

Forming High Gain Wide Beam with NULL Steering Ability to Receive UAV Signal based on Phased Array Antenna

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Abstract—Successfully achieving the mission of the unmanned aerial vehicle (UAV) requires high gain data link between the UAV and the ground control station (GCS). The antenna of the ground station must have a narrow, precisely guided beam towards the UAV. Widening the beamwidth in phased array will be on the expense of reducing the gain and increasing the possibility of receiving the interference signal, this may lead to the failure in achieving the desired link. This paper presents a new method to achieve an automatic forming of the reception beam and automatic tracking of the UAV's signal in the digital phased array without the need of the complex digital signal processing algorithms used in smart antenna. The proposed approach is based on the complex vector multiplication and phase conjugation technique. The UAV will stay on the beak of the array factor. The resulted array is a combination between the retrodirective array and the phased array, its beamwidth equal to the field of view without reducing the gain and with null steering ability. Comparison between the array response of the proposed approach and the array response of a tracking system using the Monopulse Digital Beam Forming algorithm against different values of the phase error deviation is done.

Index Terms—Enter Phased Array, phase conjugation, Retrodirective Array, geometric phase, complex vector multiplication, null steering

I. INTRODUCTION

SUCCESSFULLY achieving the mission of the unmanned aerial vehicle (UAV) and receiving all the signals sent by the UAV requires high gain data link between the UAV and the ground control station (GCS) [1]-[3], [5], [6]. The antenna of the ground station must have a narrow, precisely guided beam towards the UAV, so the angular position of the UAV will be on the boresight of the antenna and the UAV signal will be received from the beak of the antenna radiation pattern. Phased array is recently used in the GCS to achieve fast

tracking and to avoid the problems of the mechanical movement of the antenna in the traditional methods[4]-[6].

With phased array the beam can be directed towards the UAV electronically without physical movement of the array. In digital phased array the received signal at each channel will be multiplied with specific complex weight such a way the received signal from a specific direction will be added constructively and other signals will be added destructively[11]. The array response in lecture is defined as the sum of the weighted received signal at each channel and it's considered as a function of the direction of arrival of the received signal. The phased array can be adjusted to receive the signal sent from a specific direction by adjusting the phase of the complex weight of each channel to be equal to the conjugation of the geometric phase of this channel[11], [13]. The signal received on each channel is the phase shifted signal from the signal received on the reference channel due to the geometric position of the array elements and the angular position of the source signal. This phase shift is defined as the geometric phase. To find the geometric phase of each channel, the direction of arrival (DOA) of the UAV signal must be calculated by applying a direction finding algorithm[7], [8], like MUSIC algorithm[9], [10] or RSNS algorithm[4], [5]. Then after finding the geometric phase of each channel the phase of the corresponding complex weight must be adjusted to the conjugation of this geometric phase so the beam will be formed towards the UAV. To keep the UAV within the main lobe of the antenna array, a tracking algorithm must be used like "Monopulse Digital Beam Forming" algorithm[4], [5].

As a result we can see that the purpose of the tracking array in UAV applications is to keep receiving the UAV signal with high gain which means keeping the UAV within the main beam of the array response. So sometimes widening the beamwidth of the antenna array in the UAV applications is good for keeping the UAV within the main beam of the array, but it will be at the expense of reducing the gain and increasing the possibility of receiving the interference signal, this may lead to the failure in achieving the desired link.

We can see that despite the ease, flexibility, and relative simplicity of the phased array, achieving the mission of the UAV requires the application of a complex signal processing

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algorithm to determine the DOA of the UAV's signal, and also requires a precise tracking algorithm to keep the UAV within the main lobe of the antenna array, where these algorithms increase the computational cost of the phased array system and on the other hand are sensitive to the increased source of noise in phased array and require high calibration of the array[6], [12].

