Low Cost Hybrid Beamforming Network for 2-D Multi-Beams in Active Phased Array Antenna

Virendra Kumar*$^{(1)}$, Shreeshail$^{(1)}$, U. S. Pandey$^{(1)}$, K. S. Beenamole$^{(1)}$, and Ravi Kumar Gangwar$^{(2)}$
(1) Electronics and Radar Development Establishment (DRDO), Bangalore, India-560093,
(2) Department of Electronics Engineering IIT (ISM), Dhanbad -826004

Abstract

This paper presents low-cost hybrid beamforming for simultaneous multiple receive beams, reducing beam-shape loss and enhancing target detection with improved accuracy for 4-D phased array radar. Analog Beam Forming Network (ABFN), being a critical component of the proposed architecture, is described in detail, which generates independent azimuth and elevation channels to form simultaneous multiple beams in azimuth and elevation. Herein, the output of ABFN is further combined using another set of RF manifold to reduce the number of receivers and A/D converters to 99.0% - 99.5% of the total number of elements in the radar system. Grating lobe effect in multi-beam configuration, due to more than λ separation between the phase centers of linear subarrays are analyzed and optimized for multi-beam overlap and multi-beam separation. This proposed scheme reduces the cost, complexity and, at the same time, demonstrates the comparable performance of subarray level digital beamforming for multiple receive beams.

1 Introduction

Multi-Function Radar (MFR) systems are designed for surveillance, tracking, and weapon control missions. In which fundamental importance is given for target detection and estimation of the target's angular accuracy. These parameters are directly related to the radar performance in phased arrays of multi-function radar. An MFR with the capability of simultaneous multiple beams can search the entire volume with enhancing dwell time for constant update rate, thereby enhances doppler resolution, which significantly enhances the performance of radar [1]. Forming one-dimensional (1-D) simultaneous multiple beams from a common aperture employing analog (Butler, Blass matrixes, and Rotman lens) is very well reported in the open literature [1]. However, two-dimensional (2-D) multi-beam antenna arrays using the conventional BFNs suffer from high complexity and occupy a large area [1]. The Digital Beam Forming (DBF), where each TRM's output is digitized and provides a more versatile and flexible approach to generate multiple independently receive beams. Unfortunately, element level DBF requires the same number of receivers, A/D converters as the antenna elements hence, significantly increase the complexity, hardware components, power consumption, and cost of the radar system [2].

In this paper, as a trade of solution, the optimal sub-array layout is designed to generate multiple cluster beams for acceptable subarray lobes (for simultaneous beams) satisfying the requirement of reduced beam shape loss, enhance target detection capability for multi-beam surveillance and 4-D tracking radar [3]- [4].

This paper is organized as follows: phased array architecture with hybrid beamforming is presented in Sec.2, Sec.3 elaborates multi-function phased array antenna. In Sec.4, low-cost hybrid beamforming is explained. Sec.5 explains multi-channel digital beamforming, and finally, in Sec.6, conclusions are drawn.

2 Active Phased Array Architecture

Active Electronically Scanned Antenna (A-ESA) comprises solid-state T/R modules that control the phase of each antenna element, thereby steering the transmit/receive beam in any chosen direction is performed [1]. In this paper, a low-cost hybrid (analog-digital) beamforming antenna architecture as shown in Fig.1 is presented, to realize a cluster of multiple digital beams. The radar echo signal received by the antenna element is amplified at the T/R module and combined in RF manifold (subarray combiners), then divided into azimuth and elevation channels and further conditioned in Analog Beam Forming Network (ABFN) [2]. Herein, another stage of RF manifold is introduced, which drastically reduces down converters and ADCs requirement. The RF signal amplified at ABFN and combined at the third stage of RF combiner is down-converted using double conversion superheterodyne receiver (LO1 and LO2) to IF frequency as shown in Fig.1, and conditioned using anti-aliasing filter before digitisation in A/D converters for each channel [2], [4].

Complex weighing is applied at digital data using multipli-

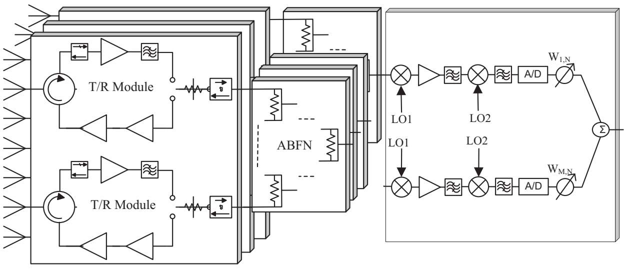

Figure 1. Hybrid beamforming phased array architecture.

cation and addition operation in DBF. By this means, beam steering is achieved for two-dimensional simultaneous multiple digital beams realisation in target spatial direction [5].

