Beamforming with Multi-Channel V-Band System-on-Chip Radar Platform for Gesture Sensing

Raghavendran Vagarappan Ulaganathan*, Thomas. F. Eibert*, Ashutosh Baheti†,
Reinhard Wolfgang Jungmaier‡, Saverio Trotta‡ and Gunnar Eisenberg‡
*Technical University of Munich, Munich, Germany 80290
†ALTEN GmbH., Elsenheimerstrasse 55, Munich, 80657
‡Infineon Technologies A.G., Neubiberg,Munich, Germany 85579
Email: raghavendran.ulaganathan@tum.de

***Abstract*—Advancements in high level integration of MMIC in package have led to the development of a system comprising of a multi-channel transceiver with antenna in package (AiP). Multi-channel systems provide additional advantage by enabling digital beamforming for direction of arrival estimation at 60 GHz. Different beamforming techniques are studied and practically implemented with a radar platform to find the location of the target. Different algorithms are compared and an overview with results are presented in this publication.**

I. Introduction

Radar sensors have a competitive edge over IR, ultrasonic, camera, LASER sensors due to their ruggedness, robustness for tough weather and lighting conditions. Radars which have been initially used for military or automotive applications are more likely to play a significant role in commercial and consumer applications in the future.

Recently, the area of gesture sensing is gaining more attraction and for this, radar can be an interesting platform. For this publication, a V band radar platform with 7 GHz bandwidth is investigated [1]. The available wide bandwidth with the radar system provides precise range resolution of two centimeters. Infineon's V-Band 60 GHz multichannel radar system with integrated antennas was developed on Infineon B7HF200 SiGe bipolar technology [2] and the entire transceiver chip (2 Tx / 4 Rx) in an embedded wafer level ball grid (eWLB) package. With eWLB package, the length of interconnections in the redistribution layer (RDL) is very short, resulting in reduced parasitics and realisation of precise low-loss transmission lines are made possible [3]. Also, passive components like antennas, filters, interconnects can be designed in the RDL for reduced losses at millimeter wave frequencies.

In this multichannel radar system, the receivers are arranged as 2×2 antenna array and the two Tx are placed in a way to keep polarization similar to Rx which helps to perform digital beamforming. Due to this Tx/Rx antenna configuration as shown in Fig. (1), the angle of the target in both the azimuthal and the elevation plane can be estimated. This configuration also enables beamforming concepts that have attracted considerable academic interest for applications like gesture sensing, home automation and indoor object tracking. This paper focuses on different Direction of Arrival (DoA) estimation techniques that are applied to the existing antenna configuration and radio frequency front-end. Techniques like spatial filtering and subspace based methods are studied and implemented in both simulation models and in measured indoor real time conditions. The perfomance of these algorithms is compared based on its DoA resolution, side lobe levels and the signal processing computations needed.

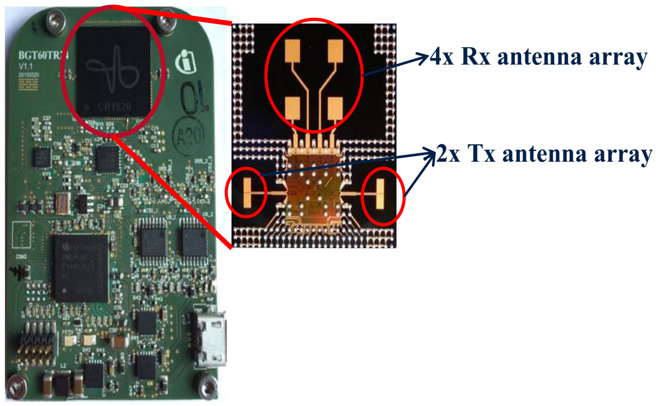

Fig. 1. Multichannel antenna configuration in V-Band system-on-chip radar sensor module

Section II discusses the data model and the assumptions considered for these DoA algorithms. Section III contains the basic theory of DoA algorithms which are implemented in this paper. Section IV contains the comparison results of simulation models and real world data for different DoA algorithms. Finally, Section V concludes the paper with the measurement results between DoA algorithms.

