URSI-RCRS 2024, ARIES/GEHU, Bhimtal, India, 22 - 25 October, 2024

Development of an FPGA based Smart Antenna System for Target Localization

Chethana P. N (1), Ishita Ghosh (2), Abhirup Bhawal (1) and Saurav Ganguly * (1)
(1) Presidency University, Bengaluru 560064, India, https://presidencyuniversity.in/
(2) Walmart Inc, Retail Intelligence, Arkansas 72716, United States of America

Abstract

The aim of this paper is to propose a cost-effective smart antenna-based radar system that can be used for target localization, that aids in search and rescue operation of trapped human lives. The whole plan of action can be sub-divided into three schemes, viz, development of a robust direction of arrival (DOA) estimation algorithm in a hostile environment; design, testing and measurement of the array of sensors for smart antenna; and implementation of the total scheme on a field programmable gate array (FPGA) platform. As per the FCC C-band classification, the frequency of operation is maintained between 3.7 GHz and 4.2 GHz, to achieve better resolution of the image and Doppler shift. Utilizing the Xilinx FPGA Spartan-7 SP701 board, the primary processes of the smart antenna system —such as the transmission and detection of RF signal are accomplished. This research and study demonstrate that a workable smart antenna system can be developed at a feasible cost and effort, that can be effectively used for direction finding and target localization in an inhospitable situation.

1. Introduction

This study proposes a narrowband, highly directional architecture of a radar imaging system based on smart antennas. In recent years, there has been an overwhelming global interest for sensing devices that can track and enable law enforcement, fire and rescue professionals, first responders, and defence forces to detect, identify, categorize, and track the whereabouts of people and moving objects that are concealed [1-5]. This technology (through the wall radar imaging or TWRI) can be investigated from the point of algorithms, modelling, testing, and system design by using smart antenna-based Space-Time Adaptive Processing (STAP) [6-9]. It requires study and analysis of the electromagnetic characteristics of the wall and materials, configuration and geometry of the antenna array, design of elements, and beamforming capabilities.

Conventional radar sensing and imaging devices are mainly built on a single directional antenna, with either distributed or collocated transceiver systems [3, 4]. The transmitting pulse generally ranges in the ultra-wideband (UWB) spectrum. UWB short signal length provide some advantages in radar sensing and detection like better resolution, reduced passive interference effect (from materials, mist, atmospheric disturbances, rain, etc.), lessening of radar dead zone, and others. But UWB, intrinsically possess certain disadvantages too. Compared to other wireless technologies, UWB signals have a shorter range, therefore for effective detection of movements or lives beyond any opaque obstacles or wall , they must be placed very close to the obstacle. This is a general drawback in situations where long-distance connectivity is necessary beyond the wall, as in expansive buildings or outside, beyond a wall. Also, use of directive horn antennas increases the system cost.

As an alternate of using a single directive antenna, utilizing a phased array system with some signal processing capabilities would yield significantly better results and efficiency in direction finding technique. These systems are popularly known as smart antennas or more recently, as multiple input- multiple output (MIMO) systems. A considerable improvements in wireless communication and radar tracking and detection are achieved by employing smart antennas with suitable algorithms for direction of arrival (DOA) estimation, spatial separation of signals and adaptive beamforming [10, 11]. For example, in radar tracking and TWRI applications smart antennas enable much more degrees of freedom (DOFs), accurate direction finding and better resolution capability for near coherent sources, at low computational complexity. Adjustments and modifications at the algorithmic level only, enhance the system to be more robust and efficient for target localization in hostile conditions (like low signal to noise ratio or SNR values, extreme multipath scenario or in the presence of high clutter). The achievement of adaptive beamforming in smart antennas contributes to enhanced tracking performance of mobile or quasi-stationary targets, as well as human hand and leg movements.

Fig. 1 shows a schematic of a smart antenna system. In most practicable instances, the phased array is a planar array structure. This results in more reliable and acceptable DOA estimation outcomes, in determination of both the azimuth and elevation angular direction of the targets. The phased antenna array structure is connected to the adaptive signal processing block (array processor), which consists of variable filter coefficients or weights, and the adaptive algorithm unit, that controls and adjusts the values of the variable weights. The DOA estimation and adaptive beamforming performance depends on the robustness of the adaptive algorithm developed. Standard blind and non-blind algorithms developed over the years are methodically available in the literature and their references [10-12].

