Implementation of Enhanced Digital Signal Processing for Wideband Phased Array Radar

Khine Zin Min[1], Zaw Min Naing[2], Thet Paing Phyo[3]

Abstract— **In this work, the comparison of time and frequency domain wideband digital beamforming processing methods based on the envelope detection was discussed and described with simulations results by using MATLAB. These processing methods use the wideband signal such as Linearly Frequency Modulated (LFM) signal. The time domain processing needs fourth times of Nyquist frequency and the frequency domain processing can reduce 16 times the rate of Nyquist frequency to get precise steering angles. Moreover, time domain digital beamforming takes longer processing times than frequency domain digital beamforming in Matlab stimulation, it will also need much signal multipliers. We implemented frequency domain beamforming method with the cascaded integrated comb (CIC) filters to reduce the sampling rate again. The implemented simulation program gives the evaluation of digital beamforming to obtain the steering target angles with the various decimation factors. The radar system examined in this paper is operating at 2.4 GHz and sixteen antenna elements with spacing λ/4 were placed in receiver side to examine the digital beamforming scheme.**

Index Terms— **Cascaded integrated comb (CIC) filters, Digital Beamforming (DBF), Linearly Frequency Modulated (LFM), Phased Array Radars, Time Domain and Frequency Domain Processing.**

I. INTRODUCTION

Digital array radar is new phased array radar that uses digital beamforming technology in transmitting and receiving. It has a very good application prospect, with digital, modular, scalable, and other excellent features. For the need of enhancing anti-interference ability, improving identification, recognition of the target, and solving the problem of radar imaging, radars transmit wideband signals for high-resolution.

The paper describes a wideband digital beamforming method, which uses the special properties of LFM waveforms. Wideband digital array radar (WDAR) is digital array radar using wideband waveforms combine the advantages of wideband signals and digital array radar. In the recent years, WDAR attracts more and more attention, becomes an important development direction of the radar. And wideband digital beamforming technology is one of the key technologies on wideband digital array radar. When radars transmit LFM signal as wideband pulse, the target signal bandwidth can be reduced greatly through enveloped detection processing and narrow-band filtering. Then beamforming can be finished in a small bandwidth, the data sampling rate reduced greatly, in favor of the project to achieve [6].

On the radar, the main purpose of using wideband signals is high-resolution, sometimes do not need deal in the whole course and the signal form is known and identified usually, such as LFM Signal. Linear frequency modulated (LFM) signal has large time-bandwidth product (TB) that can solve the contradiction between the range and distance resolution better, applicable to long-range, ultra long-range surveillance radar.

Early digital beamforming is for narrowband signals, however, narrowband digital beamformer can't solve the problem of wideband digital beamforming. Wideband signals can be seen as some narrowband signals being superposed in frequency field, but it doesn't mean that wideband array model equal to the sum of these narrowband array models, and wide band array processing is more complex.

In this paper, the comparison of time and frequency domain techniques which aid in the design and implementation of digital beamformers will be discussed and described with simulations results using MATLAB. A time domain beam former works, as the name says, by doing time-based operations. The basic operation is called "delay and sum". It delays the incoming signal from each array element by a certain amount of time, and then adds them together. Frequency domain beamforming has advantages when compared with time domain techniques. Frequency domain beamforming concepts are the result of applying the Fourier transform to the beamforming equation.

In this paper, Section II presents the digital beamforming techniques for phased array radar system. Section III mentions the implementation of proposed methods. Section IV provides the simulation results of proposed methods. Section V discusses these results in detail. Section VI provides some conclusions about the simulated phased array radar system.

II. DIGITAL BEAMFORMING TECHNIQUES

Digital Beamforming (DBF) is a combination of antenna and digital technology. Digital beamforming offers the possibility of the variety of digital signal techniques and algorithms to be performed as soon as the RF information is provided. Two main types of digital processing techniques for beamforming are

- Time domain beamforming technique, and
- Frequency domain beamforming technique

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The basic idea of time and frequency domain digital beamforming for linear phased array is described below.