II. Data Model

The data model used for the DoA algorithms depends on certain assumptions in data that was observed in the real world. The following assumptions are considered throughout the description of DoA algorithms [4]. The transmission medium between the sources and the array elements is assumed to be isotropic and linear. The signal sources are assumed to be located far from the array elements such that the wavefront generated by each signal source arrives at all elements at an equal direction of propagation and the wavefront is planar. Also, the signal sources are assumed to be narrow band such that their frequency contents are concentrated close to the carrier frequency.

A. Uniform Linear Array (ULA) Model

Infineon V-Band 60 GHz multi-channel radar systems have an ULA configuration with two receivers. Consider an ULA model with M identical omnidirectional elements that are equally spaced on a straight line. Also, the distance Δ is present between the adjacent elements. The distance between the source and the first (rightmost) element is d_d. Fig. (2) depicts the configuration of the ULA.

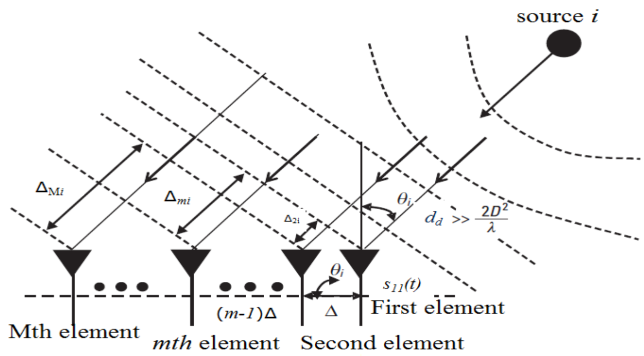

Fig. 2. Data model for DoA estimation with a linear array of M elements, adopted from [4], pg. 34.

Suppose that a planar wavefront narrowband signal is generated by the source i impinges on the array at an angle θ_i, then the signal received by the rightmost element with the delay t_d (far-field assumption) is given by

$$s_{i1}(t) = \alpha_i(t-t_d)cos[2\Pi f_c(t-t_d) + \beta_i(t-t_d)] \quad (1)$$
$$= Re\{s_i(t)\} \quad (2)$$

Also, the signal arrives at the m^{th} element with an extra distance to that of the rightmost element which is given as

$$\Delta_{mi} = (m-1)\Delta \sin\theta_i \quad \text{m=}1,\ldots,M.$$

Therefore, the signal arriving at the m^{th} element would be the delayed version of $s_{i1}(t)$ which can be expressed as

$$s_{im}(t) = Re\{s_i(t)e^{j(m-1)\mu_i}\}$$

$$\mu_i = \frac{-2\Pi f_c}{c}\Delta \sin\theta_i. \quad (3)$$

From Eq. (3), μ_i is the spatial frequency associated with the signal source that is present at an incident angle θ_i . The main objective of DoA estimation is to extract this spatial frequency μ_i from the signals received by the linear array.

Now consider, all the signals coming from d sources along with the noise is impinging on the m^{th} element. In the matrix form, it can be given as

$$\mathbf{x}(t) = \mathbf{A}s(t) + \mathbf{n}(t) \quad (4)$$

where $\mathbf{x}(t) = [x_1(t)x_2(t)\ldots x_M(t)]^T$ is the data column vector received by the array, $\mathbf{s}(t) = [s_1(t)s_2(t)\ldots s_M(t)]^T$ is the signal column vector generated by the sources, $\mathbf{n}(t) = [n_1(t)n_2(t)\ldots n_M(t)]^T$ is a zero mean spatially uncorrelated additive noises along with array steering matrix $\mathbf{A}$ with dimension $M \times d$.

B. Covariance Matrices

The signals received by the linear array were usually noise corrupted in the real world. These noises are uncorrelated, while pure signals are correlated as they are from the same sources. This concept can be used to estimate the DoA from the spatial covariance matrix of data received by an array, which are defined as

$$\begin{aligned} \mathbf{R}_{xx} &= \mathbf{E}\{\mathbf{x}(t)\mathbf{x}^H(t)\} \\ &= \mathbf{A}\mathbf{R}_{ss}\mathbf{A}^H + \sigma_N^2\mathbf{I}_M \end{aligned} \quad (5)$$

where $\mathbf{E}$ denote the statistical expectation, $\mathbf{R}_{ss}$ denote the signal covariance matrix and σ_N^2 is the common variance of the noises. Let us consider the noise corrupted signal matrix $\mathbf{X}$ composed of $\mathbf{N}$ snapshots of $\mathbf{x}(t_n)$ where n varies from 1 ...N, which is given as

$$\begin{aligned} \mathbf{X} &= [\mathbf{x}(t_1)\mathbf{x}(t_2)\ldots\mathbf{x}(t_N)]^T \\ &= \mathbf{AS} + \mathbf{N}. \end{aligned} \quad (6)$$