This paper presents a new method to achieve automatic forming of the reception beam towards the UAV and automatic tracking of the UAV's signal in the digital phased array without the need of the complex digital signal processing algorithms used in smart antenna. The proposed approach is based on the complex vector multiplication and phase conjugation technique (used in retrodirective array[14]-[17]) to find the geometric phase of each channel, so keeping the UAV on the beak of the array response within the field of view (FOV). The resulted array is a combination between the retrodirective array and the phased array, it has a widened beamwidth without reducing the gain, and with null steering ability. The proposed approach cancels the need of the complex digital signal processing algorithms (DOA, and tracking) so reducing the effect of the phase error, and on other hand reducing the computational cost of the tracking system. In this proposed approach the phase conjugated version of the received signal on each channel will be generated using the phase conjugation technique, and then the complex vector multiplication will be used to obtain the required phases of the complex weights to adjust the beam pattern of the array towards the incoming signal. As a result of using the phase conjugation technique the UAV will be always on the beak of the array response[16], so having a permanent high gain downlink during the movement of the UAV within the FOV. To eliminate the interference signal from a predefined direction, the "least squares error pattern synthesis with nulls" method[11] will be applied on the resulted complex weights to synthesis the main beam towards the UAV and nulls in the directions of the interference sources. As a result mixing between the phased array and the retrodirective array is done to get a wide beam high gain tracking array with null steering ability. To evaluate the improvement given by the proposed approach a comparison between the array response of the proposed approach and the array response of a tracking system using the Monopulse Digital Beam Forming algorithm against different values of the phase error deviation is done.

II. PROPOSED SYSTEM

We will present a proposed approach to achieve a tracking array with beamwidth equals to the FOV. This resulted array will has the ability to achieve a permanent high gain downlink between the UAV and the GCS, it also has the ability to eliminate the interference signal from a predefined direction.

A. Mathematical Representation

As a result of using the quadrature demodulation in the receiver, we can represent the received signal in the complex

form, as in (1).

$$S = e^{j\phi} \quad (1)$$

where ϕ is the phase of the received signal. By considering the first channel as a reference channel, (2) shows the complex vector representation of the signal received on the reference channel.

$$r_{ref} = e^{j\phi_{ref}} = S \quad (2)$$

Equation (3) shows the complex vector representation of the signal received on each channel.

$$r_n = e^{j\phi_n} \quad (3)$$

where n is the channel number, and ϕ_n is the phase of the received signal on the n th channel. In antenna array the received signal on each channel will be shifted from the signal received on the reference channel by the geometric phase of this channel[11], [12] as in (4).

$$\phi_n = \phi_{ref} + \phi_{gn} \quad (4)$$

where ϕ_{gn} is the geometric phase of the n th channel, which depends on the geometry of antenna elements, and the angle of arrival θ_i of the received signal. The geometric phase of each channel is given as in (4) for uniform linear array case.

$$\phi_{gn} = \frac{2\pi n}{\lambda} d \sin(\theta_i) \quad (4)$$

where d is the distance between array elements. Fig. 1. shows the phase shifts resulted due to the geometry of the antenna elements of a linear array.

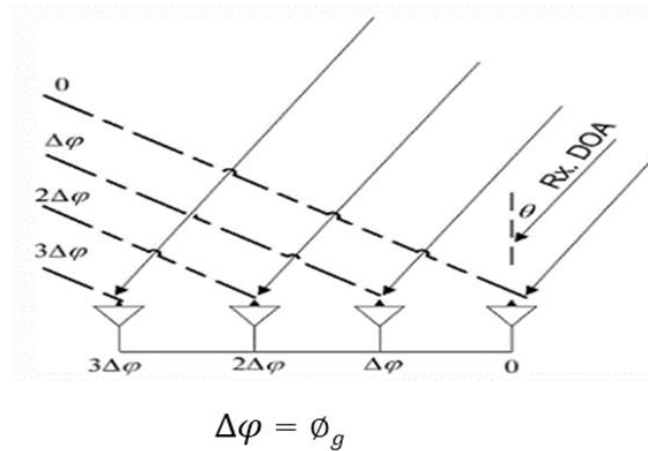


Fig. 1. Geometric phase

We can see that by multiplying the received signal on each channel by a complex weight with phase equal to the conjugation of the geometric phase, the phase shift on each channel will be compensated and the signals will be added constructively. The array response in digital phased array is

defined as the output of the beamformer (delay and sum beamformer[11]) by (5).

$$H = \sum_{n=0}^{N-1} w_n^* r_n \quad (5)$$

where w_n is the complex weight of the n_{th} channel. In the traditional phased array, to get the array response for a signal sent from a specific direction, a DOA algorithm should be used to find the geometric phase of each channel, then the required complex weight of each channel will be calculated as in (6).

$$w_n = e^{j\frac{2\pi n}{\lambda}d \sin(\theta_i)} = e^{j\phi_{gn}} \quad (6)$$

For non-isotropic array elements, the element factor must be considered in the array response formula[11], [12], so the array response for non-isotropic elements will be as (7).

$$H = EF(\theta) * \sum_{n=0}^{N-1} w_n^* r_n \quad (7)$$

where $EF(\theta)$ is the element factor.

