International Journal of Engineering Research and Development
***e**-ISSN: 2278-067X, **p**-ISSN: 2278-800X, www.ijerd.com*
Volume 4, Issue 5 (October 2012), PP. 71-76

Digital Beamforming Using Quadrature Modulation Algorithm

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Abstract:— Smart antenna technologies are emerging as an innovative way to meet the growing demand for more powerful, cost-effective and highly efficient satellite and wireless communication system. This paper presents an efficient digital beamforming algorithm used in conjunction with phase array antenna. Proposed algorithm is Quadrature modulation algorithm in which the input signal coming for each phase array antenna element is filtered and sampled. The sampled signal is digitally down converted and decimated. Then constant weight is applied to each signal and added to form the phase shifted signal.
These constant weights are further processed by beamforming network which adjust and compensates these phase shift to form the beam in desired direction ,which not in the scope of this paper.

Keywords:—Digital Beamforming (DBF), Smart Antennas, Phase Array Antenna (PAA), Digital down Conversion (DDC), Decimation

I. INTRODUCTION

Beamforming is spatial signal processing technique. It is typically used with an array of antennas in which response of an array is made sensitive to signals coming from one direction while signals from other directions are attenuated. It precisely aligns the phases of an incoming signal of different elements of an array to form a beam in a specific direction. Every antenna exhibits a specific radiation pattern. The overall radiation pattern changes when several antenna elements are combined in an array. This is due to the so called array factor: this factor quantifies the effect of combining radiating elements in an array without the element specific radiation pattern taken into account. The overall radiation pattern of an array is determined by this array factor combined with the radiation pattern of the antenna element. The overall radiation pattern results in a certain directivity and thus gain linked through the efficiency with the directivity. Generally it is used in conjunction with array of antennas so called Phased array antennas which are known for their capability to steer the beam pattern electronically with high effectiveness, managing to get minimal side-lobe levels and narrow beam-widths. This paper presents an algorithm by which we can generate phase array signals having phase offset according to known look angles of the source.

II. BEAMFORMING SYSTEM

A beamformer is a processor used in conjunction with an array of antennas to provide a versatile form of spatial filtering. The antenna array collects samples of propagating wave fields, which are processed by the beamformer. The objective is to estimate the signal arriving from a desired direction in the presence of noise and interfering signals. A beamformer performs spatial filtering to separate signals that have overlapping frequency content but originate from different spatial locations. [1]

The signal from a given source arrives at each antenna based on the displacement between the source and the antenna, so the antenna signals have relative phase and amplitude offsets as shown in Fig. 1. Beamforming adjusts the gain and phase of each antenna signal to compensate for the different delays and signal paths to each antenna. These adjustments align signals arriving from one particular direction for each antenna element.

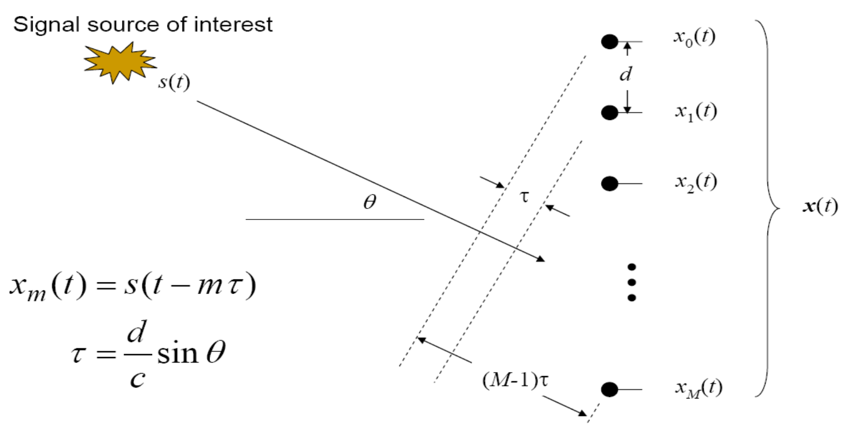

Fig. 1 Antenna array receiving signal with phase & amplitude offset

When the signals are summed together, the non aligned signals arriving from other directions cancel each other; while the signals from the beamformed direction add constructively for greatly improved signal to noise. So, by electronically adjusting the gain and phase in each path, the antenna is effectively steered for directionality.