A. Time Domain Delay Sum Beamforming

A simple time domain beamforming structure is the delay sum beamformer that the time domain antenna inputs are first delayed and then summed to give a single array output. If each antenna in the array receives a signal x(t) with the particular time-delay, recovery of signal can be performed by means of linear processing. In this case, A discrete version of a signal x(t) is obtained by assuming a sampling frequency $f_s = 1/t_s$ and $\Omega = \omega t$. Substituting $t = nt_s$, the discrete beam output is formed.

$$y_b(n) = \sum_{m=0}^{M-1} a_m x_m\,[\Omega(n - q_{mb})] \qquad (1)$$

Where $q_{mb} = t_{mb}/t_s$ represents an integer delay (number of delay units) for a given sensor input, m, and beam direction, b. To form a beam y_b in a steering direction ψ_b, the output of each sensor is delayed by an integer multiple of the sample spacing q_{mb},

where $q_{mb} = m\delta_s \sin\psi_b$ and $\delta_s = \frac{df_s}{c}$.

Since q_{mb} is integer delay, it is imperative that $\delta_s \sin\psi_b$ is an integer also. This obviously quantizes the steering directions which can be realized. A time domain delay-sum beamforming structure can be implemented as shown in Fig.1 [2].

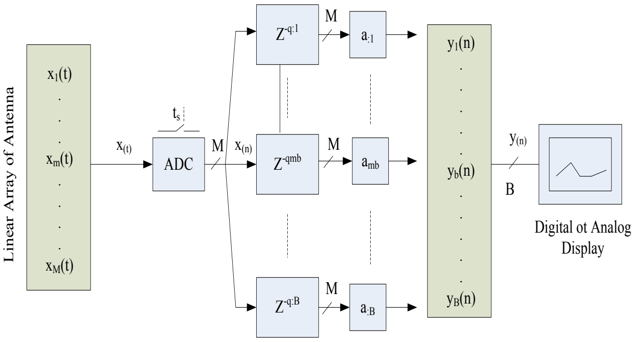

Fig -1: Time Domain Delay-sum Beamforming Structure

B. FFT Based Frequency Domain Beamforming

Frequency domain beamforming concepts are the result of applying the Fourier Transform to the beamforming equation, the beam output is

$$Y(f,\psi_b) = F\{y(t,\psi_b) = F\left\{\sum_{m=0}^{M-1} a_m x_m\,(t\text{-}t_{mb})\right\}$$

$$= \sum_{m=0}^{M-1} a_m\, X_m(f) e^{-j\omega t_{mb}} \qquad (2)$$

Where $X_m(f)$ is the fourier transform of each transducer output. Each beam is a weighted linear combination of the Fourier Transform coefficients of the received waveforms. An Inverse Fourier Transform may be required to obtain the time domain representation, however some useful features can be extracted from the transform data. The frequency domain beamforming configuration is shown in Fig.2 [2].

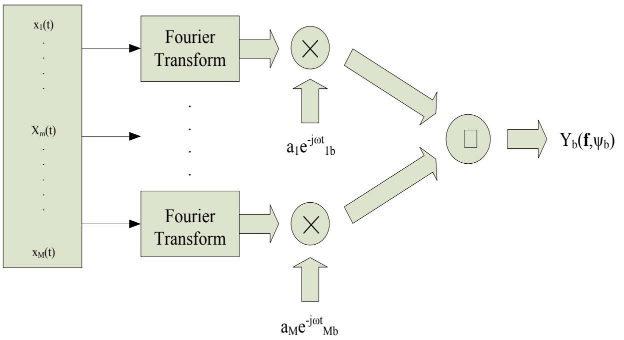

Fig -2: Frequency Domain Delay-sum Beamforming Structure

III. PROPOSED IMPLEMENTATION METHOD

The proposed method is the implementation of time and frequency domain beamforming analysis based on the envelope detection.

A. Defining Signal Model

On the radar, wide band signal such as Linearly Frequency Modulated (LFM) signal are used to obtain the high-resolution. The LFM signal has large time-bandwidth product and it can solve the contradiction between the range and distance resolution better. It is also applicable to be used for long-range and ultralong range surveillance radar. The carrier frequency changes in linearly from the initial to the end, and can be written as

$$f(t)=2\pi f_o+2\pi\mu t(-\frac{T}{2}<t<\frac{T}{2}) \qquad (3)$$

μ=B/T is frequency modulation slope, B is bandwidth, T is the pulse duration. The mathematical model of transmitted LFM signal from every channel of antenna elements can be expressed as follow

$$x(t)=\cos\left(2\pi(f_o t+0.5\mu t^2)\right), \quad -\frac{T}{2}<t<\frac{T}{2} \qquad (4)$$

