram shows the 10GbE setup within the design. The 10GbE block used is the ten_Gbe_v2 block from the BEE_XPS System Block set in the Simulink library.

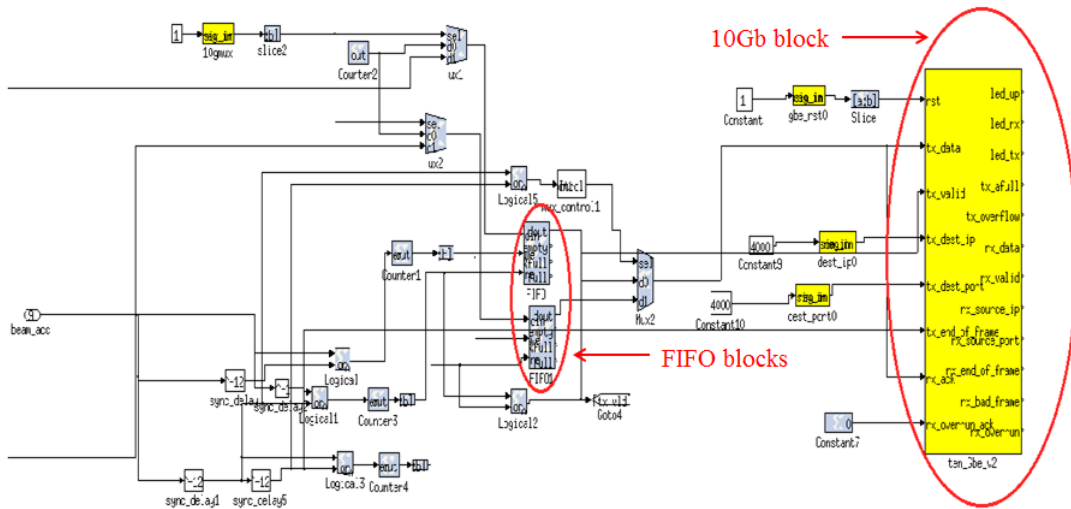


Figure 6.9: 10GbE Block in the Simulink Library

6.8 Post processing and Depacketization

6.8.1 Packet Capturing

Packet Capturing is implemented by process of capturing data from a computer network. The standard packet analyzer tool, Wireshark, has been used to verify the transfer of packets. This software gives valuable information such as rate of data transfer per packet (integration time), packet size along with various other attributes of the packet as it passes along the network. However, the actual utility for packet capture is GULP. This is an open source software which can read directly from the network interface and write to disk . The packet capturing capability of GULP is dependent on the data rate.

6.8.2 Depacketization

Depacketisation is the process of de-segmenting the packet in order to make it compatible for further processing. This is done by basic ‘C’ programming. A packet of size 2048 bytes, is split into 2 packets of size 1024 bytes each. The data packet is separated to get Real and Imaginary Values. At the output of depacketization get real and imaginary files for each beam.

6.8.3 Post Processing

In post processing, the data received from beamformer i.e. four text files real_beam1.txt , img_beam1.txt , Real_beam2 and img_beam2.txt. these file contain coherent sum of antenna signals($V_1 + V_2 + V_3 + V_4$) ,we obtain intensity from coherent sum by squaring this coherent sum output ,i.e $(V_1 + V_2 + V_3 + V_4)^2$.

$V_1 = a_1 + jb_1$, $V_2 = a_2 + jb_2$, $V_3 = a_3 + jb_3$ and $V_4 = a_4 + jb_4$ these are signals from antenna one, two ,three and four respectively .Then coherent sum of this antenna signal is complex number which contain real part $(a_1 + a_2 + a_3 + a_4)$ and imaginary part $(b_1 + b_2 + b_3 + b_4)$.after squaring real and imaginary part compute intensity.

Chapter 7

Experimental Setup

7.1 Lab Test setup

System level design of the setup:

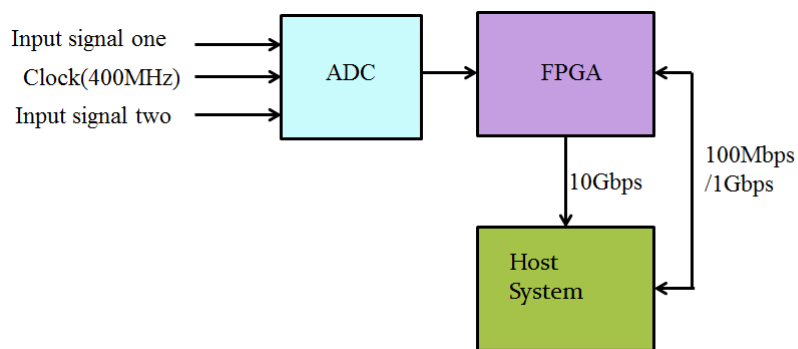


Figure 7.1: Experimental Setup

- From the figure the following details must be noted:
- The power input levels from the analog back-end or baseband systems are typically -12 to -14 dBm
- The ADC clock frequency runs at 400 MHz
- 100Mbps/1Gbps Ethernet cable is used to communicate with the PowerPC
- 10Gpbs link is used for high speed data transfer (faster integration)