III. PHASE ARRAY ANTENNA & DBF

The Phase Array Antenna is composed of a group of similar antennas, each with its power feed network, phase shifter, variable amplifiers and a summing network which gives a resulting signal representing a beam on an expected location.The complex weight associated with each antenna element is implemented by means of a variable amplifier and a phase shifter. Analog components such as Low Noise Amplifiers (LNAs) and Power Amplifiers (PA) found in the RF stages are needed in order to condition the signal to be transmitted or received by the antenna array. The purpose of beamforming is to precisely align the phases of an incoming signal from different parts of an antenna array to form a beam in a specific direction. Essentially, the signals from each of the elements are delayed such that when they are summed they all have the same delay corresponding to a specific direction. There is a physical geometric delay on the incoming wavefront that increases linearly across the array, which is then compensated for electronically prior to being summed.

An alternative approach for implementing a PAA Simulator is by means of quadrature modulation theory. In this approach, a signal is decomposed into its quadrature components which are processed separately in the baseband region using the complex weights to achieve desired beam pattern response. One way to implement quadrature modulation/demodulation is through digital beamforming. Digital beamforming consists of the spatial filtering of a signal where the phase shifting, amplitude scaling, and adding are implemented digitally.

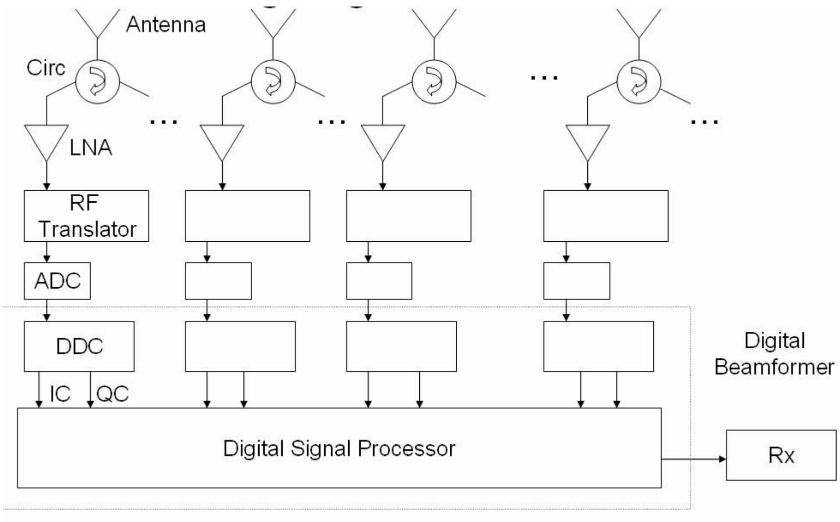

Fig. 2 Diagram of a PAA using a Digital Beamformer

Analog-to-Digital Converters (ADCs) and the Digital-to Analog Converters (DACs) are required to make the necessary transformations of the signal between the IF analog domain and the digital domain. Fig. 2 shows the architecture of a PAA using a DBF.

IV. PHASE OFFSET CALCULATION

Phase shift at each element is calculated according to look angle provided by user. These equations are valid for rectangular grid or planar geometry and triangular geometry. [2]. Phase at (m, n)th element is given by following equations

$$\Phi_p (m,n) = mT_x+nT_y \quad (1)$$

Where,

$$T_x = 2\Pi d_x/\lambda \text{ Sin } \theta \text{ Cos } \Phi \quad (2)$$

$$T_y = 2\Pi d_y/\lambda \text{ Sin } \theta \text{ Sin } \Phi \quad (3)$$

Here, θ is the Elevation angle and Φ represents Azimuth angle, whereas dx and dy represents inter-element spacing in x and y direction respectively and (m,n) is the element index.