The echo of the k^th channel is

$$x(t\text{-}t_k)=a\times\exp(j2\pi(f_o(t\text{-}t_k)+0.5\mu(t\text{-}t_k)^2\,\mathrm{rect}[\frac{(t\text{-}t_k)}{T}] \qquad (5)$$

There, $t_k=\tau_r+\tau_k$ is the delay of the echo. τ_r=2R/Cis the two-way propagation delay time, and R is the fact range of the target. τ_r is determined by channel space d and direction of the target θ, can be obtained by $\tau_k = (k-1)d\sin\theta$ previously. Besides, a is the attenuation factor dependent upon transmission distance, the target RCS, antenna gain, etc. Assume a=1.

The reference signal in the k^{th} channel generated from local oscillator is

$$x_0=x(t\text{-}t_k)$$

$$=\exp(j2\pi(f_o(t)+0.5\mu t^2))\times\mathrm{rect}(t/T) \qquad (6)$$

B. *LFM Time Domain Quadrature Beamforming*

The echo signal is a complex enveloped pass band signal which employs the quadrature sampling method to obtain a complex envelope of a bandpass signal. This quadrature bandpass signal from each sensor $x(t-t_k)$ is mixed with the reference signal x0 to obtain the demodulated signal,

$$y(t - t_k) = x_0 \times x(t - t_k) \tag{7}$$

In time domain, the demodulated signal $y(t\text{-}t_k)$ is weighted with the corresponding attenuation factor and filtered using with spatial filtering method in discrete time domain where $f_s=1/T_s$, and $\Omega=\omega t_s$ as follow.

$$y_b(n)=\sum_{k=0}^{M-1} a_k\, y_k\left(\Omega(n\text{-}q_k b)\right) \tag{8}$$

a_m is the attenuation of spatial weighting function usually defined as a window function to control the main lobe width and side lobe magnitude. $q_k b$ is discrete time delay samples from M number of antenna where it is integer for each corresponding beam direction.

$$q_k b = k\delta_s \sin\psi_b \tag{9}$$

The power of $y_b(n)$ becomes the beam pattern of steering beam direction. The maximum power of beam is occurred at the steered direction angle. The implemented LFM time domain beam former is shown in Fig.3.

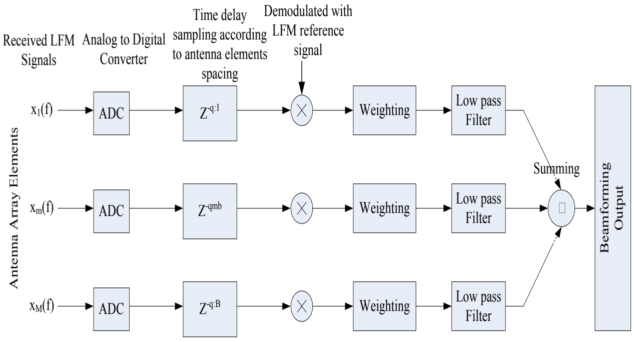

Fig -3: Developed LFM Time Domain Beamformer

C. *LFM Frequency Domain Beamforming*

In the frequency domain beamforming, the echo signal is complex enveloped pass band signal same as expressed in the above time domain beamforming. The demodulated signal $y(t-t_k)$ is obtained after the incoming signals from the array antenna elements is mixing with reference signal x_0 as mentioned in equation(6). According to the time delay transform to a phase shift in frequency domain,

$$y(t\text{-}t_k) \leftrightarrow Y(\omega)e^{j\omega t_k} \tag{10}$$

Application of a N-point Discrete Fourier Transform (DFT) to the discrete time domain demodulated signal from each sensor output $y_m(n)$, the results in frequency transformed data, $y_m(k)$ where $f_k=kf_s/N$, such that,

$$Ym(k)=\sum_{n=0}^{N-1} y_m(n)e^{\frac{j2\pi nk}{N}} \tag{11}$$

$Y_m(k)$ is an estimation of $Y_m(f)$. The frequency domain presentation of the LFM demodulated signals from the incoming signals of each antenna for beamforming equation is then, and the implemented schematic diagram for frequency domain beamforming is shown in Fig.4.
The frequency domain representation of the beamforming equation is

$$Y(k,\psi_b)=\sum_{m=0}^{M-1} a_m\, Y_m(k)e^{-j\Omega ktmb} \tag{12}$$

$$\Omega_k t_{mb}=\frac{2\pi k}{N} m\delta_s \sin\psi_b \tag{13}$$

The frequency domain of beam power $Y(k,\psi_b)$ is changed to time domain using Inverse Discrete Fourier Transform (IDFT).

$$y_b(n)=\mathrm{IDFT}\left(Y(k,\psi_b)\right) \tag{14}$$

The beam steering angle of incoming LFM signals from each antenna is occurred at the maximum power of $y_b(n)$.