In this proposed approach instead of using DOA algorithm to find the geometric phase of each channel, the complex vector multiplication will be used to find the geometric phase of each channel. Where the complex vector representation of the signal received on the reference channel will be multiplied by the complex vector representation of the phase conjugated version of the received signal on each channel separately,

The phase conjugated version of the received signal at each channel will be found using phase conjugation technique, and the complex vector representation of this signal is shown in (8).

$$r_n^* = e^{-j\phi_n} \quad (8)$$

Fig. 2. shows the representation of the complex vectors of these signals.

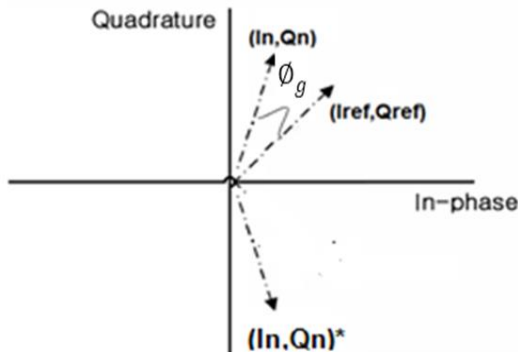


Fig. 2. Representation of complex vectors.

Equation (9) shows the resulted complex vector at each channel.

$$C_n = r_{ref} * r_n^* = e^{j(\phi_{ref} - \phi_n)} \quad (9)$$

By substituting ϕ_n from (4) in (9), the resulted complex vector will be as (10).

$$C_n = e^{-j\phi_{gn}} \quad (10)$$

We can see that, the resulted complex vector at each channel is equal to the required complex weight of each channel to form the beam towards the UAV. Equation (11) shows the resulted complex weight.

$$w_n^* = C_n = e^{-j\phi_{gn}} \quad (11)$$

So in this way we have got the required complex weight to form the beam towards the UAV without the need of a DOA algorithm. Then we can find the array response from (5).

By substituting (3), (4) and (11) in (5) the array response will be as (12).

$$H = \sum_{n=0}^{N-1} e^{j\phi_{ref}} = N * S \quad (12)$$

which represents the beak of the array factor. During the UAV movement within the FOV the complex weights of the array elements will be updated automatically according to the angular position of the UAV, so the array response will be always equal to the beak of the array factor.

B. Reducing the Effect Of Phase Error

Using the phased array results in increased sources of noise[12], The phased array is sensitive to phase error caused by random phase noise, quadrature modulation demodulation errors, and element dislocation[18]. Phase error can cause loss in gain, this may lead to the failure in achieving the desired link between the UAV and the GCS. To illustrate the effect of phase errors on the phased array performance, the phase error is considered in the array response equation. The reference[18] shows the final expression for the array response after considering all the possible phase errors as (13).

$$H = \sum_{n=0}^{N-1} w_n^* e^{j\phi_n} e^{j\delta_n} \quad (13)$$

where δ_n is the total phase error on each channel which is considered as a random variable. When the array directed towards the UAV the array response will be as(14).

$$H = e^{j\phi_{ref}} \sum_{n=0}^{N-1} e^{j\delta_n} \quad (14)$$

this equation illustrates the effect of the phase errors on the gain loss in the phased array.