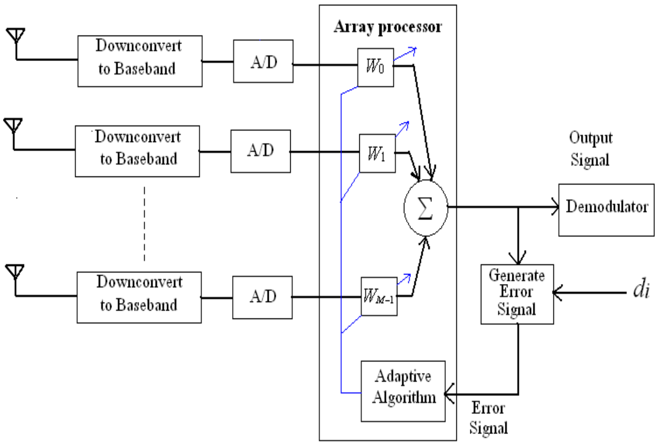

Fig. 1. A schematic of a smart antenna system or digital beamformer.

In fig. 2, the DOA estimation and adaptive beamforming capability for tracking objects of the smart antenna system is depicted, that are behind walls or other opaque obstacles [13]. The dynamic beamforming algorithm (or the adaptive algorithm) would adjust the weights as per the changing environment so that the main beam is steered (or beam steering) towards the quasi-stationary target and produce nulls (or null steering) towards intentional interferences or jammers.

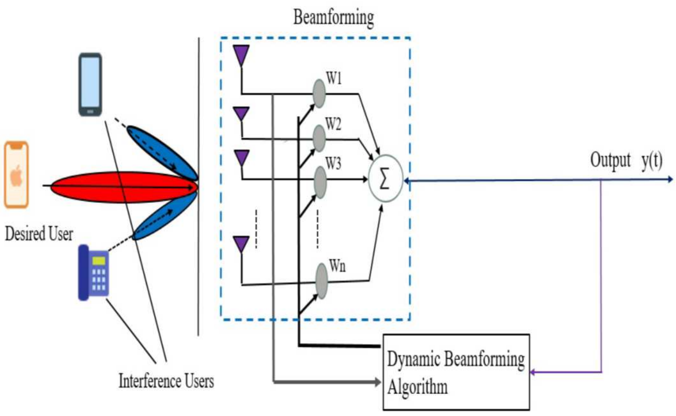

Fig. 2. A schematic of a smart antenna used to locate a target beyond an opaque obstacle. Picture courtesy, [13]

In this paper, a realistic, workable radar sensing device for through the wall imaging is proposed, using a smart antenna system, implemented on a FPGA board. The Xilinx FPGA Spartan-7 SP701 system is proposed to be used that embed the smart antenna with the phased array and the algorithms for DOA estimation and adaptive beamforming. After being generated, the signal is amplified using power amplification and then transmitted using a C-band Vivaldi antenna. The received echo signals (reflected from targets) impinge on the Vivaldi array antenna from various directions, and the FPGA acquires the signals to estimate DOA and beamform adaptively to localize and track the targets. The idea of SAR radar is used to process the signals that are received. Then, the sampled signal is transferred to a work station (or personal computer) for the image generation and processing.

2. The DOA Estimation and Adaptive Beamforming Algorithm

The algorithm for direction finding and subsequent adaptive beamforming must be such that it should be able to detect near coherent targets efficiently in a hostile environment (i.e., at low SNR values, high multipath effect and in presence of clutter). Efficiency, in this case is ascertained by high probability of resolution, and low root-mean-square-error (RMSE) in resolving the targets at low SNR values, etc. Degrees of freedom (DOFs) should be moderate enough and should not be heavily dependent on the physical array aperture. Also, the computational complexity should be within the viable bounds. A recently developed methodology, based on the blind Constant Modulus Algorithm (CMA), which is capable of resolving multiple targets efficiently at a reasonable complexity of computation, is proposed to be used in this work. Experimental results have shown that the Multi-Target Least Square Constant Modulus Algorithm (MT-LSCMA) can also null-steer (or produce nulls in specific angular directions) effectively to refute intentional jammers and clutters [9, 14, 15].