3 Multi-Function Phased Array Antenna

3.1 Electronic Scanning

The planar antenna, array factor [1] can be written as:

$$AF = \sum_{n=1}^{N} I_{1n} \left[\sum_{m=1}^{M} I_{m1} e^{j(m-1)(kd_x sin\theta cos\phi+\beta_x)} \right] \times e^{j(n-1)(kd_y sin\theta cos\phi+\beta_y)} \quad (1)$$

where I_{m1}, I_{1n} are the element excitation coefficients of the linear array in $x-$ and $y-$directions. In planer array d_x and d_y is the inter element spacing in $x-$ and $y-$ respectively. To steer the antenna beam in the spatial direction of $\theta = \theta_o$ and $\phi = \phi_o$, progressive phase shifts β_x and β_y along the $x-$ and $y-$directions can be calculated by using following equation:

$$\begin{aligned} \beta_x &= -kd_x sin\theta_o cos\phi_o \\ \beta_y &= -kd_y sin\theta_o cos\phi_o \end{aligned} \quad (2)$$

By using Eq.2 beam pointing direction of scanned beam can be calculated as

$$\begin{aligned} \phi_o &= \tan^{-1}\left(\frac{\beta_y d_x}{\beta_x d_y}\right) \\ \theta_o &= \sin^{-1}\left(\sqrt{\left(\frac{\beta_x}{kd_x}\right)^2 + \left(\frac{\beta_y}{kd_y}\right)^2}\right) \end{aligned} \quad (3)$$

3.2 Simultanious Multiple Beams

Analog beamforming networks are generally used because of less complexity and lower cost to form simultaneous multiple beams from a single aperture. An analog signal can be represented as

$$\begin{aligned} \mathbf{x(t)} &= x_R(t) + jy_I(t) \\ \mathbf{x(t)} &= \cos(\omega t) + j\sin(\omega t) \end{aligned} \quad (4)$$

where,$x(t)$ is the complex analog signal, j is $\sqrt{-1}$, $x_R(t)$ and $y_I(t)$ are the real and imaginary part of the signal. An analog multi-beam bemforming network consist of hybrid couplers and fixed-phase delay units. An amplitude weighting a_n and phase delay θ_n is applied as *"complex weight* in beamforming network and can be expressed as:

$$\begin{aligned} \mathbf{w_n} &= a_n \exp^{j(\theta_n)} \\ \mathbf{w_n} &= a_n \cos(\theta_n) + a_n j \sin(\theta_n) \end{aligned} \quad (5)$$

Hence, multiple beam signal can be expressed as

$$\begin{aligned} \mathbf{s_n(t)} = a_n[x_R(t)\cos(\theta_n) - y_I(t)\sin(\theta_n)] \\ + ja_n[x_R(t)\sin(\theta_n) + y_I(t)\cos(\theta_n)] \end{aligned} \quad (6)$$

In recent years, full-digital beamforming (DBF) has become more popular in which phase shifting and amplitude weighting are performed on each antenna element's digital streams. Then the digital signal is summed up to achieve beamforming gain and processed in real-time to form simultaneous multiple beams. Hence, simultaneous multiple digital beam patterns can be obtained by adjusting each array element's weight coefficient. Due to element level DBF, large numbers of down converters and ADCs are required, which increases the radar system complexity, power consumption, and cost.

In this paper, antenna architecture is envisaged in a combination of an analog RF and a digital beamformer, which can leverage analog and digital beamforming benefits. It reduces the hardware and signal processing complexity for optimal performance of phased array multi-function radar, i.e., Beam shape Loss, Angular Accuracy [3]- [4]. Herein, due to subarray configuration, spacing among the subarrays' phase center does not confirm for electronic scanning criteria. Hence, the grating lobe appears in radiation patterns of synthesized digital beams and limits the multibeam separation, and increases the beam overlap. To meet the said contradicting requirement of a cluster of simultaneous multiple beams, subarray size is optimized for an acceptable level of grating lobes [4]. Grating lobes are calculated by Eq.7.

$$\frac{\lambda_o}{d} + 1 > max|\sin\theta_n|, \qquad n = 1, \cdots, N. \quad (7)$$

Where d is the subarray spacing in either x-axis or y-axis, and N is the no in a cluster of the beam in Az/El.