7.2 FPA setup

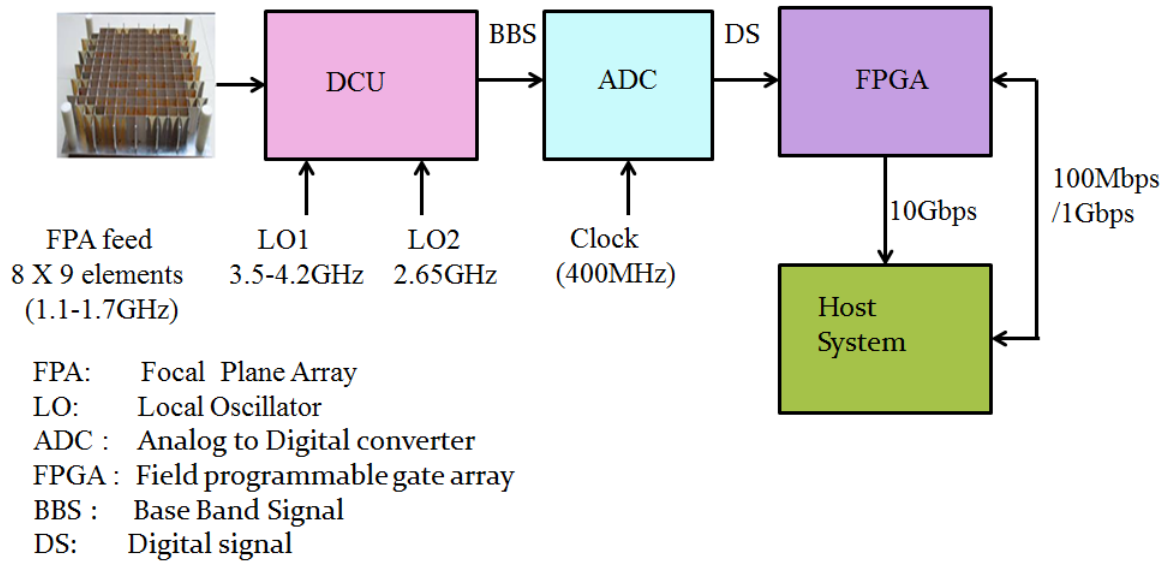


Figure 7.2: FPA test setup

From the figure the following details must be noted:

8 × 9 focal plane array feed operated at 1.1 to 1.7GHz

DCU convert RF signal in to base band signal(0-240MHz)

The ADC clock frequency runs at 400 MHz

100Mbps/1Gbps Ethernet cable is used to communicate with the PowerPC

10Gbps link is used for high speed data transfer (faster integration)

Steps: 1) Radiate -10dBm tone signal at 1.1GHz

2) measure power at the input of DCU i.e -69dBm

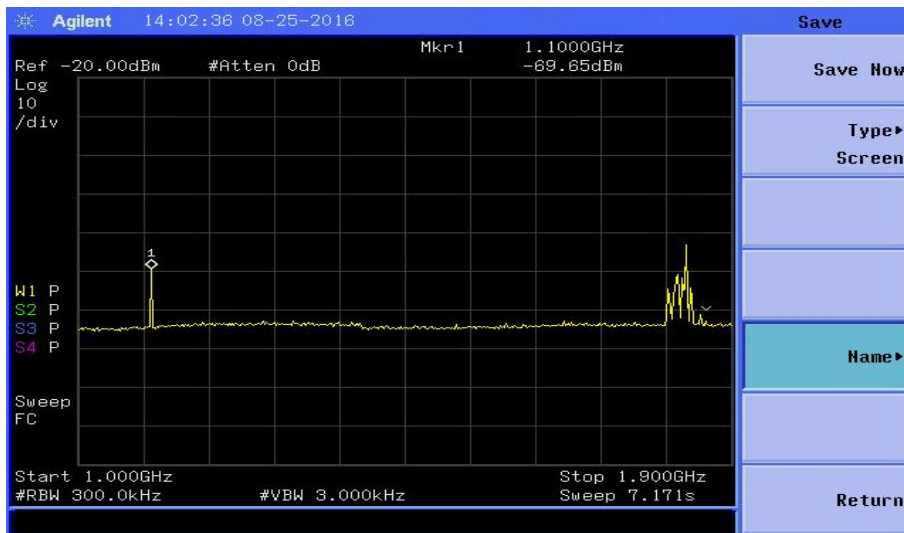


Figure 7.3: DCU input at 1.1GHz

- 3)set local oscillator
LO1=3.6GHz at 17dBm
LO2=2.65GHz at 17dBm
- 4)Mesure output power of DCU at 150MHz,i.e

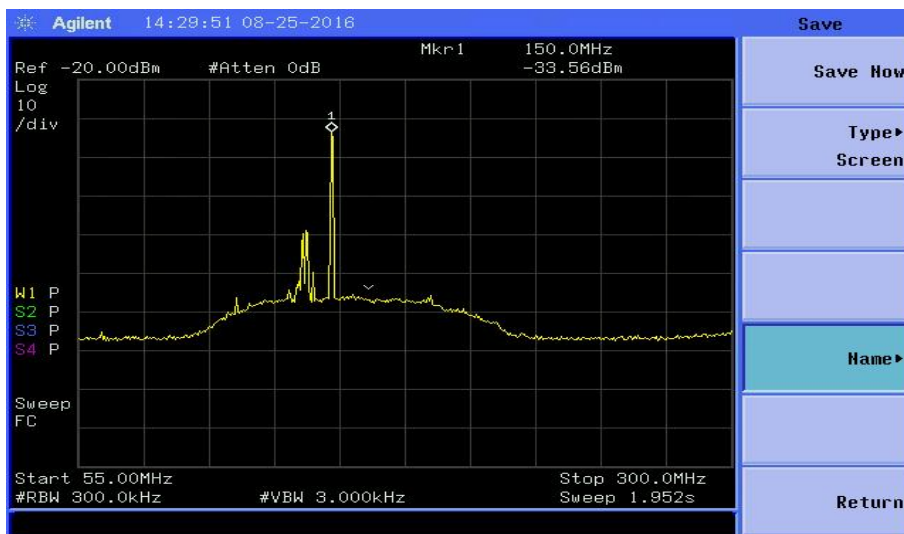


Figure 7.4: DCU output at 150MHz

- 5)Apply this DCU output signal(Base Band signal)to the FPGA based beamformer

Chapter 8

Results And Analysis

Four antenna two beam coherent beamformer design first tested in lab by using noise source output and sine wave as an input. Further tested with GMRT antenna signals(single antenna two polarization) and FPA setup.Data obtain from beamformer analyzed using MATLAB code.

8.1 Lab Test

8.1.1 Case1:Check phase multiplication part by applying sine wave one in phase and another out of phase

Description:Apply sine wave of 100MHz -17dBm power level as an input .First signal multiplied with zero phase and another with 180 degree phase using python script. Record beam data(nearly 100 UDP packets).Beamformer output contain beam one data and beam two data.

