FPGA Implementation of a Phased Array DBF using a Latch Method

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Abstract — Timing resolution plays significant role in generating digital phased array beams. In this paper we present a latch method for FPGA implementation of digital beamforming (DBF) for an ionospheric radar. The radar requires a constant phasing vector to steer the beam over a specified region of the ionosphere. Sixteen digital beams are derived from the vector with beam resolution of approximately three degrees. The phasing weights can be employed either in the time domain or in the frequency domain. Comparison of phase delay and time delay methods is presented for broadband frequencies of the radar. Performance of the proposed DBF system is presented including speed limitations.

Index Terms — Field Programmable Gate Array (FPGA), Digital Beamforming (DBF), Tasman International Geospace Environment Radar (TIGER).

I. INTRODUCTION

With the introduction of fast reconfigurable devices and technology, it is now possible to realize beamforming techniques in a Field Programmable Gate Array (FPGA) with much accuracy and ease. Digital Beamforming (DBF) has many advantages over conventional analog phasing including flexible antenna patterns, multiple beams without any degradation, and closely spaced beams [7]. To add this flexibility to the radar we investigate hardware efficient algorithms and evaluate their implementation.

Tasman International Geospace Environment Radar (TIGER) is one component of the SuperDARN network that analyzes the space weather in southern hemisphere. The phased array pulses are modulated using analog heterodyne operations with limitations of the analog inflexibility. Currently we are investigating different methods to implement this radar onto reconfigurable devices. Most of the radar would be in the digital domain and configuration could be changed on the fly.

In section II TIGER interferometer is described where fixed beams are produced with a predefined direction. The radar phasing is based on constant time delay. This is because beam direction is fixed even with variable frequency range. A comparison of time and phase delay beamforming is addressed in section III. A basic design for FPGA implementation is proposed in section IV, latching a clock cycle delay for each input channel. The proposed design is implemented using Visual HDL tools. Timing waveforms are discussed in section IV for eight channels, rest of the eight can be produced using mirror symmetry. Limitation of the proposed method is addressed using angle resolution in section V. In the last section conclusions are drawn.

II. ANTENNA GEOMETRY FOR TIGER

The phasing of signals extends the transmission or detection range of a transmitter or receiver. Phased array antennas are used to steer a narrow beam over an arc from a fixed antenna geometry. For each transmitter or receiver the direction is adjusted with systematic phase delays to each of the antennas in the array. In the TIGER antenna array, the antenna elements are arranged with uniform spacing, as shown in Figure 1, where d is inter-element spacing, \( \theta \) is angle normal to modulated wave. It is obvious that the modulated wave by element \( N \) will be delayed by a differential distance of \( d \sin \theta \) compared with a wave at element \( N+1 \). If we consider the phase of the transmitted signal is zero at the origin, then the phase lead at element \( N \) to that element at origin is \( Nd\sin \theta \), where \( k=2\pi/\lambda \) is a space constant. The operational frequency of the HF radar is 8 to 20 MHz, therefore the wavelength varies using the relationship \( c = f\lambda \), and \( c \) is the velocity of light in the vacuum. The number of array elements and a space between them determine the beamwidth and size of sidelobes [5].

The angle resolution of the TIGER phasing array can be calculated using antenna geometry shown in Figure 1. The time delay required to introduce a half beam step of 1.5 degrees off center for the first beam is 1.3ns for our 15.24 meter antenna spacing. Successive antennas in the array must be stepped by the same 1.3ns for this beam. The second beam will be a full beam step of 4.5 degrees (the initial 1.5 degrees plus the 3 degrees beam step size) and antennas will need a time delay of 3.9ns for 3.9ns time step between successive antennas.
The phase delay could be implemented in the frequency domain or in the time domain. In the following section, we compare both techniques.

A Comparison of Phase and Time Delay Beamforming

In the literature, beamforming methods are broadly categorized as weighting coefficients in the time domain and in the frequency domain. In this section we demonstrate that the time domain method is more suitable for constant beam span of the radar [3]. Simulation results were obtained using the geometry displayed in Figure 1 and based on isotropic radiators. In the current system uniform distribution is used for transmission; therefore results are presented for this type of pulsed transmission.

1 Phase Delay Beamforming

We start with the frequency domain methods, where a phase delay is inserted for beam steering. The array factor for the phased array geometry can be written as [4]

$$\text{Array Factor} = \sum_{n=0}^{N-1} \exp \left[ \frac{j2\pi f_n}{\lambda} \sin \theta + \alpha \right]$$

and phase delay $\alpha$ for transmitted frequency $f_0$ can be defined as

$$\alpha = \frac{2\pi f}{\lambda_0} \sin \theta_0$$

The electrical spacing $d/\lambda$ increases with frequency and therefore beamwidth becomes narrower at higher frequencies. This effect is shown in Figure 2 when the operational frequency is varied from 8MHz to 20MHz. For a signal modulated at 8MHz, the first null beamwidth (FNBW) is 5.5 degrees and at 20MHz this becomes 2 degrees. In the frequency dependent method, the phase delay introduces overlap at lower and higher frequencies as the phase delay that produces the correct beam at lower frequencies will not work for high frequencies. In order to produce equivalent beams at different frequencies, the phase delay must be varied with frequency.

![Figure 1](image1.png)

Figure 1 (a) A generic linear phased array (b) constant differential distance in the TIGER antenna geometry.

![Figure 2](image2.png)

Figure 2 Phase delay beam steering (a) First Null Beamwidth (FNBW) is 5.5 degrees at 8MHz, and (b) FNBW is 2.0 degrees at 20MHz.

A close view of the above beam patterns reveals that with the phase delay technique, direction of the beams is changed at different frequencies. A larger picture of the above results is illustrated in Figure 3 comparing second beam from the bore sight. For constant phase weights, change in the frequency causes squint in the beam direction.