4 Low-Cost Hybrid Beamforming Network

Multifunction Phased array radars require low beam-shape loss for a high update rate with a short searching time. This paper proposes a low-cost multi-channel hybrid beamforming architecture for subarray level clusters of multiple-beam formation to confirm for contradicting requirement.

4.1 Analog Beam Forming Network (ABFN)

The implementation methodology of the proposed scheme is illustrated in Fig.2 (a) as arrangements of antenna element satisfying the grating lobe requirement mention in Eq.7 for electronic scanning. Herein, two rows and four columns of radiating elements are summed using Wilkinson power combiner/divider and form 32 element subarray. In Fig.2 (b) phase centers of the 32 element subarrays are shown. In the next stage of analog beamforming, four such subarrays are combined and further divided into two channels as shown in Fig.3 to form independent azimuth and elevation channels. Further to that, in the next stage of analog beamforming, azimuth-azimuth and elevation-elevation channels are combined using the Wilkkanson power divider/combiner. Vertical and horizontal linear arrays of subarrays are shown in Fig.2(c) and (d) respectively, which forms multi-channels for down-conversion and digitization.

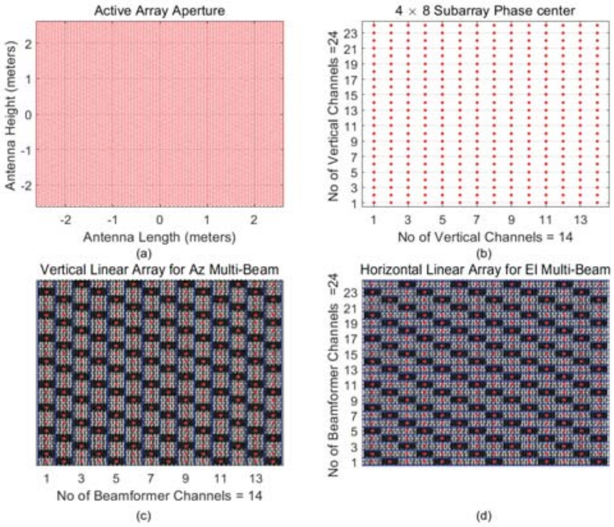

Figure 2. (a) Antenna aperture, (b) Subarray phase center, (c) Verticle linear arrays for El multibeam, and (d) Horizontal linear arrays for El multibeam.

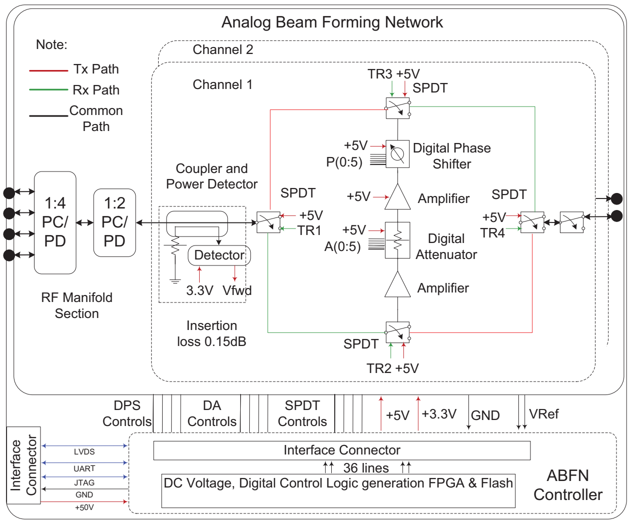

Figure 3. Functional block diagram of ABFN.

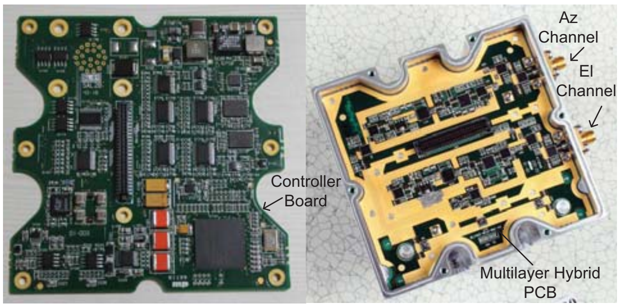

Figure 4. Realized ABFN on multilayer hybrid PCB.

