A Comparative Study of Different DOA Estimation Schemes and Adaptive Beam Forming Techniques for Target Detection and Tracking

Susaritha U.S
Dept. of Electronics Engineering, Madras Institute of Technology Campus, Anna University, Chennai, India

Ganesh Madhan. M
Dept. of Electronics Engineering, Madras Institute of Technology Campus, Anna University, Chennai, India

Ragupathi. R
Dept. of Electronics Engineering, Madras Institute of Technology Campus, Anna University, Chennai, India

Ashita Priya Thomas
Dept. of Electronics Engineering, Madras Institute of Technology Campus, Anna University, Chennai, India

ABSTRACT
This paper reports a comparative study of different Direction of Arrival (DOA) estimation methods and application of adaptive beam forming for target detection and tracking. DOA algorithms such as Beamscan, Minimum variance distortion less response (MVDR), Multiple Signal Classifier (MUSIC), root-MUSIC, Estimation of signal parameters via rotational invariance (ESPRIT) have been investigated, with initial data obtained from Received Signal Strength (RSS) measurement in a Wi-Fi environment. Location estimation using root-MUSIC and ESPRIT algorithms have been carried out for a moving target. Optimum combination for best performance is identified. Simulations have been carried out in MATLAB tool.

Keywords
Received signal strength indication (RSSI), Direction of arrival (DOA), Root Mean Square Error (RMSE), Signal Strength Set Identifier (SSID), Signal estimation, Adaptive beam forming.

1. INTRODUCTION
Location estimation and tracking of objects and vehicles have become important in recent days. Significant efforts have been made towards the development of efficient approaches for target localization and tracking. Location tracking can be done with RSSI based techniques [1], but the accuracy of localization highly depends on the path loss model. Fluctuations in environment conditions affect the localization results. Recently Wi-Fi technology has been widely deployed for LAN applications and this can be used for position determination [2]. In our previous report [3], we have estimated the location based on RSSI in a Wi-Fi environment and a maximum deviation around 7.6 % was observed. In order to improve the localization accuracy and to track effectively, DOA estimation along with adaptive beam forming is required. Adaptive beam forming ensures that even when RSSI methods fail to localize target, it tracks the target successfully. The accuracy is dependent on correct DOA estimation of the required signal and cancelling the interferences. Hence a combination of RSSI, adaptive beam forming and DOA estimation techniques can provide successful localization and tracking.

RSSI based location estimation in wireless sensor networks have been investigated by Raida Al Alawi [1]. The results of this work reveal the feasibility of RSSI based localization algorithm in designing real-time position monitoring system. Location estimation has been done using trilateration. The Root Mean Square (RMS) node positioning error was computed as the distance between the actual and the estimated position of the target node. Nwalozie et al [4] have compared various adaptive beam forming algorithms such as Direct matrix inversion, constant modulus algorithm, least square constant modulus algorithm, Least mean square (LMS) algorithm and Recursive LMS algorithms. Solution for Fast Mobile Target Tracking based on Kalman Filter and MUSIC Algorithm is proposed in Ref [5], where, tracking error was obtained to be less than one degree. Passive location of non co-operative emitters can be achieved by triangulation, direction of arrival measurements or by trilateration, time difference of arrival (DTOA) measurements, which require cross correlation processing to determine the emitter location. Both techniques when used separately result in ambiguities in a multiple-emitter environment when the various source emissions overlap in time/frequency and space. F.J Berle [6] had described a concept of a mixed triangulation/trilateration emitter location system in order to circumvent the ambiguities. He has found that the measurement accuracy is strongly dependent on target geometry relative to the baseline between the measuring sensor pair. Based on the approach of Ref.[6], this paper focuses on combining trilateration and DOA estimation techniques for detection and tracking.

2. DOA ESTIMATION AND BEAMFORMING [7]
The major classification of DOA estimation schemes includes conventional and adaptive methods. Maximum signal power is detected when the DOA of the signal matches with the steering direction of the array. Detailed descriptions of various algorithms are provided in Refs [7-10]. However, we brief about the schemes which are used in this work, in the following paragraphs.

2.1 Beamscan Algorithm
The beamscan algorithm develops conventional beam scans over the region of interest and computes the square of the

signal magnitude [8]. The signal power reaches a maximum at the impinging angle, as illustrated by the following expression.

$$P_{norm}(\theta) = a^H(\theta)\ \mathrm{R}_{xx}\ a(\theta) / a^H(\theta)\ \mathrm{a}(\theta) \quad (1)$$

Where, a(θ) is the steering vector array, Rxx is the input data covariance matrix and H denotes the transpose of the matrix.