This equation denotes the stacked noise corrupted signals received by the array elements at different snapshots. Now, the estimate of the data covariance matrix $\mathbf{R}_{xx}$ can be given as

$$\mathbf{R}_{xx} = \mathbf{E}\{\mathbf{X}^H\mathbf{X}\}. \quad (7)$$

This fundamental data matrix is more robust against noise and hence used by beamforming and subspace DoA algorithms to extract the degree of correlation of the data signals.

III. DoA ALGORITHMS

A. Receive Beamforming Techniques

The basic principle of receive beamforming is to steer the array response in a particular direction at a specific time and measure the output power. When the steered direction coincides with the DoA of a signal, the maximum output power is observed. DoA algorithms differ in the design of an appropriate form of output power. With the knowledge of the array steering matrix $\mathbf{A}$, the weight vector $\mathbf{w}$ can be varied and linearly combined with the received data to form a single output signal $y(t)$. The total averaged output power of an array over N snapshots can be given as

$$P(\mathbf{w}) = \mathbf{w}^H\mathbf{R}_{xx}\mathbf{w}. \quad (8)$$

Here, different beamforming techniques are developed to estimate the average output power with different choices of weighting vector $\mathbf{w}$.

1) Conventional Beamformer: For the conventional beamformer, the weight vector $\mathbf{w}_{con}$ is normalized as

$$\mathbf{w}_{con} = \frac{\mathbf{a}(\theta)}{\sqrt{\mathbf{a}^H(\theta)\mathbf{a}(\theta)}}. \tag{9}$$

The weight vector can be visualised as a spatial filter such that a peak is observed in the power spectrum at the DoA angle but attenuate the output power for signals at all directions. By inserting the above Eq. (9) in Eq. (8), the output power as a function of angle of arrival is obtained as

$$P(\theta) = \frac{\mathbf{a}^H(\theta)\mathbf{R}_{xx}\mathbf{a}(\theta)}{\mathbf{a}^H(\theta)\mathbf{a}(\theta)}. \tag{10}$$

2) Capon Beamformer: A conventional beamformer works well with a single incoming signal impinging on the array. But, when there are multiple signals, the array output power contains signal contributions from the desired as well as the undesired angles [4]. A Capon Beamformer [5] overcomes this problem by forming nulls in all other directions except the look direction. The weight vector can be written as

$$\mathbf{w}_{CAP} = \frac{\mathbf{R}_{xx}^{-1}\mathbf{a}(\theta)}{\mathbf{a}^H(\theta)\mathbf{R}_{xx}^{-1}\mathbf{a}(\theta)}. \tag{11}$$

Again, for the above weight vector, the spatial power spectrum can be expressed as

$$P(\theta) = \frac{1}{\mathbf{a}^H(\theta)\mathbf{R}_{xx}^{-1}\mathbf{a}(\theta)}. \tag{12}$$

B. Subspace Technique-MUSIC algorithm

MUSIC (Multiple signal classification) is a very high resolution DoA algorithm which operates mainly on the data covariance matrix $\mathbf{R}_{xx}$. $\mathbf{A}$ has full column rank and the signal correlation matrix $\mathbf{R}_{ss}$ is non-singular as long as the incident signals are not highly correlated [6]. Also it implies that the incident signals are less than the antenna elements.

Since $\mathbf{A}$ has full rank and $\mathbf{R}_{ss}$ is nonsingular, this implies

$$\mathbf{A}^H\mathbf{q}_i = 0. \tag{13}$$

From Eq. (13), the $M - d$ eigen values are orthogonal to the d steering vectors that create the matrix $\mathbf{A}$. This can be expressed as

$$\{\mathbf{a}(\theta_1), \ldots, \mathbf{a}(\theta_d)\} \perp \{\mathbf{q}_{d+1}, \ldots, \mathbf{q}_M\}. \tag{14}$$

From the above Eqs. (13)-(14), it is seen that the eigen vectors of the covariance matrix $\mathbf{R}_{xx}$ are present in either of two orthogonal subspaces. The steering vectors corresponding to signal subspace are orthogonal to the noise subspace namely $\mathbf{V}_n = [q_{d+1}, \ldots, q_M]$. Therefore, the MUSIC power spectrum is given by

$$P(\theta)_{MUSIC} = \frac{1}{\mathbf{a}^H(\theta)\mathbf{V}_n\mathbf{V}_n^H\mathbf{a}(\theta)}. \tag{15}$$

The DoAs of the multiple signals impinging the array can be identified by locating the peaks using the above equation (15).