In Fig.3, the functional block of Analog Beam Forming Network (ABFN) for the generation of independent azimuth and elevation channels, digital controls for digital attenuator, phase shifter, and SPDT switches are shown. ABFN has a 10 Mbps LVDS interface to receive commands for different radar operation modes and control bits for digital attenuator, phase shifter, and SPDT settings. ABFN is realized as shown in Fig. 4 on multilayer laminate, digital controls, and DC power on FR4 substrate and RF circuit on Rogers RT duroid as hybrid PCB. The proposed scheme mentioned in Sec.4.1 requires various RF manifold before down-conversion and digitization of the multi-channels [1]-[2], which is beyond this article's scope.

5 Multi-Channel Digital Beam Forming

Active phased array architecture illustrated in Sec.2 and shown in Fig.1 is having multiple subarrays for indepented vertical azimuth and horizontal elevatin channels. RF signals are received from multiple channels, double down converted and then digitized using high-speed ADC. The digital IF samples are translated to baseband by a direct-digital synthesizer (DDS). Digital baseband signal can be represented as

$$x_i = I_i + jQ_i \tag{8}$$

Where, I_i and Q_i are the 'in-phase' and 'quadrature' signal of the i_{th} subarray channel. Let's assume complex weight vector $\mathbf{w}$ is denoted as

$$\mathbf{w} = \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_N \end{bmatrix} = \begin{bmatrix} w_{1,1} & w_{1,2} & \cdots & w_{1,M} \\ w_{2,1} & w_{2,2} & \cdots & w_{2,M} \\ \vdots & \vdots & \ddots & \vdots \\ w_{N,1} & w_{N,2} & \cdots & w_{N,M} \end{bmatrix} \tag{9}$$

where $W_{N,M} = a_{n,m}e^{j\phi_{n,m}}$ ($m = 1, \cdots M$ and $n = 1, \cdots N$) is the complex weight for the subarray index n^{th}, m^{th}. Herein, $a_{n,m} = 1$ for equal amplitude weighting across the subarrays and $\phi_{n,m}$ is the steering phase for DBF beams. Hence, by making an appropriate weighting at subarray level DBF, independently controlled multiple digital beams can be synthesized within the constraints of subarray GL. The beam pattern can be represented as

$$y(t) = \mathbf{w}^H x(t) \tag{10}$$

The DBF formes optimal cluster of beams and beam layout by utilizing the steering weightings as shown in Fig.5(a) and (b). Since digitization is at subarray level, subarray greating lobes are visible because subarray phase center spacing is more than λ. Subarray GLs are tabulated in Table.1 for Az/El multi-beam. Synthesized azimuth and elevation multibeam patterns as shown in Fig.5(c) and (d). A fully flexible cluster of simultaneous multi-beams as shown in Fig.5(e) are formed; and processed by signal processors for target detection. Since cluster of multiple beams are steered simultaneously, a target may be detected in multiple beams depending on the target SNR.