This scheme has to determine the maximum power for all values of "θ" and hence becomes cumbersome. In the case of linear array, FFT can be used for detecting the power. The resolution of this approach is higher for small array aperture. But this scheme is restricted to single source cases, as it fails for multipath and multi source conditions.

2.2 Minimum variance distortion less response beam former (MVDR)

MVDR method [8] improves the performance by avoiding the unwanted signals. This scheme minimizes the array output power and the spectrum is given by

$$P_{MVDR}(\theta) = 1/[a^H(\theta)\ \mathrm{R}^{-1}{}_{xx}\ \mathrm{a}(\theta)] \quad (2)$$

This approach does not have array restrictions and leads to better resolution. However, it needs increased power and does not perform well under multiple source environments.

2.3 Subspace based techniques

These techniques determine the signal space based on the received data and evaluate the DOA.

2.3.1 Multiple signal classification (MUSIC)

MUSIC provides a precise evaluation of DOA. It is also based on the concept of orthogonality of signal vector to noise vector. The expression for music spectrum is given by

$$P_{MUSIC}(\theta) = 1/\{a^H(\theta)\ \mathrm{V}_n\ \mathrm{V}_n{}^H\ \mathrm{a}(\theta)\} \quad (3)$$

where Vn is the noise vector.

The DOA is "(θ)" when PMUSIC(θ) reaches a maximum. The peaks of the spectrum reveal the DOA. The resolution of this approach depends on the sensor parameters.

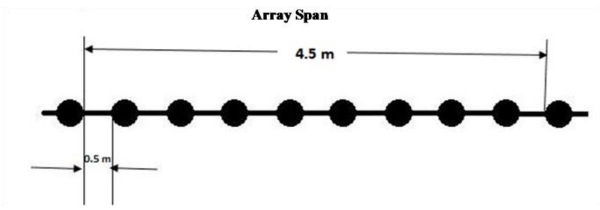

Fig 1: Uniform linear array

2.3.2 Root-MUSIC algorithm

Root-MUSIC is an approach that provides straight forward computation of DOA. This scheme is classified under Model-Based Parameter Estimation (MBPE) technique. This scheme utilizes the roots of the signal Eigen vector lying in the unit circle, to determine the DOA of the sources. However this technique is limited to linear array cases.

Table 1. ULA specifications

No. of elements	10
Signal frequency	300 MHz
Element spacing	0.5 m
Propagation speed	3e8 m/s
Wavelength	1 m
Gain at steering angle	10 dB
1-D array span	4.5 m

2.3.3 Estimation of Signal Parameters via Rotational Invariance technique (ESPRIT)

The property of rotational invariance of the signal space is utilized to detect the DOA, in this case. The unique feature of this scheme is that it requires less computation and direct evaluation of DOA. But its use is restricted due to the need of more number of sensors.

2.4 Adaptive beamforming techniques

Adaptive Beam forming [9-10] uses a number of antennas or sensors to evaluate the DOA in a noisy environment. It also cancels the effect of inference signals. The implementation schemes include Minimum Variance Distortion less Response (MVDR) and Linearly Constrained Minimum Variance (LCMV). MVDR is limited by the self nulling condition; however this problem is overcome in LCMV approach.

3. ANALYSIS AND RESULTS

For localization, three Wi-Fi access points or base stations were considered. The device to be tracked accesses these stations using Wi-Fi, and transmits the information regarding the received signal strength from them, to the stations.

Table 2. DOA Estimates

Impinging source Broadside (°)	**Beam -scan (°)**	**MVDR (°)**	**MUSIC (°)**	**Root MUSIC (°)**	**ESPRIT (°)**
40, -20	40, -20	40, -20	40, -20	40.0038, -20.0004	-19.9981, 39.9984
25, 40	25, 40	25, 40	25, 40	25.0005, 39.9987	25.0009, 40.0015
30, 40	35, 71	30, 40	30, 40	30,40	29.9977, 40.0041
35, 40	37, 64	35, 40	35, 40	34.9973, 40.0004	40.0031, 34.9918
37, 40	38, 66	38, 14	37, 40	36.9940, 40.0017	36.9851, 40.0008

Using the obtained RSSI values and the path loss model, target position was determined by application of trilateration algorithm. However, the accuracy of the location estimation depends on the loss model. This data is used as the initial conditions for the tracking simulation. For analysis of DOA algorithms, a Uniform Linear Array (ULA) has been used. Table 1 gives the specifications of the ULA and Figure 1 shows a descriptive picture of the array considered for the study.