Result

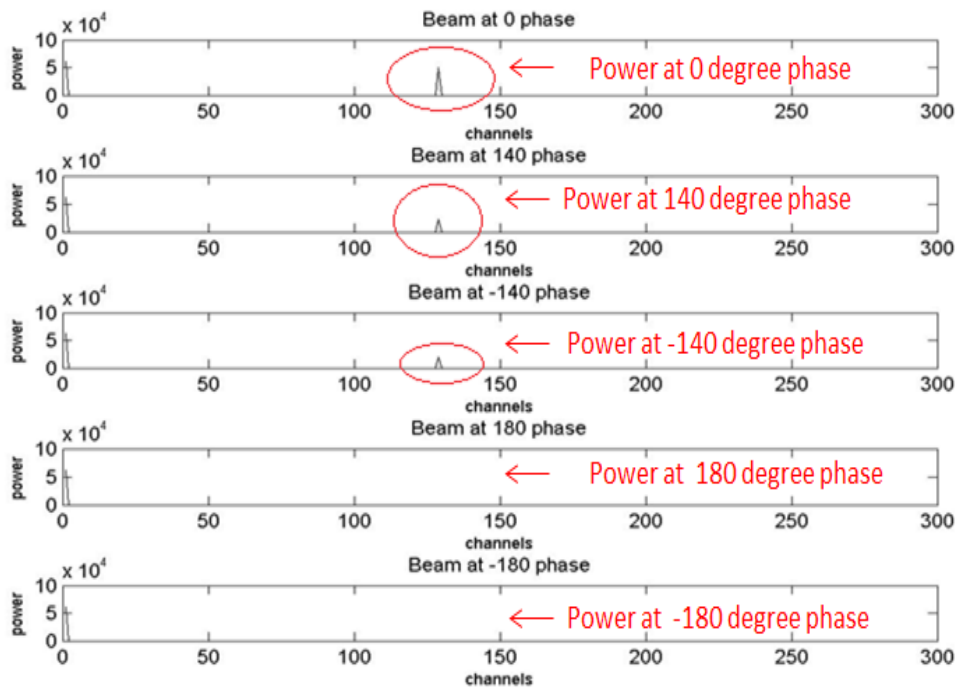


Figure 8.1: Sine wave lab test beam-former output at 0,140,-140,180 and -180 degree phases

Analysis: Beam one and two contain coherent sum real and imaginary part. Beam data is coherent sum of in phase and outoff phase sine wave. Therefore wave cancelation observe in beam .

8.1.2 Case2: Analyze the effect of different phases on the beamformer output

Description: Apply sine wave at 100MHz -17dBm power level as an input. First one input signal multiply with different phases, phase shift in steps of 10 degree and it varies from -180 to 180 degree at each stage record beam data.

Result:

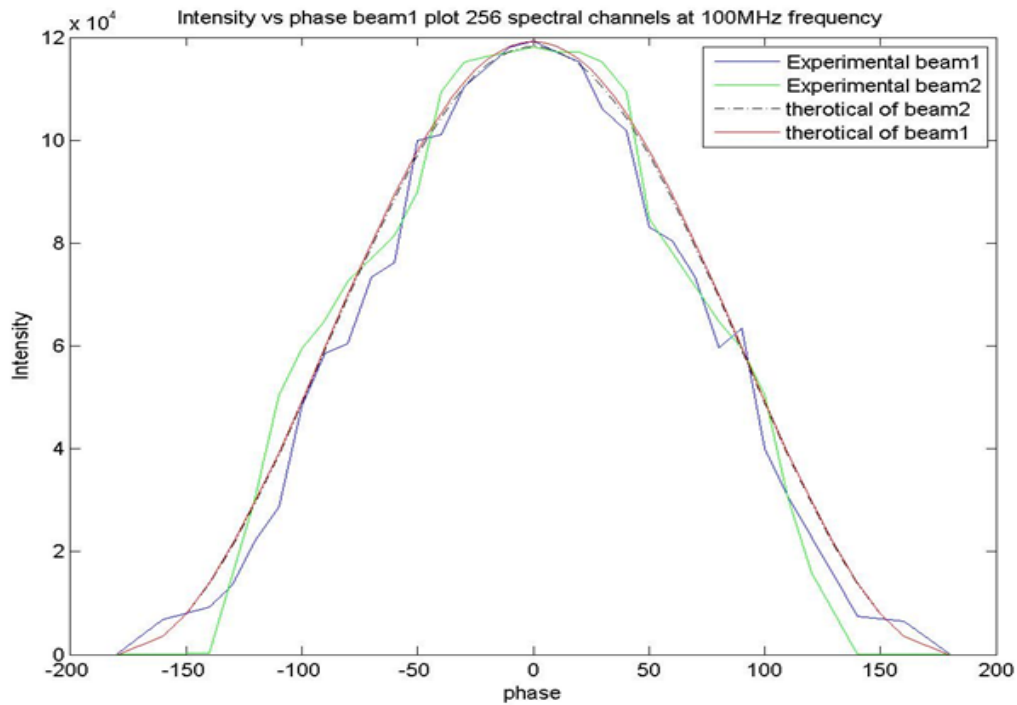


Figure 8.2: Sine wave lab test beam-former output intensity vs phase plot

Analysis: Analyze the effect of phase on intensity. Plot intensity at every phase. At phase -180 and 180 degree observe zero power because addition of two sine waves which are out of phase from each other. At zero two sine waves add in phase therefore get maximum amplitude.

8.1.3 Case3: Analyze effect of phase multiplication on correlator output

Description: Used noise source as an input to the design. Apply zero phase to the both inputs. Then record correlator data. Then apply -120, 120, 180 and -180 degree phases to the one input and kept other input zero. Record correlator data at every step and plot it.

Results:

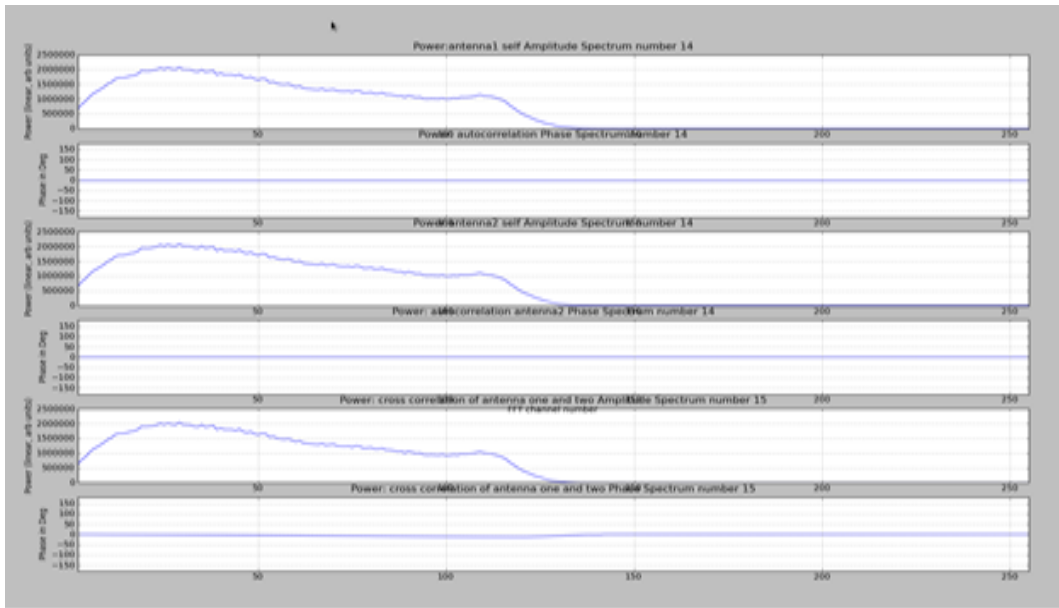


Figure 8.3: Noise source lab test correlator output with both inputs zero degree phase

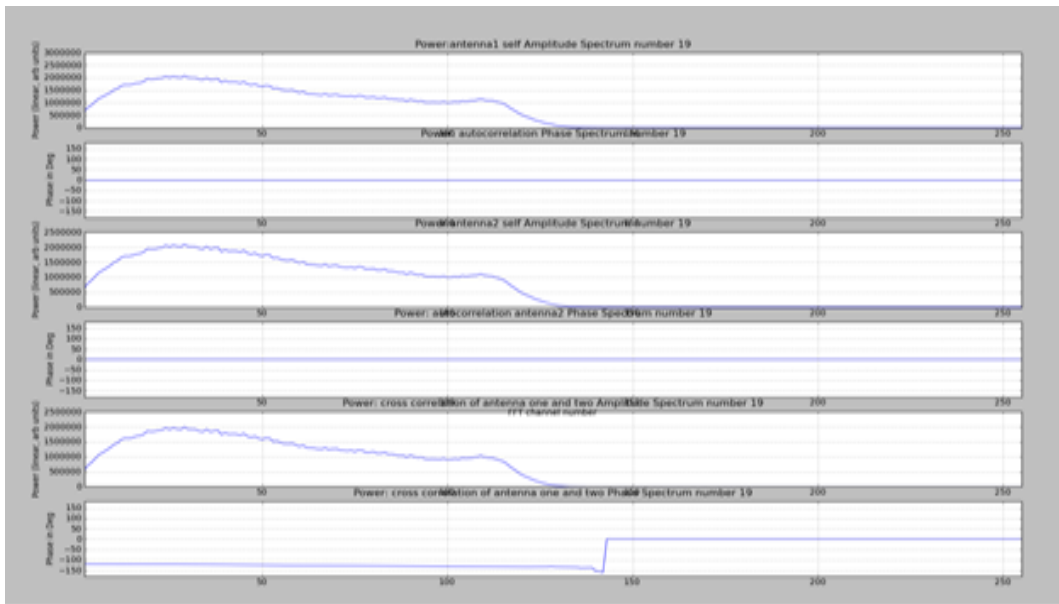


Figure 8.4: Noise source lab test correlator output one input at zero degree phase and another at -120 degree phase

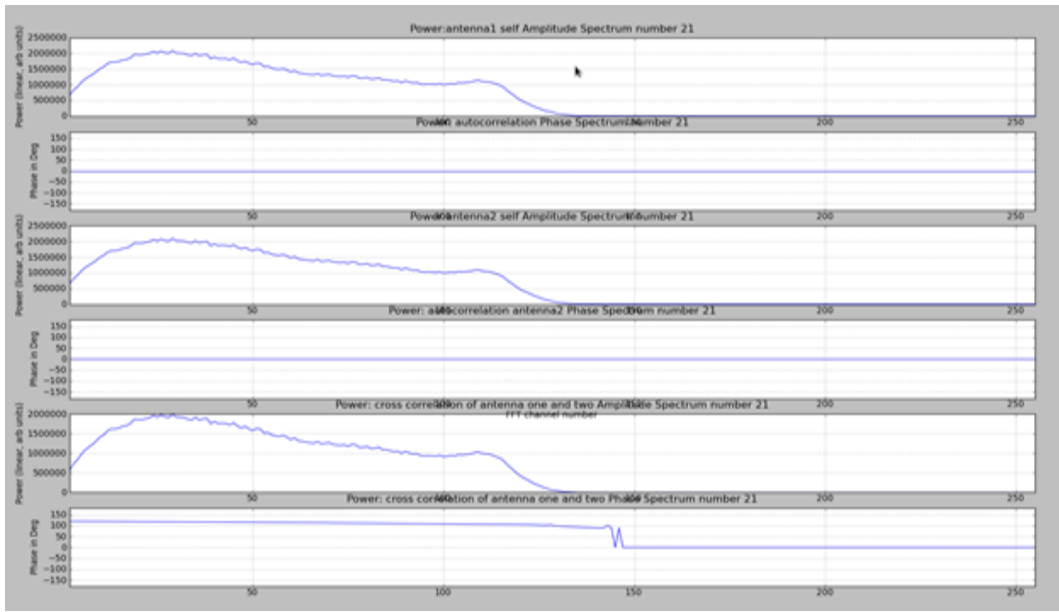


Figure 8.5: Noise source lab test correlator output one input at zero degree phase and another at 120 degree phase