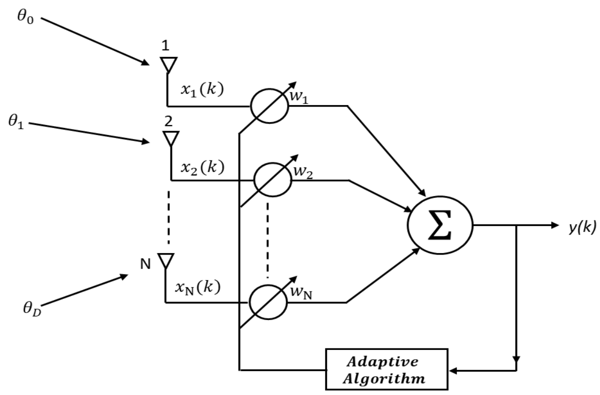

Fig. 3. An adaptive beamforming representation with blind algorithm

In the above illustration (fig. 3), a schematic of blind approach of adaptive beamformer is depicted. Signals reflected from targets (or echo signals) and signals originating from jammers, impinge on the antenna array from various angular directions θ_i. The array output y, at the k^{th} snapshot is given by:

$$y(k) = \boldsymbol{w}^H.\boldsymbol{x}(k) \qquad (1)$$

where $\boldsymbol{w} = [w_1, w_2, \dots \dots w_N]^H$ is the array weight vector, and $\boldsymbol{x}(k)$ is the received signal vector, which can be written as:

$$\boldsymbol{x}(k) = \boldsymbol{A}.\boldsymbol{s}(k) + \boldsymbol{n}(k) \qquad (2)$$

where $\boldsymbol{s}(k)$ is the vector of the impinging signals and $\boldsymbol{n}(k)$ is the AWGN vector, generated at each array element. The matrix $\boldsymbol{A}$ is known as the steering vector matrix or the array manifold matrix that carry the information about the angular direction of the impinging signals. Using MT-LSCMA, the direction of arrival (DOA) or location of the target/jammer can be found out by optimizing [9, 14]:

$$\hat{\theta}_k = \underset{\boldsymbol{\theta}}{\operatorname{argmin}} \frac{\widehat{\boldsymbol{a}}_{\boldsymbol{k}}.\boldsymbol{a}(\boldsymbol{\theta})}{\|\boldsymbol{a}(\boldsymbol{\theta})\|} \tag{3}$$

where $\boldsymbol{a}(\boldsymbol{\theta})$ is the steering vector. The beam-steering equation for weight updation is given by [14]:

$$\boldsymbol{w} \approx \widetilde{\boldsymbol{\mathcal{R}}}_{xx}^{-1}.\boldsymbol{A}(\theta) \tag{4}$$

where $\widetilde{\boldsymbol{\mathcal{R}}}_{\boldsymbol{xx}}$ is the array correlation matrix.

2.1. Simulation Results

Numerical simulations are carried out with direction finding and refuting jamming directions in a laboratory setup, employing MT-LSCMA algorithm.

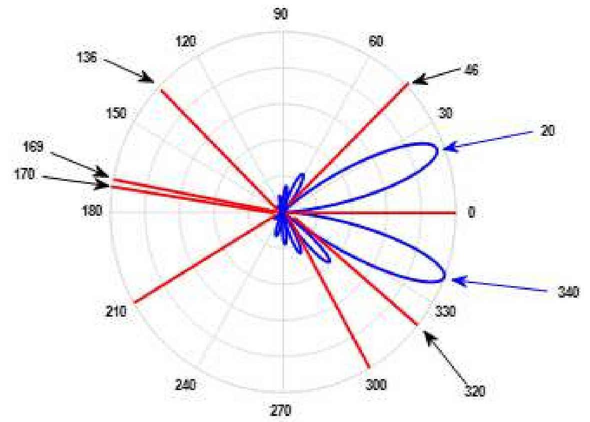

Fig. 4. Beam-steering and null-steering capabilities of MT-LSCMA. The main beam is formed towards the DOAs of the two target, at $340^0$and 20^0 . The eight multipath interferences / jammer DOAs are at $0^0, 46^0, 136^0, 169^0, 170^0, 210^0, 300^0$ and 320^0, at which, nulls are produced

The above figure (fig. 4) depicts a promising simulation result. The DOAs of two potential targets at 20^0 and 340^0 are identified and beam-steering along their direction is accomplished. Also, nulls are produced (null-steering) along the direction of jammers and/or multipath interferences. The whole simulation is carried out at SNR = -10 dB.

3. Implementation by FPGA with Vivaldi Antenna

The goal of implementing FPGA system is to provide the control function and incorporate the functionalities that the radar sensing system needs. In this work, it is proposed to use the Xilinx FPGA Spartan-7 SP701 board, Vivaldi antenna interfacing facilities [2, 16-18]. The working frequency range is fixed at as per the FCC assigned C-band, between 3.7 GHz and 4.2 GHz, to achieve better resolution of the image and Doppler shift.