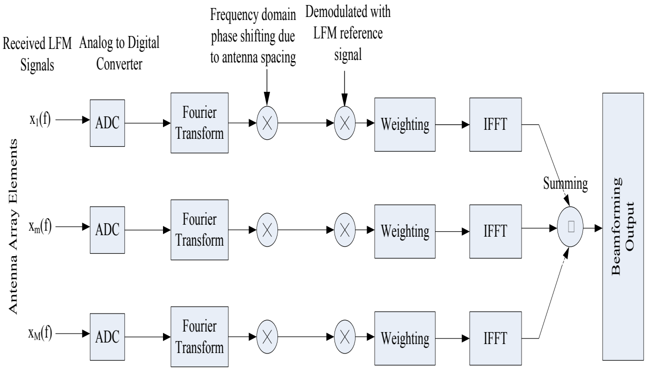

Fig -4: Developed LFM Frequency Domain Beamformer

According to the simulation results, time domain digital Beamforming used much higher Nyquist rates than frequency domain Beamforming to obtain the precise steering angle. So we implemented frequency domain beamforming method with the cascaded integrated comb (CIC) filters to reduce the sampling rate again. A common method of multirate sampling is used to achieve the desired sampling rate by using different decimation factors 2, 4, 8, 16, 32, 64 and 128. The implemented block diagram of frequency domain beamformer based on Multirate Filter Bank is shown in Fig.5.

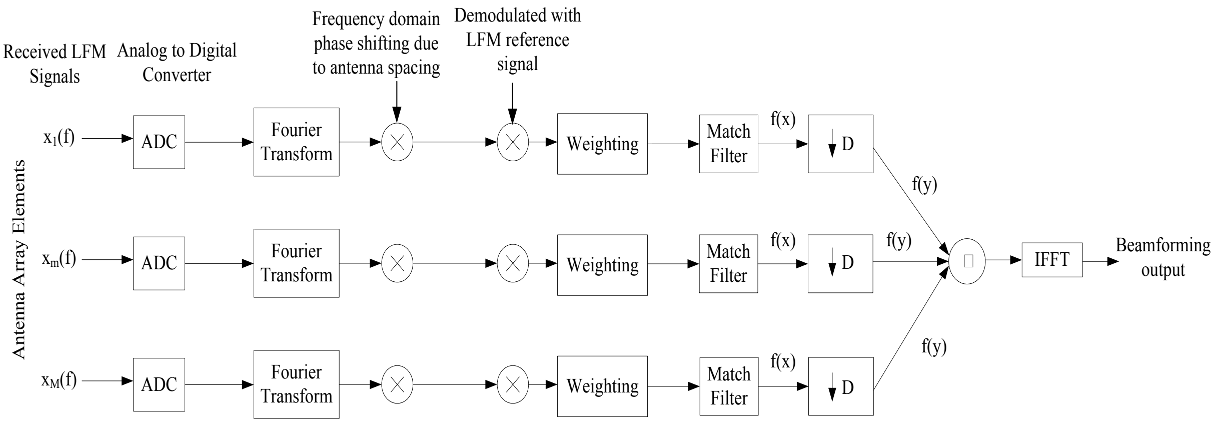

Fig -5: Block diagram of frequency domain beamformer based on Multirate Filter Bank

IV. SIMULATION RESULTS

Firstly, the transmitted LFM signal is created according to the LFM mathematical model expressed in equation (2). These transmitted LFM signals from 16 elements are delayed according to the antenna spacing. The sample transmitted signal from the first 4 antenna elements is shown in Fig.6.