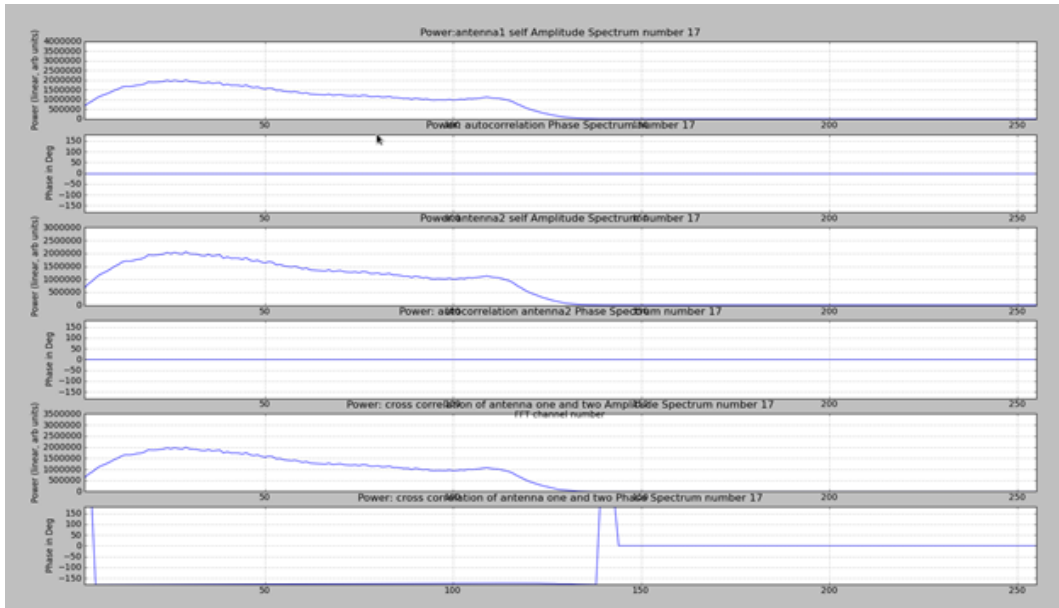


Figure 8.6: Noise source lab test correlator output one input at zero degree phase and another at -180 degree phase

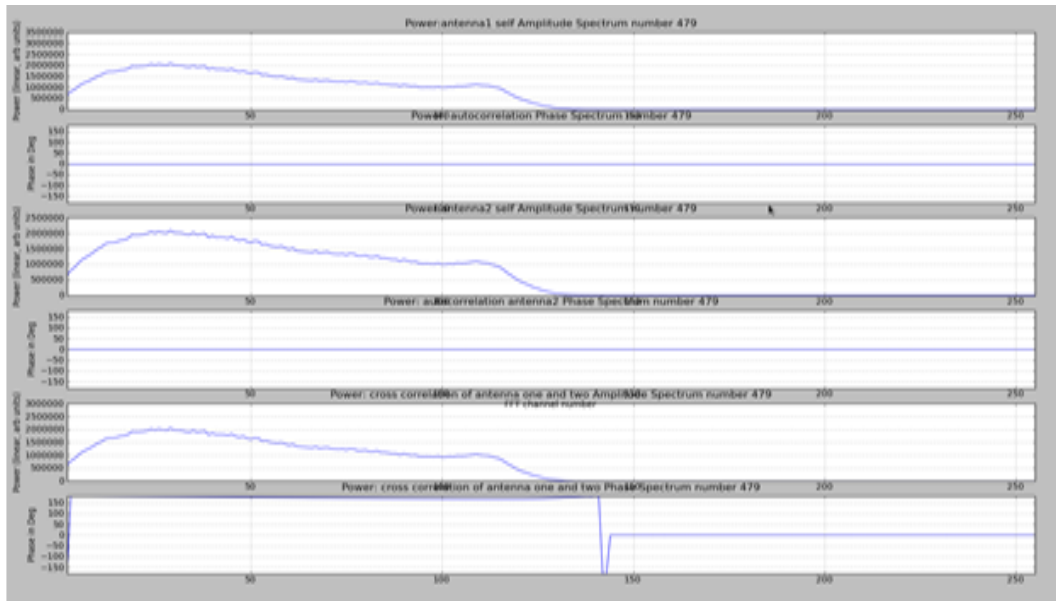


Figure 8.7: Noise source lab test correlator output one input at zero degree phase and another at 180 degree phase

Analysis: Observe cross correlation phase variation with input signal phase multiplication.

8.1.4 Case4: Check coherent sum block correlated noise as an input with different number of antennas

Description: Apply four digital copy of noise source as an input to the design. Before coherent sum using antenna selection logic select number of antennas one to four and record beam data at every step.

Results:

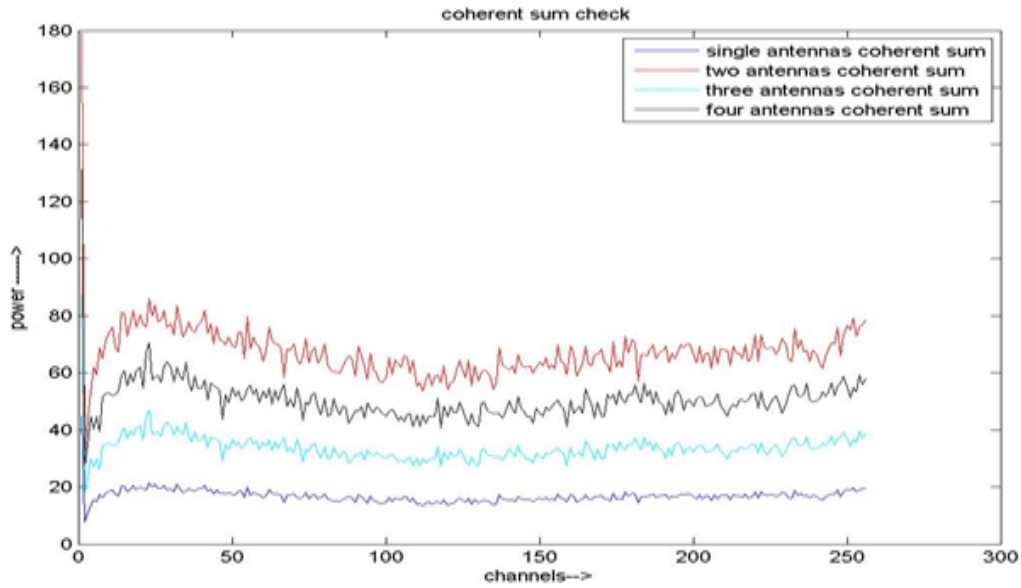


Figure 8.8: Noise source lab test beam output with different number of antennas

Analysis: Coherent sum of four antenna signals is four times than single noise signal. It means coherent sum block is working.

8.2 GMRT antenna test

8.2.1 Case1: Analyze the effect of phase correction of antenna signal on correlator output

Description: Apply single input two polarization signals to the design because focal plane array element place very close to each other therefore delay correction part not included in design. Record cross correlation phase value and apply these phase as a weight to the antenna. Record correlator data after and before phase correction.