V. QUADRATURE MODULATION ALGORITHM

The design can be divided into three main stages

1) RF Modulation stage
2) Digital-Down Conversion stage
3) Constant Weight Multiplication stage

RF Modulation Stage: It is important to remember that this stage is not implemented digitally (technically, it is not part of the PAA Simulator), but it is essential in the implementation of the PAA and thus, its design is also explained in this section. It is the first stage in the implementation of a PAA system. It is also called RF Translator stage. After the incident plane wave has been received by the antennas of the PAA, the incoming signal arrives at the RF Modulation Stage. This stage is often required because the incoming signal's frequency components are high compared to the speed of the ADCs and analog signal modulation is needed to shift the signal's frequency components into a lower frequency band. The RF Modulator is implemented using an RF Mixer. RF Mixers are available as Integrated Circuits (ICs) component packages and can be bought from commercial microwave components stores. RF Mixers need to receive sufficient signal power in its input ports in order to work properly. In PAA systems, the power of the signal found at the output port of each antenna in the array is very low. Since the first stage of a receiver has a major effect on the noise performance of the system, it is necessary to include Low Noise Amplifiers at the RF Modulator Stage. The LNA's help to reduce the Noise Figure in a microwave circuit and increase the Signal-to-Noise Ratio (SNR) of the PAA system. Therefore, the RF Modulator Stage of each antenna channel has one LNA and one RF mixer. An intermediate stage found in the antenna receiver channel of a PAA implemented using DBF is the ADC. The ADC transforms the analog signal found in the output of the RF Translator into a digital representation for further processing by the DBF. ADCs implement the operations of sampling, quantizing, and encoding of the analog signal.

Digital-Down Conversion: The first stage of the DBF Receiver (the second stage in antenna channel) is the Digital-Down Conversion Stage. The DDC receives an incoming digital IF signal (usually from an ADC), and modulates the signal into baseband and produces an in-phase signal and a quadrature signal as outputs. The design of the DDC can be implemented using FPGAs or dedicated ICs. The quadrature modulation is performed by the multiplication of the IF signal with a digital oscillator. The implementation of the digital oscillator is accomplished using a direct digital Synthesizer (DDS).
Direct digital synthesis is a technique by which a sinusoidal signal is created by the generation of digital numbers which controls the input of a sinusoidal look-up table. A single DDS must be used for all the channels in the DBF receiver in order to assure proper synchronization between the signals of each antenna channel. After the in-phase and quadrature signals have been produced, a lowpass filter is used to remove image frequency components located on both signals. In PAA applications, the received RF signals are centered at a high carrier frequency, which imposes the need for fast ADCs and DDCs with high sample rate frequencies. On the other hand, cost limitations and simplicity motivates the need to use Digital Signal Processors (DSPs) working at low sample rate frequencies in the final stages of the DBF.

Constant Weight Multiplication: The CWM receives the in-phase baseband signal, the quadrature baseband signal, and the magnitude of the complex weight and the phase of the constant weight as inputs. Constant Weights are the phase offsets at each elements of PAA. Fig. 3 shows quadarture modulation algorithm in form of flow chart, and Fig. 4 shows implementation of quadrature modulation algorithm in from of block diagram.