![Figure 3](image3.png)

Figure 3 A close view of the above beam patterns reveals that with the phase delay technique, direction of the beams is changed at different frequencies.
From above discussion it is concluded that the phase delay beamforming is not suitable for broadband application such as TIGER. In the next section we discuss phasing vector using time delay weights.

2 Time Delay Beamforming

For time delay beam steering, a constant delay is used for a broad range of frequencies. The array factor can be written as

\[
\text{Array Factor} = \sum_{\theta=0}^{\theta} \exp \left( \frac{2\pi}{\lambda} \sin \theta + \omega \Delta t \right)
\]

where time delay is

\[
\Delta t = \frac{d}{c} \sin \theta
\]

An example is shown in Figure 4 demonstrating the time delay beamforming at lower and higher frequencies. The output beam span is of similar form to Figure 2 with the exception of two factors. The first is less overlap error at higher frequencies at the output of the antennas [3]. Secondly, comparison of Figure 2 and 4 reveals that the time domain method has a constant phase span at lower and at higher operational frequencies. The time delay technique introduces a frequency dependent phase delay so that at any particular frequency, identical results are produced.

For the time domain approach, sets of time delays are required for each beam direction and these sets of delays are constant for all frequencies. This means that for a sixteen element array with sixteen beam directions, sixteen sets of sixteen time delays are required. It should be noted that left/right symmetry of the beam scanning can be included so that delays can be shared for beams left and right of the bore sight. In this way eight pairs of eight delays can generate all sixteen beams for the sixteen antennas.

Now similar to the frequency dependent method, a simulated result is shown in Figure 5 comparing beam direction at lower and higher frequencies. Since frequency is inversely proportional to the wavelength therefore beam becomes narrower at high frequency. However direction of the beam is identical to lower frequency beam.
Hence our discussion concludes that the time domain beam steering is better approach for the radar operation. In the next section a new hardware efficient method is proposed to generate phasing signals for the radar in the digital domain.

III PROPOSED DBF METHOD

In the simplest form, DBF can be introduced using fixed clock cycles for each channel. In this way, a time delayed version of the signal is readily available using a set of ripple latches which are sequentially clocked. Such a system is described in Figure 6.

The synthesized digital signal carries a phase delay for each channel. The phase delay is also dependent on the fixed phased array antenna geometry shown in Figure 1, the antenna spacing is 50 feet or 15.24 meters. The synthesized RF signal is divided into parallel channels. The phase delays for the channels are derived from the time vector. The effect of digital quantization can significantly be reduced using an analog reconstruction filter (ARF) after the D to A. The phased RF signal is passed through the transmitter/receiver switch and sent to the antenna for transmission.

IV FPGA IMPLEMENTATION

DBF can be synthesized onto an FPGA to introduce the flexibility of beam direction and beam resolution. A proposed DBF system is presented in the last section, now we will discuss simulation and synthesis of the phased array system. Resolution of the timing delay depends on a sampling period and input clock rate. The timing weights are assumed for symmetrical Gaussian pulses and synthesized for Xilinx Virtex II device. The Gaussian pulses are simulated using Visual HDL and synthesized with Xilinx ISE tools.

A timing delay model is shown in Figure 7 using Visual HDL software tool. We consider a symmetrical Gaussian modulated signal driven by the beamforming network. A 14 bit modulator output is assumed for beam steering; the DAC resolution in the proposed system is 14 bits [2]. The RF data is converted into parallel form and one clock cycle delay is inserted in each parallel sequence. Eight channels are simulated to span total of approximate 25 degrees.

A timing diagram illustrates the function of the timing vector for each channel in Figure 8. For a selected carrier frequency, the RF signal generates eight beams and the other eight beams on the opposite side of the array normal are produced in a similar way. Each channel represents phasing equivalent of one clock cycle, where one clock cycle contains twenty clock units. The time period of the clock depends on the available system requirement. For example to derive 1.3nsec time delay the clock speed should be around 800MHz. For finer control of the delay
times the system could be made to operate in subclock cycles consisting of a number of clock units. When implemented on Virtex II, the DBF requires almost eight slices since each slice can hold two registers or latches.

![Clock required in latch method](image)

**Figure 8** Timing delay for each channel.

Obviously the ‘bucket brigade’ technique will produce the desired timing delay. However this scheme requires a clock doubler for Virtex II FPGA since maximum clock frequency for this device is 420MHz. In the next section clock limitation of the DBF method is addressed using angular resolution.

V Speed Limitation of theProposed Method

A simplistic way to realize DBF is introducing a sample delay directly to the synthesized signal. This method is dependent on the input clock rate and clock requirement is considerably higher. A limitation of this technique is that the clock must run with a 1.3ns period (or approximately 800MHz) to introduce precision of less than 1.5 degrees. A graph is plotted in Figure 9, showing the required clock speed against beam width resolution. For higher phase resolution, input clock speed is also higher. The average resolution of three degrees is possible with the Virtex II device which requires less than 400MHz clock speed.

To overcome the clock rate limitations of the latch method, multirate filters can be used [1]. Multirate filters provide higher sampling rate than the input clock. Implementation of such scheme is currently under investigation.

VI Conclusions

In this paper we have presented a reconfigurable DBF using a latch method. A constant time delay is introduced to steer the beam to scan ionospheric irregularities. The phase delay for sixteen channels can be introduced in the time domain or frequency domain. However time domain approach is more useful for TIGER operation. The constant time vector generates almost constant beam span at lower and higher frequencies and beam direction is also constant. The proposed DBF scheme is synthesized using Visual HDL and implemented on Virtex II. Function of the DBF is successfully tested using a fixed clock delay.

REFERENCES