Results:

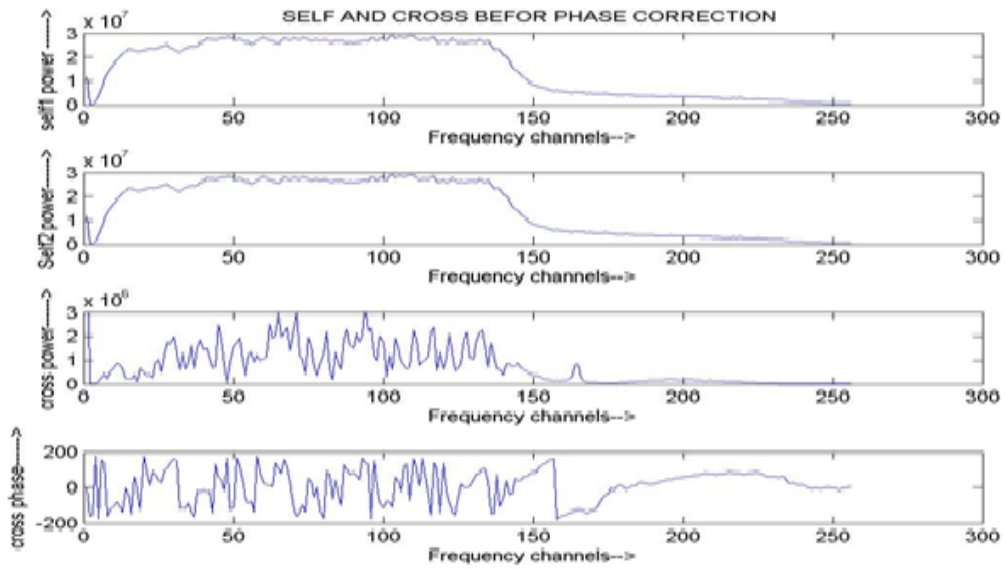


Figure 8.9: Antenna test source 3C48 correlator output without phase correction

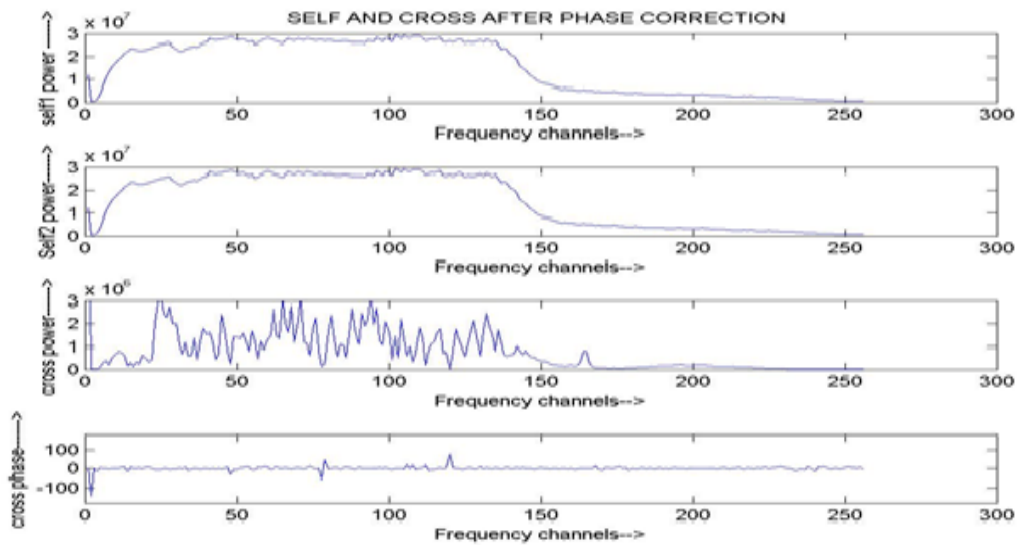


Figure 8.10: Antenna test source 3C48 correlator output with phase correction

Analysis: After phase correction or weight multiplication cross correlation phase become zero.

8.2.2 Case2: Analyze the effect of phase correction on beamformer output

Description: Apply single input two polarization signals to the design because focal plane array element place very close to each other therefore delay correction part not included in design record cross correlation phase value and apply these phase as a weight to the antenna. Record beamformer data after and before phase correction.

Result:

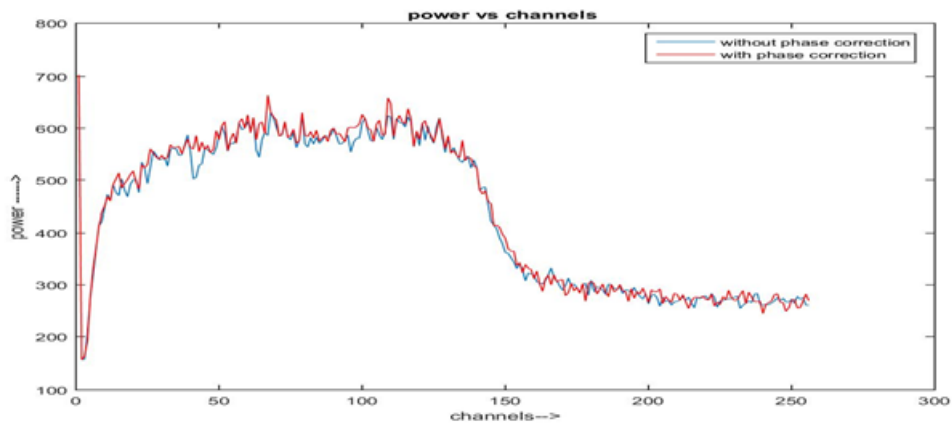


Figure 8.11: Antenna test source 3C48 beam-former output

Analysis: After phase correction observed little bit improvement in power because after phase correction this beamformer work as a coherent beamformer.

8.2.3 Case3: Analyze effect of phase correction on intensity by elevation scan

Description: Apply single antenna two polarization as an input. Select strong source like CASE. Measure on source power and equalize it. record beam data five degree before and after on source with 30 arc min/min speed. point antenna on source correct phases again record elevation scan beam data 5degree before and after on source with 30 arc min/min speed.