In the proposed approach the phase error of each channel will be included in its complex weight and thus the phase error of each channel will be compensated. By considering the phase error of each channel, the complex vector representation of these signals from (2)(3)(8) will be modified to (15)(16)(17).

$$r_{ref} = e^{j(\phi_{ref} + \delta_0)} \quad (15)$$

$$r_n = e^{j(\phi_n + \delta_n)} \quad (16)$$

$$r_n^* = e^{-j(\theta_n + \delta_n)} \quad (17)$$

where δ_0 is the phase error on the reference channel. Then by multiplying the vectors(15) and (17) the resulted complex vector will become (18).

$$C_n = e^{j(-\theta_{gn} - \delta_n + \delta_0)} \quad (18)$$

So the complex weight of the corresponding channel will be (19).

$$w_n^* = e^{j(-\theta_{gn} - \delta_n + \delta_0)} \quad (19)$$

By substituting (19) in (13), the array response will be as (20)(21).

$$H = \sum_{n=0}^{N-1} e^{j(\theta_{ref} + \delta_0)} \quad (20)$$

$$H = N e^{j\theta_{ref}} e^{j\delta_0} \quad (21)$$

By Comparing (21) with (14) we can see that in the proposed approach the effect of the phase errors will be reduced to the case of a single antenna system, where the phase noise simply rotates the phase of the received signal while the signal amplitude is not affected.

C. Interference Signal Elimination

To eliminate the interference signals from predefined directions the “least square error pattern synthesis with nulls” method will be used. Equation (22) gives the synthesized beam(array response) using the least square error method for the case of linear array with zero order nulls,

$$B_o(\theta) = B_d(\theta) - \sum_{m=1}^{M_0} a_m B_c(\theta - \theta_m) \quad (22)$$

where M_0 is the number of the interference signals, $a_m B_c$ is the weighted conventional beam directed towards the interference source, and B_d is the desired beam(desired array response). The desired beam in this proposed approach will be synthesized using the complex weights resulted from the complex vector multiplication. The conventional beam will be given by (23).

$$B_c(\theta - \theta_m) = \frac{\sin(N\pi kd(\frac{\sin\theta - \sin\theta_m}{2}))}{\sin(\pi kd(\frac{\sin\theta - \sin\theta_m}{2}))} \quad (23)$$

The weight vector will be given with (24),

$$a = w_d^H C_0 [C_0^H C_0]^{-1} \quad (24)$$

where C_0 is the null constraint $N \times M_0$ vector, and N the number of array elements.

$$C_0 = [V_k(k_1) : V_k(k_2) : \dots : V_k(k_{M_0})]$$

$V_k(k)$ is the array manifold vector for a wavenumber towards the interference source.

The desired beam will be updated according to the UAV

movement within the FOV, therefore using the least square error method the synthesized beam will always have a main lobe directed towards the UAV with nulls directed towards the interference sources. As a result we get an array response with beam width equal to the FOV, and with the ability of null steering.

III. SIMULATION AND RESULTS

A uniform linear array with eight dipole elements was used to verify the proposed approach using matlab simulation environment.

The complex weights that resulted from (11) of the proposed approach were tested for different angular positions of the UAV, where the resulted complex weights at each angular position were applied separately on a traditional phased array of the similar case (same element number, and same distance between the elements) and then the array response of this similar case array was found using (5). Fig. 3. shows the formed beam pattern(array response) in a similar case phased array.

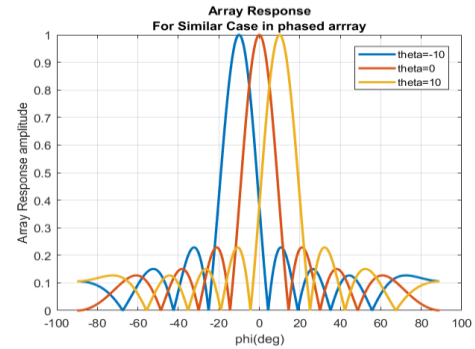


Fig. 3. Synthesized pattern with the resulted weights

We can see that the phased array has a peak of the array response at each angular position of the UAV, so it's the same case as if we used the required weights calculated using (6). Fig. 4. Shows the polar plot of this array response for these angular positions.