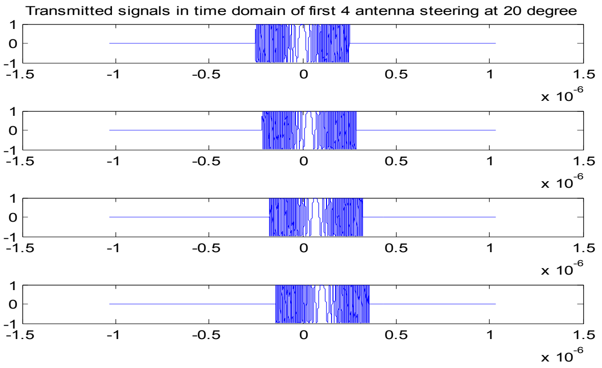

Fig -6: Transmitted Signals from the First Four Antenna Elements

The enveloped transmitted signal of over all elements array when space time delay signals comes out from the 16 antenna elements is shown in Fig.7.

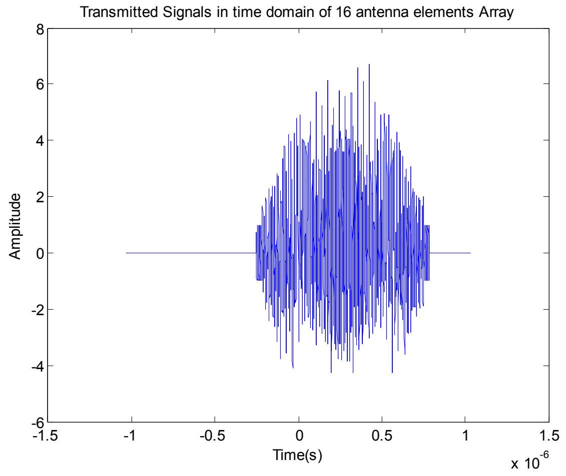

Fig -7: Enveloped Transmitted Signal of Over All Elements Array

The incoming complex echo signal is received by each antenna element and then these signals are demodulated using with reference LFM signals. The demodulated signals from 16 antennas are shown in Fig.8. The demodulated signals are weighted using rectangular window and spatial filtering according to summing of time delayed signal.

The output signals of after spatial filtering is shown in Fig.9. Those two figures are targeted for 20 degree. Due to the signals are come from every direction, the power of sum of spatial filter signals are calculated for all directions and obtains the beam pattern of LFM echo signal.

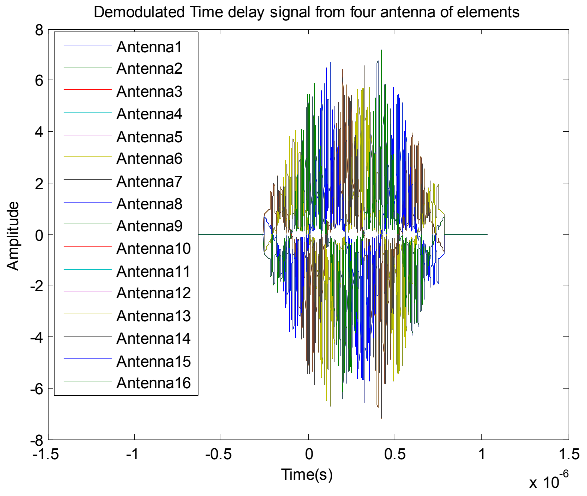

Fig -8: Demodulated Signals from 16 Elements Array at 20 degree

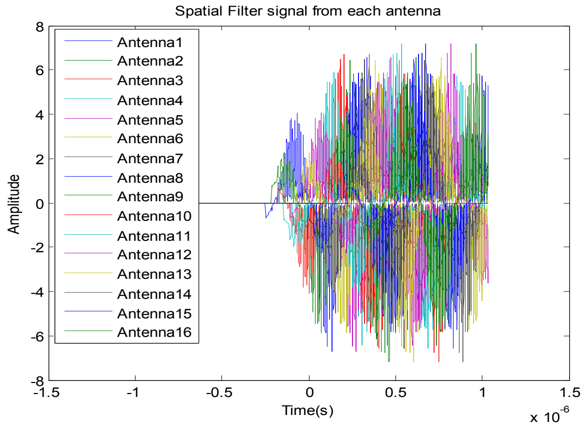

Fig -9: Output Signals after Spatial Filtering at 20 degree

According to the beam pattern, the occurrence of maximum power represents the steering direction angle of echo return from the target. In simulation of the frequency domain beamforming system, the transmitter design and LFM transmitted pulse are the same as time domain simulation.