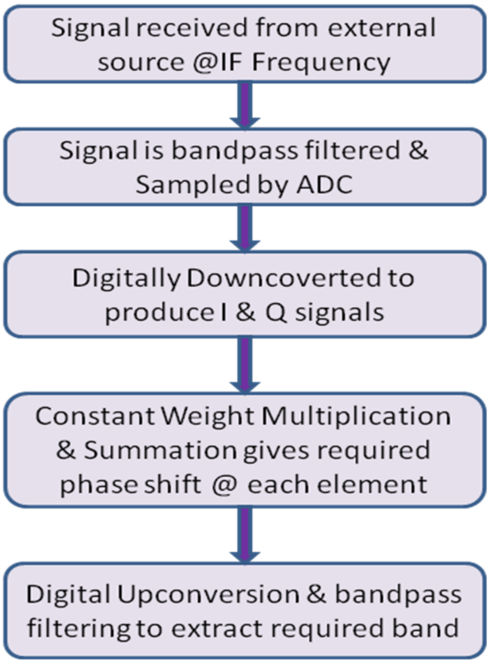

Fig. 3 Quadrature Modulation Algorithm

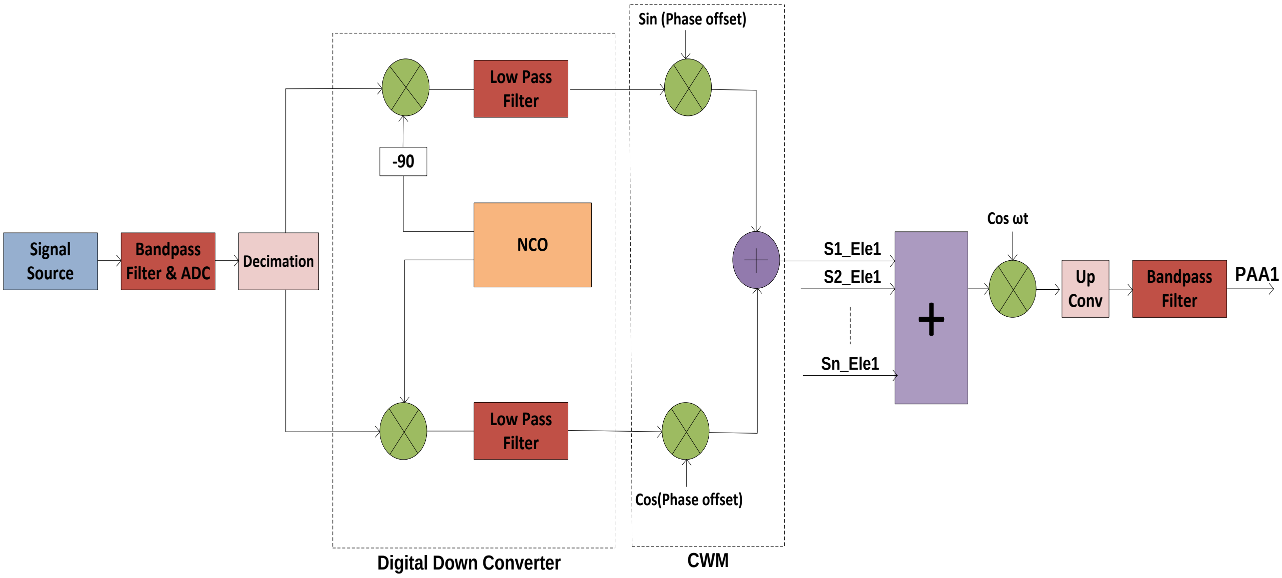

Fig. 4 Block Diagram of Quadrature Modulation Algorithm

VI. MATHEMATICAL MODEL

The incident plane wave on an antenna array's receiver can be modeled by the following equation

$$f(t,p) = x(t-\tau_n)\cos\left(\omega_{rf}(t-\tau_n)\right)$$

$$= x(t)\cos\left(\omega_{rf}t-\theta_n\right) \quad (5)$$

Where, $\theta_n = \omega_{rf}\tau_n$

After the incident plane wave has been received by the antennas of the PAA, the incoming signal arrives at the RF Modulation Stage. This stage is often required because the incoming signal's frequency components are high compared to the speed of the ADCs and analog signal modulation is needed to shift the signal's frequency components into a lower frequency band. If the RF Modulation Stage has a Local Oscillator (LO) with a frequency of WLO, then the signal modulation operation can be described in the form:

$$g_n(t) = x(t)\cos\left(\omega_{rf}t-\theta_n\right)\cos(\omega_{lo}t) \quad (6)$$