Result:

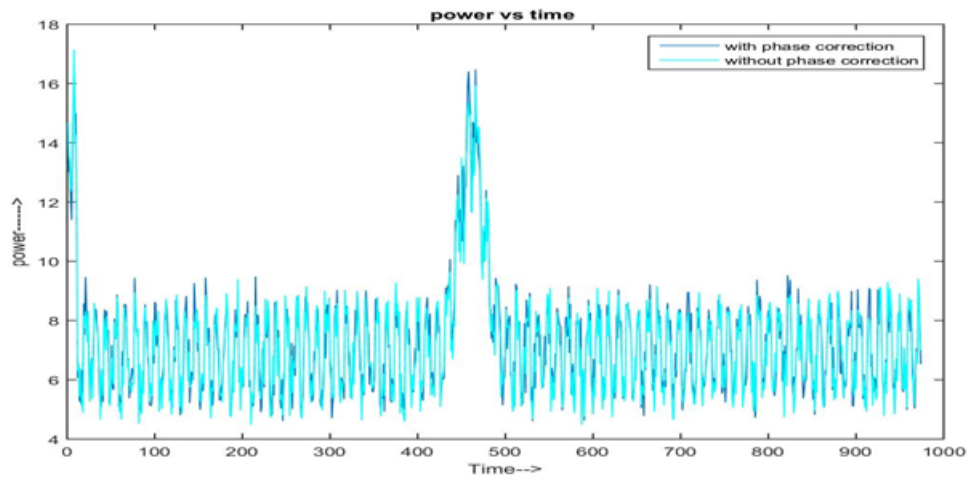


Figure 8.12: Antenna test source CASA elevation scan with 30arcmin/min 10degree correlator beamformer output

Analysis:After phase correction observe little bit improvement in power.

8.3 FPA test

8.3.1 Case1:Check phase multiplication part by applying sine wave one in phase and another out off phase

Result:

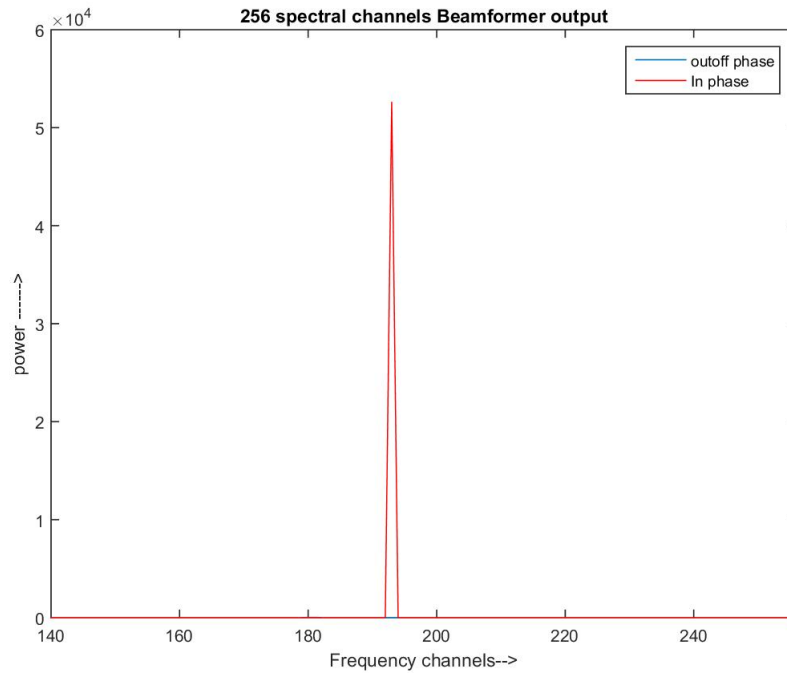


Figure 8.13: Sine wave radiation test beamformer output

8.3.2 Case2: Analyze effect of phase multiplication on correlator output by radiation test

Description: Radiate tone signal at 1.1GHz at -10dBm power level by omnidirectional antenna. Captured this signal using 8x9 Focal Plane Array field and using down conversion unit (DCU) converted this RF signal into base band signal at 150MHz. Apply this tone signal to FPGA setup. Record cross correlation phase value and apply these phase as a weight to the antenna. Record correlator data after and before phase correction.

Result:

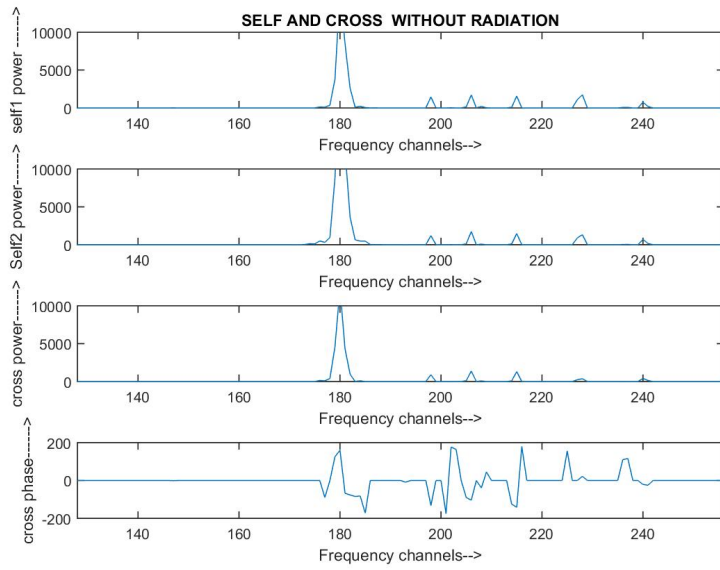


Figure 8.14: FPA test correlator output without radiation

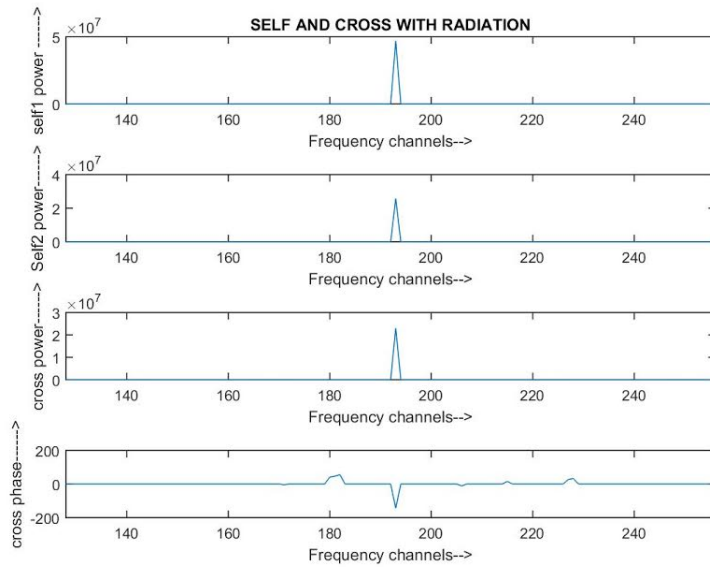


Figure 8.15: FPA setup radiation test correlator output without phase correction

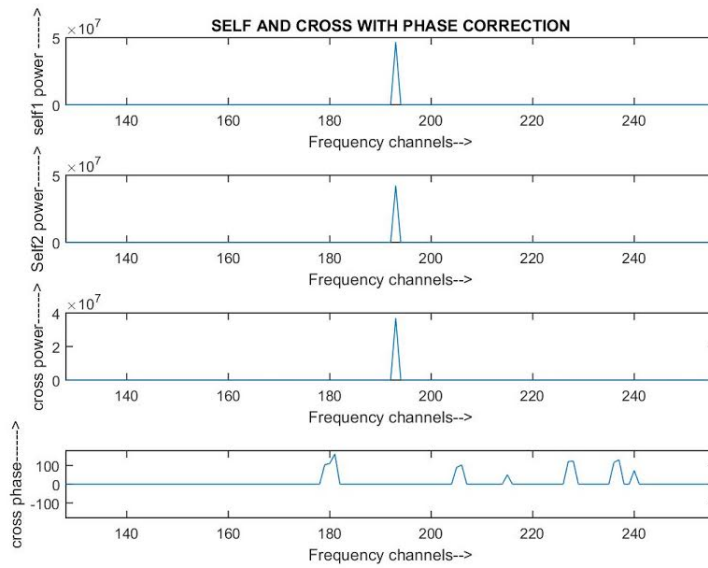


Figure 8.16: FPA test correlator output with phase correction

Analysis:After phase correction or weight multiplication cross correlation phase become zero.

8.3.3 Case3:Analyze the effect of phase correction on beam output

Description:Radiate tone signal at 1.1GHz at 15dBm power level by omnidirectionnal antenna.Captured this sigal using 8x9 Focal Plane Array feild and using down conversion unit(DCU) converted this RF signal in to base band signal at 150MHz.Apply this tone signal to FPGA setup.Record cross correlation phase value and apply these phase as a weight to the antenna. Record beamformer data after and before phase correction.

Result:

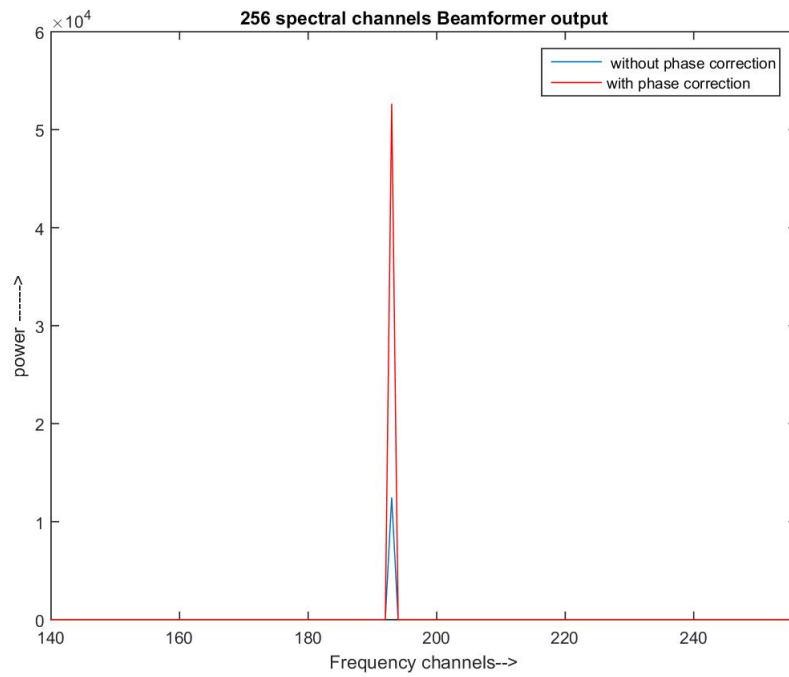


Figure 8.17: FPA setup radiation test beamformer output to observe phase correction effect

Analysis: After phase correction observed improvement in power because after phase correction this beamformer work as a coherent beamformer.

Chapter 9

Conclusion

9.1 Conclusion

Four element single polarization two beam for focal plane array on single ROACH board is design and tested with noise source and with GMRT(single pixel feed) antenna

- 1)Proposed design tested with weight multiplication algorithm this show the working of phase correction algorithm for the PoCo .
- 2)With weight multiplication algorithm observed coherent beamformer output (Intensity).This show the Intensity with phase correction little bit greater than without phase correction.
- 3)Tested coherent sum part of at zero phase design with noise source adding different number of identical inputs observed N time improvement in intensity for inputs.this show signals coherently added.

9.2 Future work

The designing of four element two beam coherent beamformer on single FPGA is a part of the new e-GMRT project. So, it has got lots scopes for future improvisations. The following future works are recommended: 1)Design can be tested with focal plane array system by radiating signal using directional antenna

- 2)The number of FFT points can be improve for higher resolution over the band by implementing design in ROACH2 environment which is having more resources than ROACH1.
- 3)ROACH two environment can form more number of beams on single board.
- 4)Number of beams and inputs can be increased using FX-beamformer concepts.

Chapter 10

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Acknowledgement

I would like to express my sincere gratitude towards **Gaint Meterwave Radio Telescope (NCRA-TIFR)** for providing an the opportunity of giving out this project. I would like to thanks **Mr. Kaushal Buch** and **Mr. AjithKumar.B** for their valuable guidance,continuous support and giving their precious time in every possible way in spite of their busy schedule.

I sincerely thank to **Prof. Jayaram Chenglur ,Prof Nissim Kanekar** and **Prof. Yashwant Gupta** for supporting me in this project.

I offer my gratitude to all the members of the backend team at GMRT for helping me whenever required. Finally I express my sincere thanks to all those who helped me directly or indirectly in many ways in completion this project.