DOA estimates were obtained using the above mentioned algorithms and are tabulated as in Table 2. All simulations have been carried out using MATLAB software.

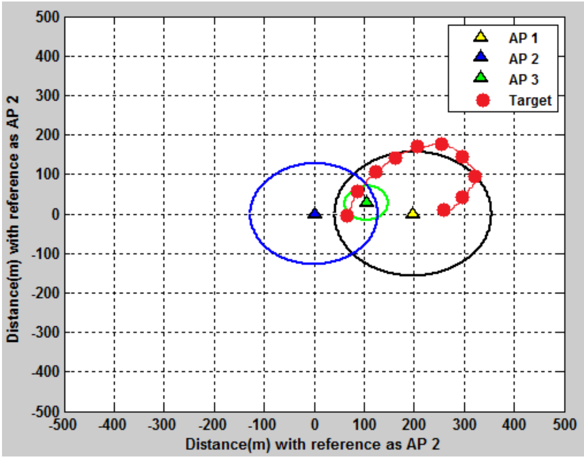

Fig 2: Path traced by the target object

When the signals arrived from directions, which are separated less than the beam width of beamscan beam former, improper estimates were obtained. For two signals impinging at 30° and 40°, the DOA estimates were obtained as 35° and 71° respectively, using beamscan algorithm. For the same values of impinging angle, as taken for beamscan algorithm, i.e. 30° and 40°, DOA estimates were obtained correctly using MVDR method, as its beamwidth is smaller than beamscan beamformer.

Table 3. DOA estimates using Root MUSIC and ESPRIT

Target Coordinates		Elevation angle (°)	Azimuth angle (°)	Broadside angle (°)	DOA Estimates (°)	
x(m)	y(m)				ROOT MUSIC	ESPRIT
60	20	51.3247	1.9092	1.1929	1.1887	1.2221
90	60	34.7365	33.6901	27.1191	27.1617	27.1139
120	100	25.6474	39.8056	35.2475	35.2712	35.3434
140	140	20.7470	45.0000	41.3955	41.3514	41.4334
200	180	15.5750	41.9872	40.1207	40.0895	40.1796
250	185	13.5582	36.5014	35.3287	35.3517	35.4247
300	150	12.6044	26.5651	25.8767	25.9198	25.8544
320	100	12.6098	17.3540	16.9227	16.9326	16.8949
300	45	13.8870	8.5308	8.2796	8.2999	8.2696
250	10	16.6866	2.2906	2.1941	2.2082	2.2247

For signals separated with a space less than MVDR beamwidth, MVDR does not resolve them and super resolution techniques are adopted. Root MUSIC, MUSIC and ESPRIT give correct estimates when impinging source angles are at 37° and 40° whereas MVDR fails. Hence, it is clear that beamscan algorithm gives improper estimates for closely spaced signals. Further, MVDR also fails if difference in source signal directions is less than its beam width. Better resolution is achieved by MUSIC, Root-MUSIC and ESPRIT algorithms.

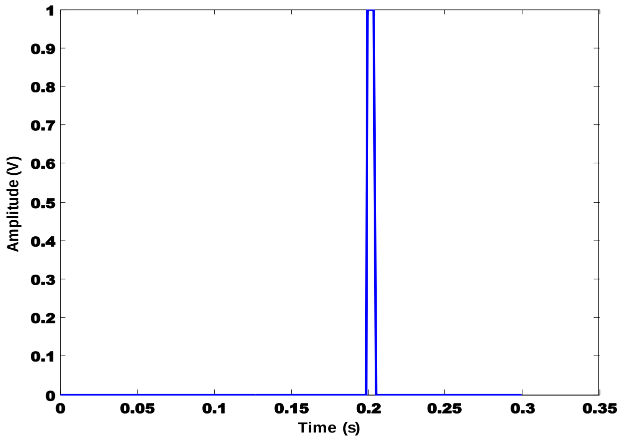

Fig 3: Received pulse at antenna array

The scenario considered for the tracking analysis is illustrated in Figure 2, where the base stations or Access Points used are denoted by AP1, AP2 and AP3. The location of AP2 is fixed as reference (0, 0). The location of AP1 and AP3 are kept as (198.1, 0) and (106.56, 27.44) respectively. The dots joined by a line in Figure 2 indicate the path traced by the object. The initial position of the target in the path is given by the coordinate (60, 2) and was found using trilateration. Considering the antenna array to be placed at AP 2, for the path tracked by an object in the Figure 2, continuous DOA estimates were obtained using root-MUSIC and ESPRIT algorithms. These estimates are tabulated in Table 3.