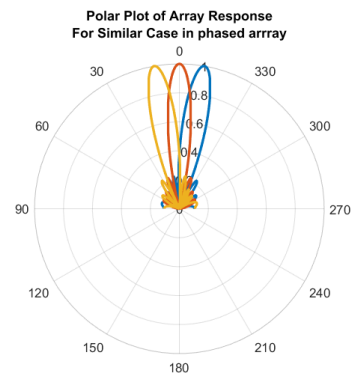


Fig. 4. Polar plot of the synthesized pattern with the resulted weights

We can say that the proposed approach give the required weights to form the beam towards the UAV in the phased array without the need to use a DOA algorithm, so the

proposed approach reduces the computational cost of the tracking system. The ability of the proposed array to track the UAV during its movement within the angular range $[-90^\circ +90^\circ]$ was tested by applying the resulted complex weights at each angular position on a traditional phased array of the similar case. Fig. 5. shows the polar plot of the beam pattern in the traditional phased array if it uses the resulted weight from the proposed approach when the UAV moved from $[-90^\circ +90^\circ]$.

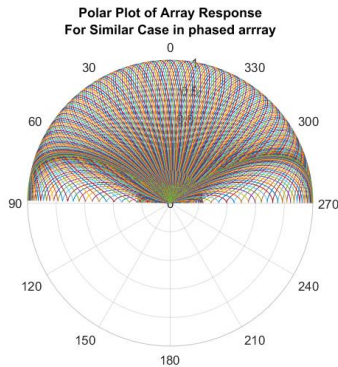


Fig. 5. Tracking the UAV angular position

We can see that during the UAV movement the complex weights was updated automatically to give the peak of the array response, so achieving the tracking of the UAV angular position without the need to use a tracking algorithm.

The array response for the proposed array was found from (12) after considering the element factor. The elements used in this simulation were dipole antennas, and their element factor is given by (25).

$$EF(\theta) = \cos(\theta) \tag{25}$$

Fig. 6. shows the resulted array response.

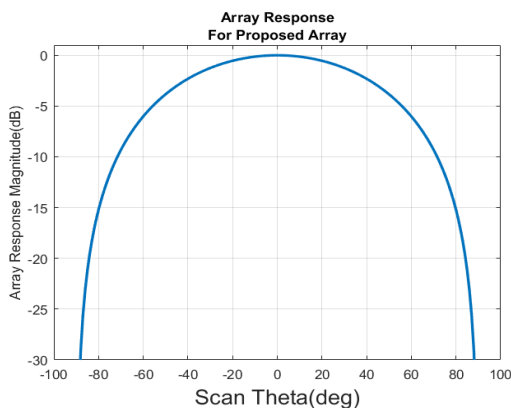


Fig. 6. The resulted array response

As a result we get an array with beam width equal to $[-45^\circ +45^\circ]$, which is equal to the FOV.

The improvement that the proposed approach given was evaluated by comparing its array response with the array response of a tracking array system using the digital beamforming monopulse tracking algorithm, against different values of the phase error deviation. The phase error was

supposed as a random variable with uniform distribution as in (26).

$$\delta_n \sim U[-\sigma_{max}, \sigma_{max}] \tag{26}$$

where σ_{max} is the phase error deviation $0^\circ \leq \sigma_{max} \leq 180^\circ$. The array response here was calculated from section 2B when the UAV moves within the FOV and after considering the element factor, Fig. 7, Fig. 8, and Fig. 9. show the array response for different values of the phase error deviation.