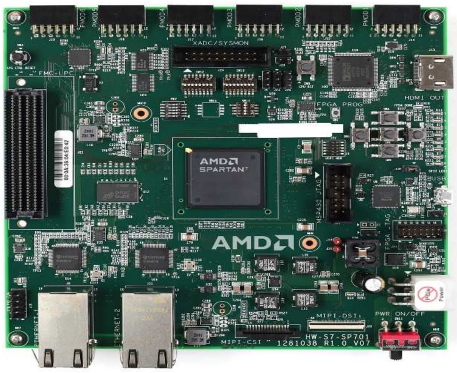

Fig. 5. FPGA Spartan-7 with FMC board, make: Advanced Micro Devices-Xilinx

The actual board on which the smart antenna system is to be implemented is shown in fig. 5. The block diagram of smart antenna functions, put into effect on FPGA, is shown in fig. 6.

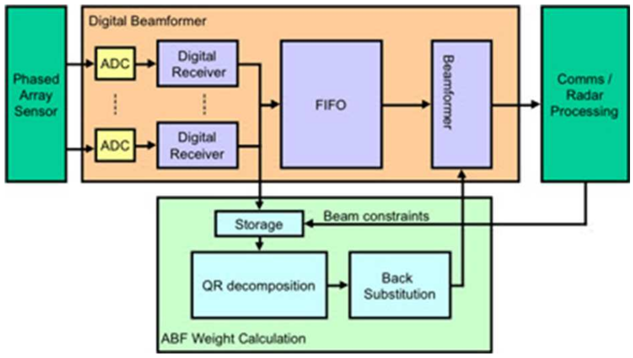

Fig. 6. Block diagram of smart antenna tasks implemented on FPGA.

4. Conclusion

This paper briefly describes an implementation design of a radar sensing system, operated in C-band, utilizing the Xilinx FPGA Spartan-7 SP701 board. The application of the model finds suitability in the domain of through the wall radar imaging, in search and rescue operation of trapped human lives beyond a wall or concealed under the rubbles. The proposed model is distinct and more effective than the traditional models since it uses Vivaldi antennas to collect radar returns (or impinging signals) and uses an MT-LSCMA based smart antenna algorithm for DOA estimation, signal separation, and adaptive beamforming. The array output signals are processed using the concept of SAR radar. Finally, the image processing and generation is performed and observed in a workstation.

5. References

[1] Moeness G. Amin and Fauzia Ahmad, Chapter 17 - Through-the-Wall Radar Imaging: Theory and Applications, Editor(s): Nicholas D. Sidiropoulos, Fulvio Gini, Rama Chellappa, Sergios Theodoridis, Elsevier - Academic Press Library in Signal Processing, vol. 2, pp. 857-909, 2014, ISBN 9780123965004, DOI: https://doi.org/10.1016/B978-0-12-396500-4.00017-X

[2] Yunqiang Yang and Aly E. Fathy, "Development and Implementation of a Real-Time See-Through-Wall Radar System Based on FPGA", *IEEE Transactions on Geoscience and Remote Sensing*, vol. 47, no. 5, pp. 1270-1280, May 2009.
DOI: https://doi.org/10.1109/TGRS.2008.2010251.

[3] Puli Kishore Kumar and T. Kishore Kumar, "Ultra-wideband Impulse-based Radar Signals for Through-the-wall Imaging", *Defense Science Journal* (DRDO-India), vol. 62, no. 3, pp. 187-192, May 2012. DOI: https://doi.org/10.14429/dsj.62.843 .

[4] P. K. M. Nkwari, S. Sinha and H. C. Ferreira, "Through-the-Wall Radar Imaging: A Review", *IETE Technical Review* – Taylor & Francis, vol. 31, no. 6, pp. 631 – 639, September 2017.
DOI: https://doi.org/10.1080/02564602.2017.1364146 .

[5] Fulai Liang, Hao Lou, Yang Zhang , Hao L v , Xiao Yu, Qiang An, Zhao Li, and Jianqi Wan, "Through-the-wall high-dimensional imaging of human vital signs by combining multiple enhancement algorithms using portable LFMCW-MIMO radar", *Measurement* – Elsevier, vol. 195, Article no. 111074, 31 May 2022, DOI:
https://doi.org/10.1016/j.measurement.2022.111074 .