Using trigonometric identities, the signal g'n(t) can be represented as a sum of two cosines

$$g_n(t) = \frac{x(t)}{2}\left[\cos(\omega_{IF}t-\theta_n)+\cos(\omega_{IM}t-\theta_n)\right] \quad (7)$$

$$Where \quad \omega_{IF} = \omega_{RF}-\omega_{lo} \text{ and } \omega_{IM} = \omega_{RF}+\omega_{lo} \quad (8)$$

If a passband filter is used centered at the signal's component with wIF as its center frequency, the output signal obtained is:

$$g_n(t) = x(t)\cos(\omega_{IF}t-\theta_n) \quad (9)$$

The angular displacement, which represents the time delay of the incoming plane wave between the antennas of the array, is left unchanged in a modulation operation. After the incoming signal in an antenna channel has been modulated into an intermediate frequency and the signal higher frequency is at least half as small as the sampling frequency, the ADCs with a sampling rate TS can be used to transform the signal into a digital representation

$$g_n(m) = g_n(t)|t = mt_s = x(mt_s)\cos(\omega_{IF}mt_s-\theta_n) \quad (10)$$

To simplify the mathematical representation of the signal gn[m], the constant ts in the signal x[mts] will be omitted and the variable $\omega_{if} = \omega_{if\ ts}$ will be used to distinguish the cosine component in the digital signal representation from its analog representation. After making such simplifications, the digital signal observed in each DBF receiver channel n of the PAA

$$g_n(m) = x(m)\cos(\omega_{IF}m-\theta_n) \quad (11)$$

It is important to observe that the digital representation of the DBF receiver signal contains the phase delay φ associated with the time delay found in each n element of the PAA.

VII. SIMULATION RESULTS

Simulations have been performed using MATLAB and MATLAB Simulink. Figure below shows signal received by each PAA element having phase offset according to known look angle of the source.