In an example shown in Fig.5(f), a target is detected in

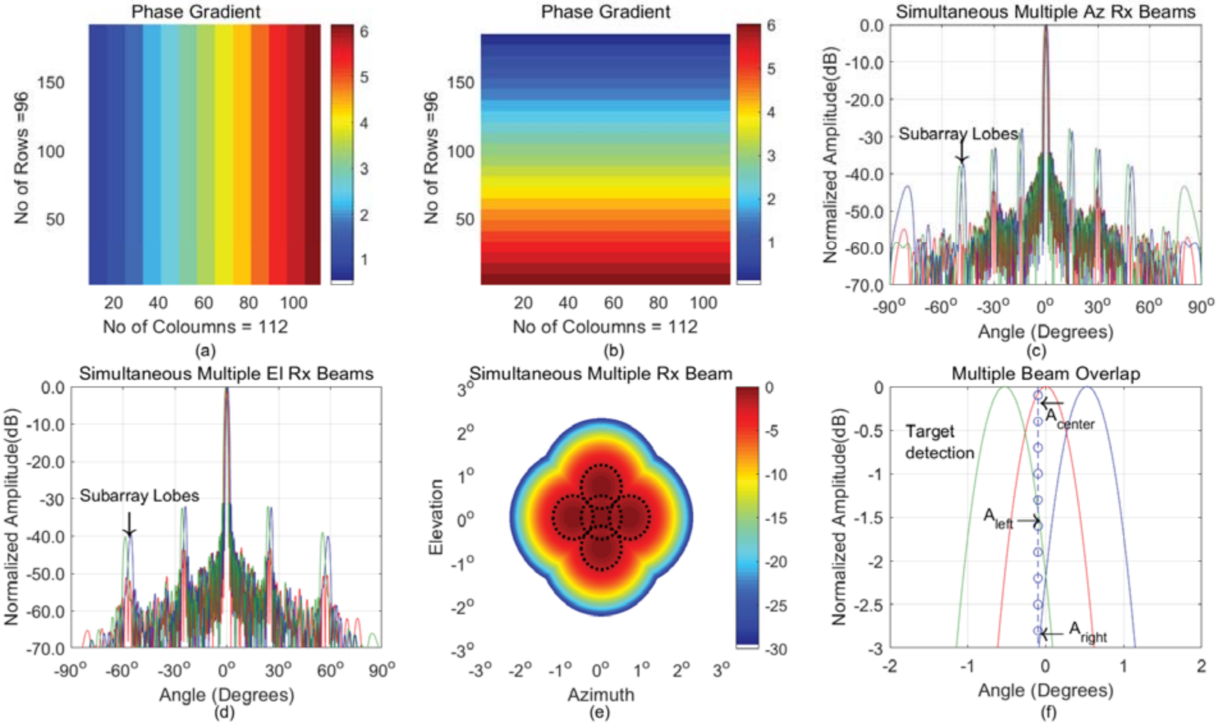

Figure 5. (a) Phase gradient for Az multi-beam (b) Phase gradient for El multi-beam (c) and (d) Az and El multi-beam patterns showing subarray GL effect (e) Cluster of multi-beams (f) Target detection in multi-beam configuration.

Table 1. Subarray Lobes in Multibeam Configuration

Rx Multibeam Overlap(dB)	Az GL Peak in dB	El GL Peak in dB
0.5dB	$\leq -27dB$	$\leq -32dB$
1.0dB	$\leq -25dB$	$\leq -29dB$
2.0dB	$\leq -22dB$	$\leq -27dB$

multiple beams whereas, A_{left}, A_{center} and A_{right} is the normalized amplitude of target echo. Since a cluster of five beams, as shown in Fig.5(e), is synthesized within the 3dB beamwidth of transmit beam. Hence beam shape loss can be reduced to 1.75dB from 3dB, and the target detection and angular accuracy are improved in the proposed configuration.

6 Conclusion

In this paper, a low-cost hybrid beamforming network for 2-D multibeam is presented by utilizing multiple stages of analog beamforming and subarray level DBF within the constraint of acceptable grating lobes due to the subarray effect. Analytical and simulation results are presented to produce multiple receiving beams by applying digital signals' re-steering within the transmit beam's 3dB beamwidth. This improves the average detection performance inside the 3dB beamwidth of the transmitting beam and finally enhances the radar's search performance.

7 Acknowledgements

The authors acknowledge their gratitude towards the Director LRDE for support during the work.

References

[1] R. J. Mailloux, *"Phased Array Antenna Handbook"*, 2nd ed. Chap.8, Artech House, Norwood, MA

[2] F. Gholam, J. Via and I. Santamaria, "Beamforming Design for Simplified Analog Antenna Combining Architectures," in *IEEE Transactions on Vehicular Technology*, vol. 60, no. 5, pp. 2373-2378, Jun 2011, doi: 10.1109/TVT.2011.2142205.

[3] Y. Li, H. Lv, Sun Peng and Zhang Xin-yu, "Study on search performance of subarray multi-channel phased array radar based on multiple received beams,"*IET International Radar Conference 2013*,2013, pp. 1-6.

[4] Yu, Kai-Bor. "Digital beamforming of multiple simultaneous beams for improved target search", inÂİ *2009 IEEE Radar Conference (2009)*: 1-5.

[5] M. C. Tan, M. Li, Q. H. Abbasi, and M. Imran, "A Flexible Low-Cost Hybrid Beamforming Structure for Practical Beamforming Applications,"*2019 IEEE International Symposium on Radio-Frequency Integration Technology (RFIT)*, Nanjing, China, 2019, pp. 1-3, doi: 10.1109/RFIT.2019.8929162.