The received LFM signal is collected from the 16 antenna elements of linear array and then these signals are demodulated with reference signal from local oscillator. After demodulation, the intermediated frequency (IF) is obtained and these IF signals are transformed to frequency domain as shown in Fig.10 and it is for 40 degree steering angle. And then the signal is phased shifted and weighting using rectangular windowing function in frequency domain. After shifted and weighted, the signals are transformed to time domain using Inverse Fourier Transform and the output is summed to obtain the beam pattern output.

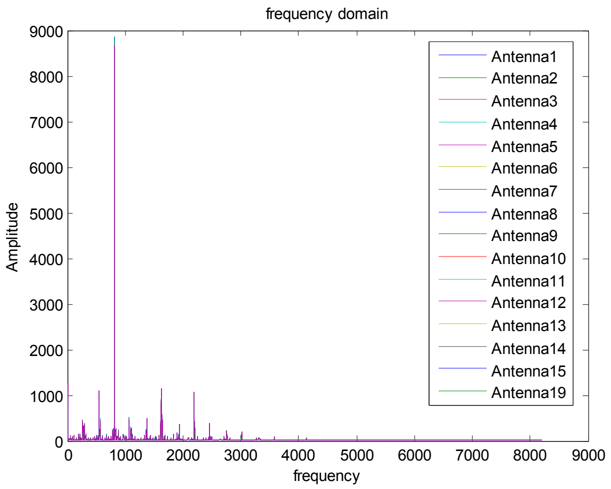

Fig -10: Demodulated Signals from each Antenna in Frequency Domain steering at 40 degree

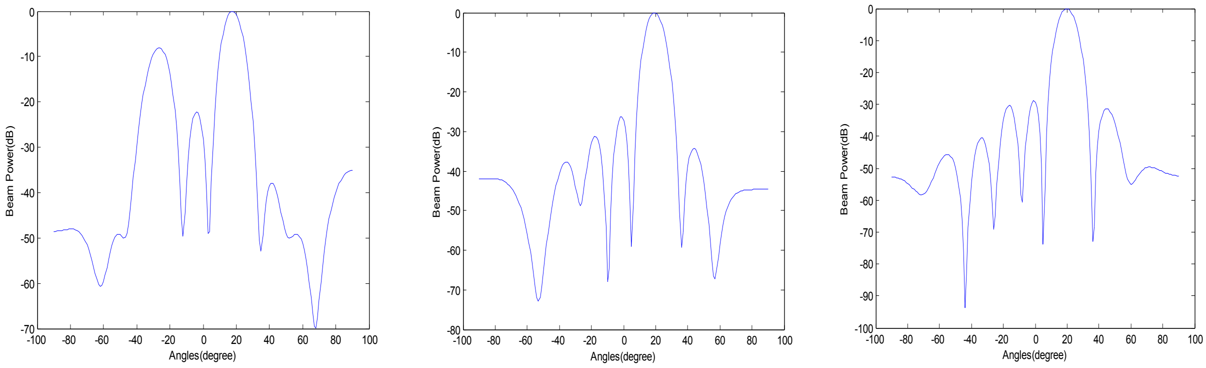

Fig -11: (a), (b) and (c) Time Domain Beamforming Results of Steering at 20 Degree using different Nyquist sampling frequencies

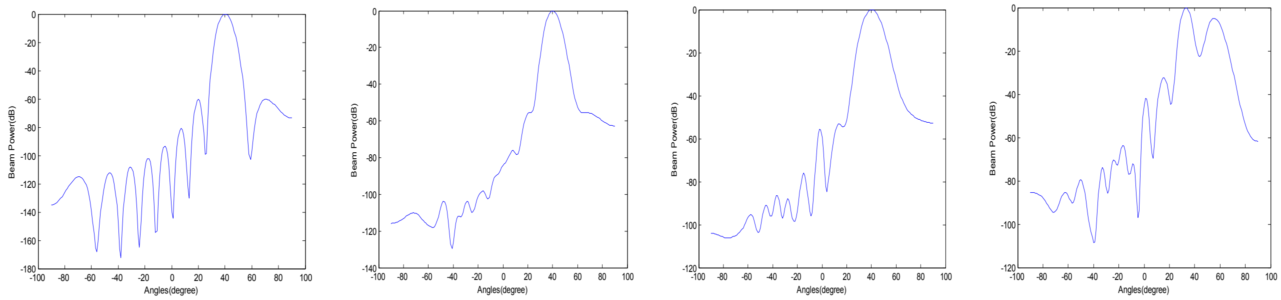

Fig -12: (a), (b), (c) and (d) Frequency Domain Beamforming Results of Steering at 40 Degree using different Nyquist sampling frequencies

The following table shows the Time Domain and Frequency Domain Beamforming Results using different Nyquist sampling frequencies. The processing time and obtaining of our precise targeted angle by using various Nyquist frequencies of frequency domain processing and time domain processing can be seen in that table.