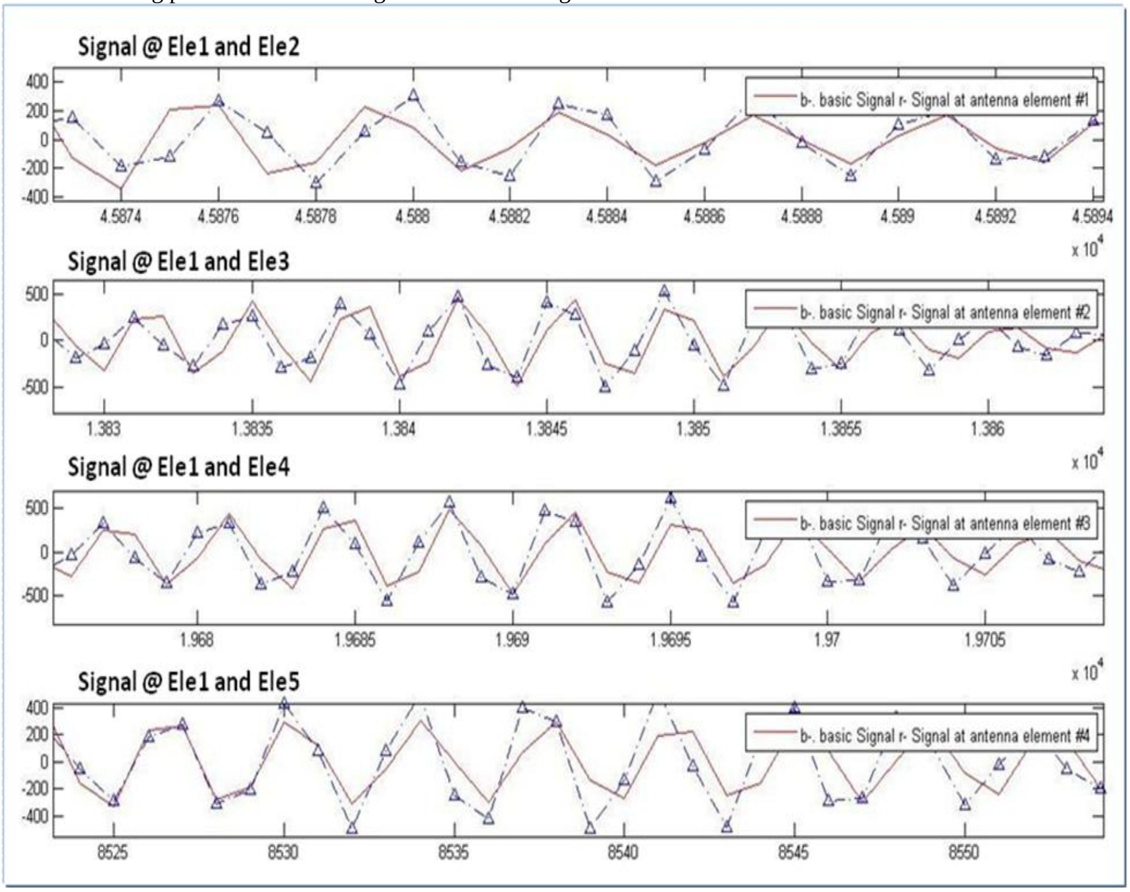

Fig. 5 Phase offset signals at each PAA elements

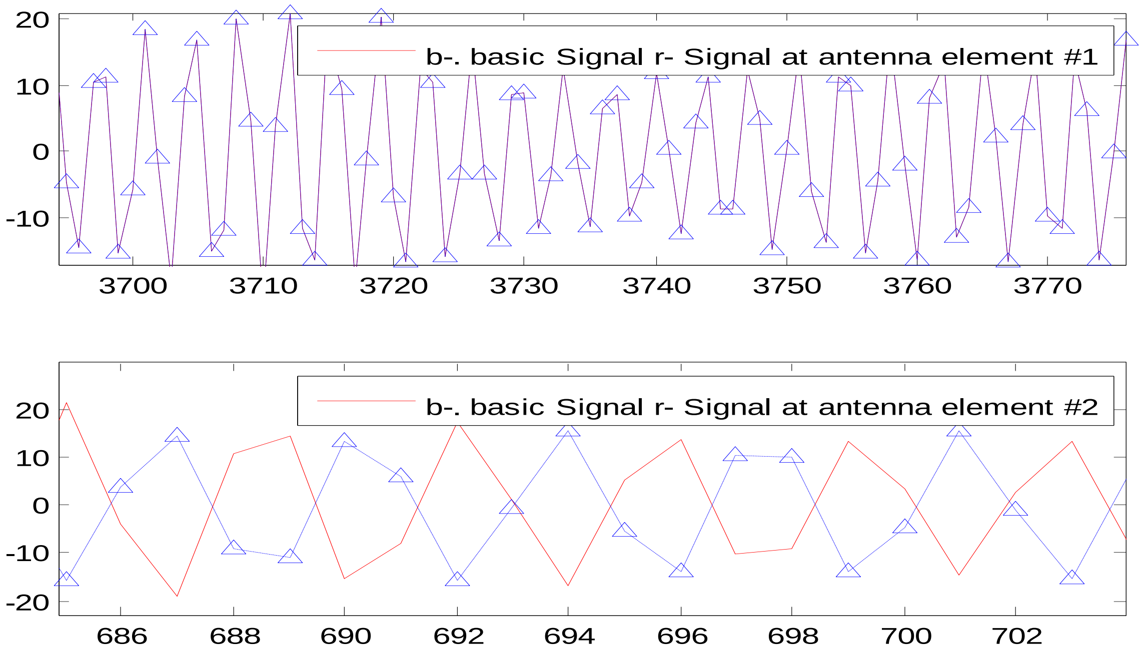

Fig. 6 Phase offset of 0º and 180º between reference and signal received by PAA element

VIII. CONCLUSION

Quadrature modulation algorithm discussed in this paper is very efficient algorithm to generate phase array signals received by phase array antenna and use it in digital beamforming. Algorithm disussed here can be implemented on FPGA and demonstrate, test and validate digital beamforming on ground.

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