[6] Alexiou, Angeliki and Haardt, Martin, "Smart antenna technologies for future wireless systems: Trends and challenges", *Communications Magazine* - IEEE, vol. 42. pp. 90 – 97, 2004.
DOI: https://doi.org/10.1109/MCOM.2004.1336725.

[7] Saurav Ganguly, Jeevan Kerketta, Puli Kishore Kumar, and Mainak Mukhopadhyay, "A study on DOA estimation algorithms for array processing applications", in the proceedings of IEEE - 2017 International Conference on Computing and Communication Technologies for Smart Nation (IC3TSN), 12-14 October 2017, Gurgaon, India. DOI: https://doi.org/10.1109/IC3TSN.2017.8284451 .

[8] Mingyue Zhai, "Smart Antenna Technology in Mobile Communication and Its Research Progress", in the proceedings of IEEE- 2017 International Conference on Computer Technology, Electronic s and Communication (ICCTEC), 19-21 December 2017, Dalian, China.
DOI: https://doi.org/10.1109/ICCTEC.2017.00311 .

[9] Saurav Ganguly**,** Jayanta Ghosh, Kishore Kumar P and Mainak Mukhopadhyay, "An efficient source localization method in presence of multipath using smart antenna system", *Journal of Scientific & Industrial Research*- NIScPR-CSIR (India), vol. 79, no. 12, pp. 1069-1073, December 2020. DOI: https://doi.org/10.56042/jsir.v79i12.35127 .

[10] Gross, Frank B. Smart Antennas with MATLAB®. 2nd ed. New York: McGraw-Hill Education. 2015, https://www.accessengineeringlibrary.com/content/book/978007182238, ISBN: 9780071822381 .

[11] Van Trees, H.L. Optimum array processing: Detection, Estimation and Modulation Theory-IV. Hoboken, NJ: Wiley. 2004, ISBN: 978-0-471-46383-2
DOI: https://doi.org/10.1002/0471221104 .

[12] Ganguly S, Ghosh J, and Kishore P. K, "Performance Analysis of Array Signal Processing Algorithms for Adaptive Beamforming", in proceedings of URSI Asia Pacific-Radio Science Conference (AP-RASC), 09-15 March 2019-New Delhi, India.
DOI: 10.23919/URSIAP-RASC.2019.8738291 .

[13] Hasibul Islam Imon, Md. Asikur Rahman, Md. Mahfuz Reza, Amit Karmaker, and Md. Abir Hossain, "Traffic Aware Dynamic Beamforming Antenna Design For 5G Communication", 31 May 2024, PREPRINT (Version 1) available at *Research Square*, DOI: https://doi.org/10.21203/rs.3.rs-4393228/v1 .

[14] Saurav Ganguly, Ishita Ghosh, Puli Kishore Kumar, Indranil Sarkar, Jayanta Ghosh and Mainak Mukhopadhyay, "Advancements in Jammer Location Identification and Suppression: Employing a Multi-Target Least Square Constant Modulus Array Approach", *Traitement du Signal*-IIETA, vol. 41, no. 2, pp. 629-641, April 2024. DOI:
https://doi.org/10.18280/ts.410207 .

[15] Saurav Ganguly, Sarkar I, Maity T, Mukhopadhyay M, Ghosh J and Kishore Kumar P, "Adaptive blind channel equalization in multipath environment", in topics of *Intelligent Computing and Industry Design (ICID)-Ethics and Information Technology (ETIT)*, pp. 23-26, 25-26 July 2020, Kolkata, India. DOI:
https://doi.org/10.26480/etit.02.2020.23.26 .

[16] Karmakar A, Bhattacharjee A, Saha A, and Bhawal A, "Design of a fractal inspired antipodal Vivaldi antenna with enhanced radiation characteristics for wideband applications", *IET Microwave. Antennas Propagation*-Wiley, vol. 13, no. 7, pp. 892-897, 2019, DOI: https://doi.org/10.1049/iet-map.2018.5360 .

[17] Tahar Z, Dérobert X, and Benslama M, "An ultra-wideband modified Vivaldi antenna applied to through the ground and wall imaging", *Progress Electromagnet Research-C*. vol. 66, pp. 111-122, 2018, DOI: https://doi.org/10.2528/PIERC18051502 .

[18] Bhattacharjee A, Bhawal A, Karmakar A, Saha A, and Bhattacharya D, "Vivaldi antennas: a historical review and current state of art", *International Journal of Microwave and Wireless Technologies*, vol. 13, no. 8, pp. 833-850, 2021, DOI:
https://doi.org/10.1017/S1759078720001415 .