Table -I: Time Domain and Frequency Domain Beamforming Results using different Nyquist sampling frequencies

Digital Beamforming Scheme	Targeted Steering angle (degree)	Beam power output (degree)	Nyquist frequency	Processing Time (s)	Results
Time Domain	20 20 20	18 19 20	1 2 4	3.501833 6.590825 12.096059	Fig11.(a) Fig11.(b) Fig11.(c)
Frequency Domain	40 40 40 40	40 40 40 33	1 1/8 1/16 1/32	1.053632 0.110790 0.057331 0.107949	Fig12.(a) Fig12.(b) Fig12.(c) Fig12.(d)

According to the simulation results, we can see that the time domain beamforming need fourth times Nyquist frequency rate to get our targeted steering angle. In frequency domain beamforming, the 16th times Nyquist frequency rate can reduce to get our targeted steering angle. But after reducing 32 times Nyquist rate we miss with our targeted steering angle.

By using the enveloped detection processing, the desired steering angle can be obtained with more efficient processing rate and hardware complexity can also be reduced in wideband digital beamforming radar application. However, time domain digital beamforming used much higher Nyquist rates and much processing time than frequency domain beamforming to obtain the precise steering angle. So we chose the frequency domain beamforming to implement with cascaded integrated comb (CIC) filters in order to reduce sampling rate. Figures 13, 14 and 15 show the corresponding results for 0, 30 and 60 degree beamforming using various decimation factors.

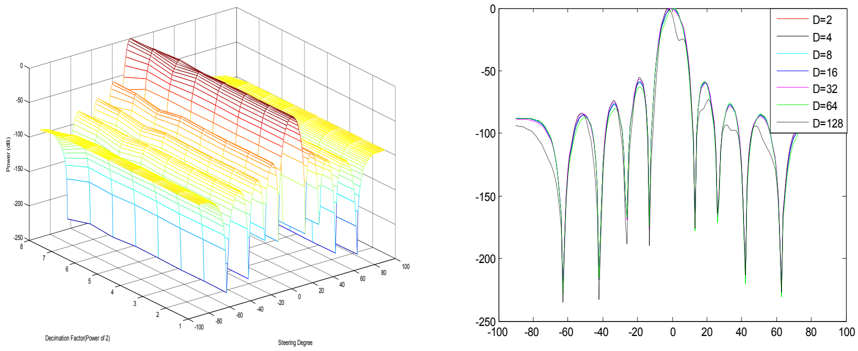

Fig -13: Simulation results for 0 degree beamforming using various decimation factors

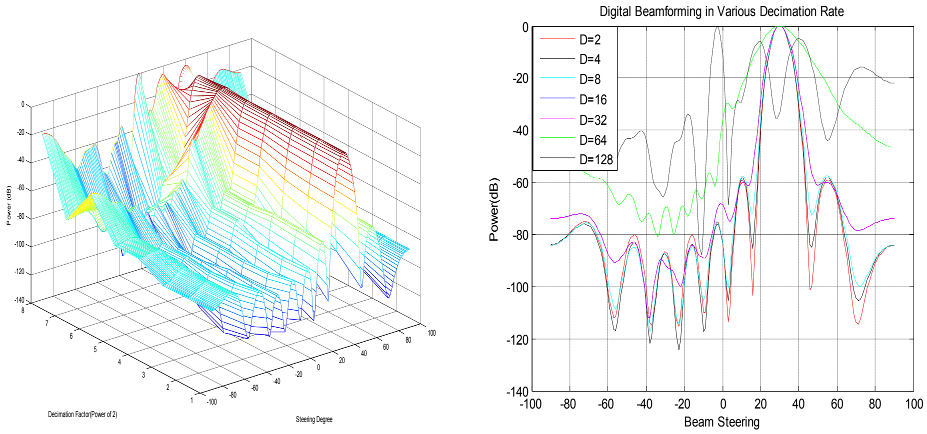

Fig -14: Simulation results for 30 degree beamforming using various decimation factors