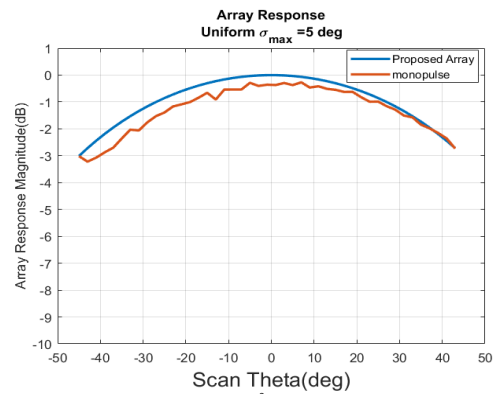


Fig. 7. Array response at $\sigma_{max} = 5^\circ$



Fig. 8. Array response at $\sigma_{max} = 20^\circ$

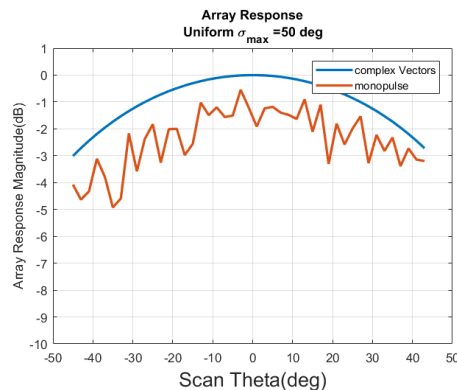


Fig. 9. Array response at $\sigma_{max} = 50^\circ$

We can see that the array response doesn't affected by the phase error while the monopulse tracking array is sensitive to the phase error and it requires high calibration of the array. These results show the advantage that the proposed approach

cancel the need to use the DOA and tracking algorithms in addition to reducing the computational cost of the tracking system.

The least square error method was applied on the resulted complex weight to add the null steering ability to the proposed array. The case of linear array with zero order null was taken. For simplicity one interference source at the angular position -5° was supposed. Then the resulted complex weights for different angular positions of the UAV were applied on a similar case phased array. Fig. 10. shows the formed beam pattern in a similar case in phased array with null at the angular position of the interference source and beam formed towards the UAV angular positions.

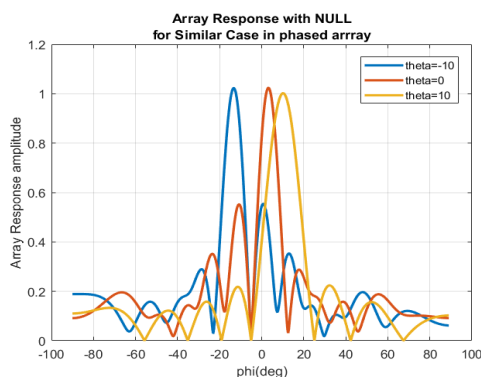


Fig. 10. Synthesized pattern with the resulted weights and UNLL

Fig. 11. shows the polar plot of the beam pattern in the phased array if it uses the least square error method on the resulted weights from the proposed approach when the UAV moves from $[-90^\circ +90^\circ]$.

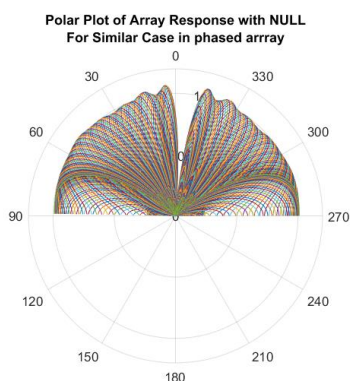


Fig. 11. Polar plot of the synthesized pattern with the resulted weights with NULL

It shows that, using the proposed approach with the least square error method, the array response will be always equal to the beak of the array factor of the phased array at the angular position of the UAV and null towards the interference source. The array response for the proposed array after applying the least square error method on its complex weights was drawn from (22) and the element factor was considered. Fig. 12. shows the array response.

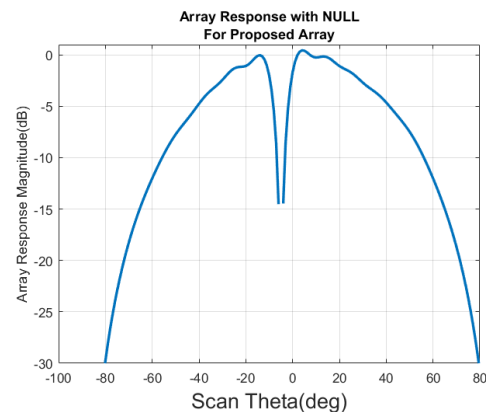


Fig. 12. The resulted array response with NULL

As a result we get an array with beam width equal to $[-45^\circ +45^\circ]$, which is equal to the FOV with the ability to null steering.

IV. CONCLUSION

This paper shows a proposed structure of a digital array receiver used for tracking the signal sent from UAV to GCS, which has a combination between phased array and retrodirective array. Generating the IQ signals of the received signal and its phase conjugated version, give the ability to find the geometric phase of each channel by multiplication of complex vectors and canceling the need for using complex signal processing algorithms which have a high computation cost. It achieves a significant reduction in computational complexity, in addition to automatic detection and tracking of the UAV signal, so a permanent high gain downlink is obtained. An array with beam width equal to the FOV and gain equal to the case of narrow beam array with the ability to null steering, is obtained. Generating the phase conjugation of each channel separately, it can be applied on a conformal array case. The matlab simulation shows the efficiency of this proposed approach.