IV. Results

A. Comparison of Simulation and Real World Data for DoA Algorithms

Considering the ULA model in our existing multichannel system, the DoA algorithms were simulated by placing a single target for 256 snapshots with $M = 2$ antenna elements and SNR was assumed to be 20 dB.

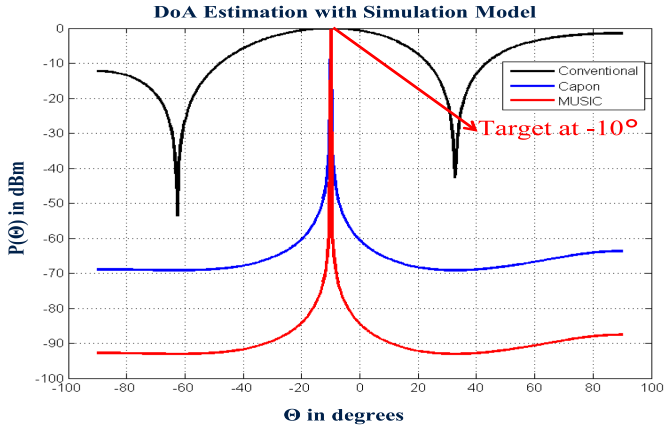

Fig. 3. Comparison of Conventional, Capon and MUSIC DoA simulation models for a single target at $-10°$ with 2 Rx

From the above Fig. (3), it is seen that the conventional beamformer beamwidth is broad and the sidelobes are really high. Capon and MUSIC algorithm have low side lobe levels but comes with increased computational complexity. Fig. (4) here shows a target at $-10°$ with increased sidelobe levels.

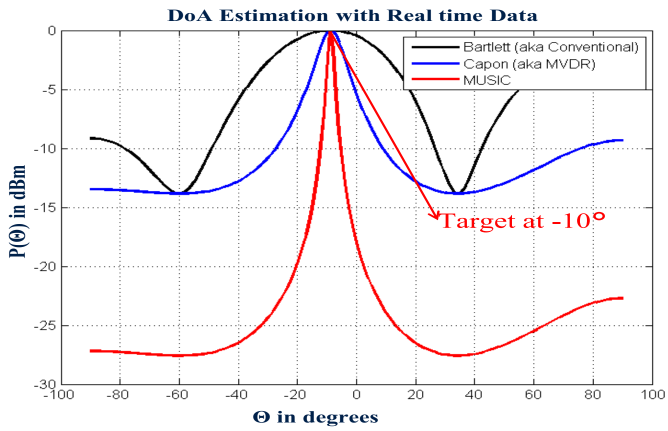

Fig. 4. Comparison of Conventional, Capon and MUSIC DoA for indoor real world environment for a single target at $-10°$ with 2 Rx

Also, the DoA resolution was calculated at half power beamwidth and the comparison is shown in the table I.

B. Beamscanning in Both Azimuthal and Elevation Plane

Beamscanning is performed using the four receivers by algorithmically applying proper phase shifts. This facilitates the change in direction of main beam to a particular expected angle and the return power is measured. Fig. (5) shows

TABLE I
COMPARISON OF DOA ALGORITHMS

DoA algorithm	DoA resolution	Sidelobe level	Computational complexity
Conventional	20°	-8 dBm	Covariance matrix calc.,
Capon	10°	-13 dBm	Inverse covariance matrix
MUSIC	less than 5°	-28 dBm	Signal/noise subspace calc.,

the beamscanning setup with the radar module's main beam steered along an imaginary plane.