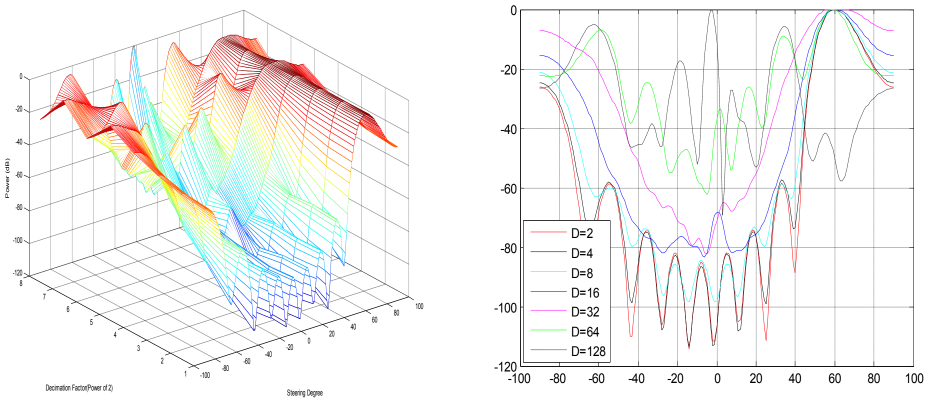

Fig -15: Simulation results for 60 degree beamforming using various decimation factors

The following table shows the beam power output results using with various decimation factors. Here, we can get our targeted steering angles by using up to 32 decimation factors. By using over 32 decimation factors such as 64 and 128, we can see that the beamforming output of the steering angles is not the same anymore with our targeted angles.

Table -II: Beam Power Output Results using with Various Decimation Factors

Targeted Steering angle (degree)	Beam power output (degree)	decimation factor	Results
0 deg	1deg	64	Fig (13)
0deg	-2deg	128	Fig(13)
30deg	30deg	64	Fig(14)
30deg	-3deg	128	Fig(14)
60deg	59deg	64	Fig(15)
60deg	-3deg	128	Fig(15)

V. DISCUSSION

The radar system examined in this paper is operating at 2.4 GHz. Sixteen antenna elements were placed in a λ/4 to examine the digital beamforming scheme. In Fig 11, the targeted steering angle is 20 degree but it cannot be got when the Nyquist frequency is used once and twice times in the time domain processing. It needs fourth times of Nyquist frequency to get precise steering angle. In Fig 12, the aim angle 40 degree can be got when using once time of Nyquist frequency. The rate of Nyquist frequency as 8 and 16 times can also be reduced. But maximum reducing time is 16. By reducing 32 times of Nyquist rate, it reached 33 degree and it got 7 degree mismatch of our aim angle. According to the simulation results, time domain digital Beamforming used 64 times Nyquist rates than frequency domain Beamforming to obtain the precise steering angle. Since Time Domain Digital Beamforming takes thirty longer processing times than Frequency domain digital beamforming in Matlab stimulation, it will also need much signal multipliers.

The implemented program is verified with the enhanced digital signal processing for digital beamforming in phased array radar system by using multirate digital down conversion. Cascaded integrated comb (CIC) filters are used to reduce the sampling rate. The implemented simulation program gives the evaluation of digital beamforming to obtain the steering target angles with the various decimation factors 2, 4, 8, 16, 32, 64 and 128. The system can give the precise steering angle up to decimation factor 32. Reducing sampling rate gives less signal samples, computational complexity, memory requirement and faster processing speed.

VI. CONCLUSIONS

In order to reduce the computation of wideband signal digital processing, a wideband digital beamforming method based on enveloped detection processing is present in this paper. In this paper, time domain and frequency domain beamformers could be expected to operate on signals in a wide frequency range. But time domain beam former needs high speed Analog to Digital Converter (ADC) because the beamforming process depends on the resolution of time samples and the precision of time delay samples. In the frequency domain beamforming, it does not depend on the sampling frequency. A MATLAB model using the phased array toolbox of a sixteen-element slotted waveguide array operating at 2.4 GHz with λ/4 spacing was simulated. The high sampling rates increase the high speed ADC and large amount of memory will require to handle these high sampling rates. Therefore, the implementation of multirate filter structure combined with a Frequency domain beamforming will make sure to reduce the sampling rate and increase processing efficiency of the system.

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