REFERENCES

- [1] Hüseyin Okcu, "Operational Requirements of Unmanned Aircraft Systems Data Link and Communication Systems," *Journal of Advances in Computer Networks*, vol. 4, No. 1, March 2016.
- [2] Franc Dimc and Tone Magister, "Mini UAV communication link systems," Conference: ICTS, International Conference on Traffic Science, December 2006.
- [3] *Handbook of Unmanned Aerial Vehicles*, 3rd ed., Kimon P. Valavanis., George J. Vachtsevanos, Springer Dordrecht Heidelberg New York London, 2015.
- [4] Rakesh Kumar Sharma and Braj Bihari Soni "Analysis of a Radar system for UAV Tracking using MATLAB," *International Journal of Engineering and Technical Research(IJETR)*, vol. 7, Issue-6, ISSN: 2321-0869 (O) 2454-4698 (P), June 2017.
- [5] ShihYuan Yeh, "Development of a Digital Tracking Array with Single-Channel RSNS and Monopulse Digital Beamforming," M.S. thesis, Naval Postgraduate School., Monterey, December 2010.
- [6] Lars-Eirik Dalbakk, "Antenna System for Tracking of Unmanned Aerial Vehicle," M.S. thesis, Norwegian University of Science and Technology., Trondheim, Norway, June 2014.
- [7] Caleb Fulton , Mark Yeary , Daniel Thompson ,John Lake , and Adam Mitchell, "Digital Phased Arrays: Challenges and Opportunities," *Proceedings of the IEEE*, vol. 4, No. 1, March 2016.

- [8] Iyemeh Uchendu, and James Kelly, "Survey of Beam Steering Techniques Available for Millimeter Wave Applications," Progress In Electromagnetics Research B, Vol. 68, 35–54, May 2016.
- [9] Jeffrey Foutz, Andreas Spanias, and Mahesh K. Banavar, "Nonadaptive Direction of Arrival Estimation," in *Narrowband Direction of Arrival Estimation for Antenna Arrays*, Morgan & Claypool Publishers, 2008.
- [10] Youssef Khmou, Said Safi, and Miloud Frikel, "Comparative Study between Several Direction of Arrival Estimation Methods," Journal Of Telecommunications And Information Technology, 2014.
- [11] Harry L. and Van Trees, "Synthesis of Linear Arrays and Apertures," in *Optimum Array Processing. Part IV of Detection, Estimation, and Modulation Theory*, John Wiley & Sons, Inc, New York 2002.
- [12] *Phased Array Antenna Handbook*, 2d ed., Robert J. Mailloux, Artech House antennas and propagation library, 2005.
- [13] Gouri Nayana N, Nishesh Tiwari, and Rama Rao, "An Overview on Beamforming and its Issues for 60 GHz Wireless Communications," ITSI Transactions on Electrical and Electronics Engineering (ITSI-TEEE), vol. 1, Issue -4, 2013.
- [14] Lei Chen, Yu Chun Guo, Xiao Wei Shi, and Tian Ling Zhang, "Overview on the Phase Conjugation Techniques of the Retrodirective Array," International Journal of Antennas and Propagation, Article ID 564357, 2010.
- [15] Chuo Yang, and Ai-xin Chen, "A direct conversion phase conjugation arithmetic for retrodirective antenna array system," IEEE, 4th International Symposium, 2011.
- [16] Kevin M. K. H. Leong, Ryan Y. Miyamoto, and Tatsuo Ito, "Ongoing Retrodirective Array Research at UCLA," Tech. Rep. OF IEICE, SPS2002-08, 2002.
- [17] D.S.Goshi, K.M.K.H.Leong, and T.Itoh, "Recent advances in retrodirective system technology," IEEE, Radio and Wireless Symposium, 2006.
- [18] Marcos Chi Lim Siu, "Effects Of Local Oscillator Errors On Digital Beamforming," M.S. thesis, Naval Postgraduate School., Monterey, March 2016.

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