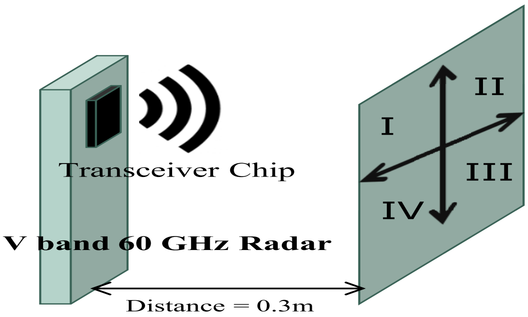

Fig. 5. Beamscanning setup with the radar module scanning an imaginary plane.

Fig. (6) resembles the indoor lab setup with the main beam steered along the four quadrants.

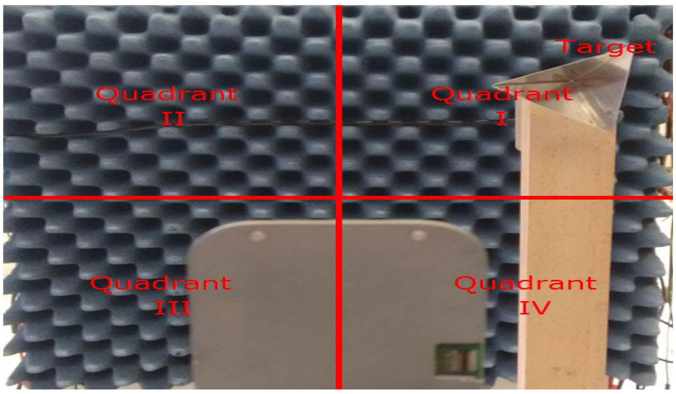

Fig. 6. Radar module's main beam steered along the four quadrants.

Also, the Fig. (7) and (8) show that the maximum power is returned (dark red region) from the quadrants 2, 1, 3 and 4 indicating the target detection at a particular azimuthal and elevation angle with an accuracy of $\pm 5°$ and the least power return is indicated as dark blue region.

V. CONCLUSION

In this paper, different DoA estimation algorithms have been presented on Infineon's V-band 60 GHz multichannel radar system. The underlying data model has been explained with regards to the theory of uniform linear arrays and the signal covariance matrices. From the three implemented algorithms, the MUSIC algorithm performs best with a good

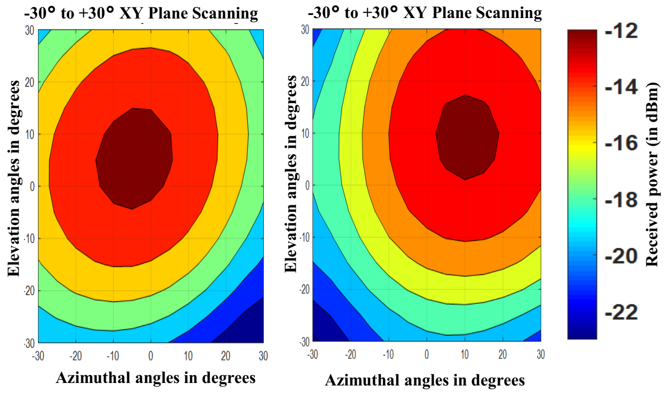

Fig. 7. Beamscanning resulting with targets at quadrant 1 and quadrant 2 respectively.

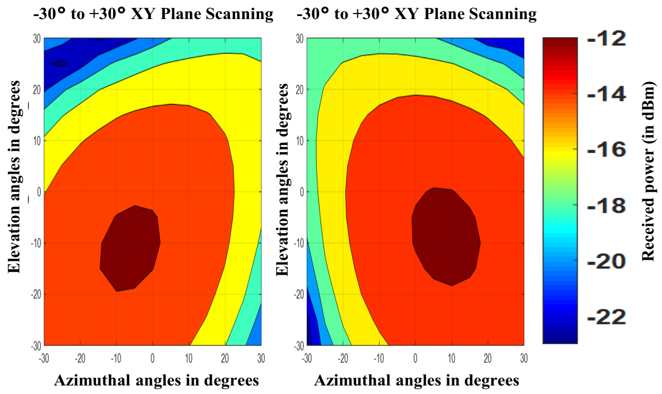

Fig. 8. Beamscanning resulting with targets at quadrant 3 and quadrant 4 respectively.

DoA resolution of less than 5°. Also, Capon serves well compared to a conventional beamformer with reduced sidelobe levels of about -6 dB. By applying phase shifts on the four receivers, beamscanning can be performed for measuring the return power from the four quadrants in front of the radar board.

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