From the results tabulated in Table 3, it is found that the maximum deviation from the original DOA estimates is 1.41 % and 3.06% for root-MUSIC and ESPRIT algorithm respectively. Thus root-MUSIC algorithm is found to provide better DOA estimates than ESPRIT algorithm, for the system under study.

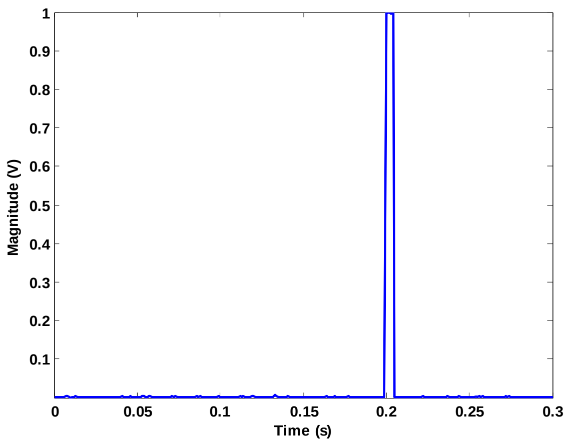

Fig 4: MVDR output in the presence of interferences

Adaptive beam forming is implemented for an antenna array for receiving a narrow band signal in the presence of noise and interference. Figure 3 shows the received signal, which is assumed to impinge on the array at 45° azimuth and 0° elevation. We first investigate the performance of MVDR in this scenario. Two interference signals are simulated to arrive from 30° and 50° in azimuth. MVDR algorithm effectively cancels the interferences and recovers original signal. This observation is shown in Figure 4.

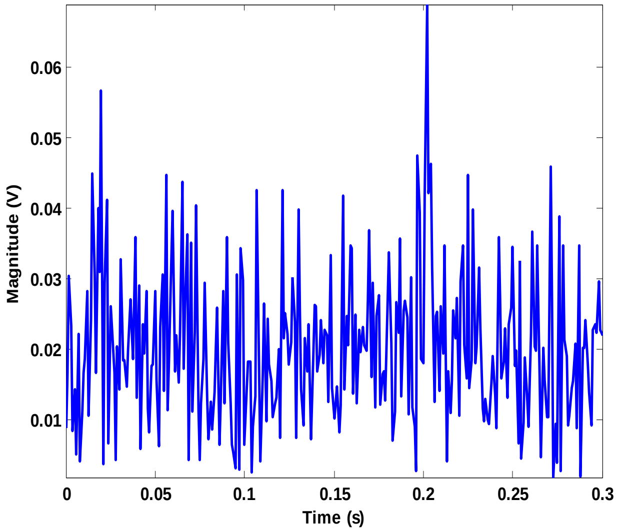

Fig 5: Output of MVDR with signal direction mismatch

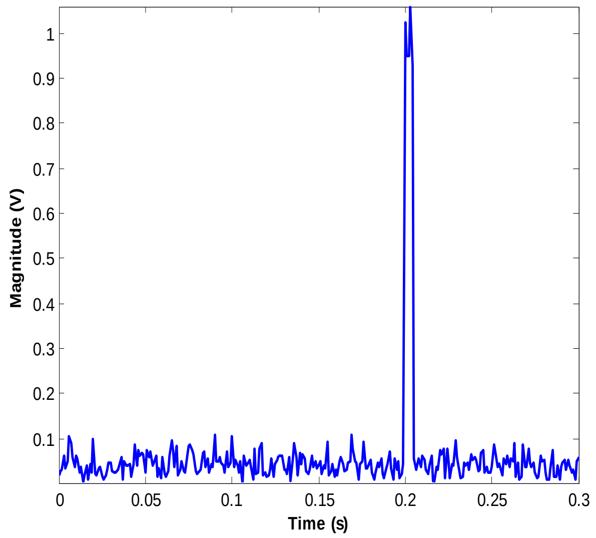

Fig 6: LCMV beamformer output with signal direction mismatch

However, MVDR fails in case of self-nulling. To implement this case, the real signal is considered to arrive from a direction of 45° azimuth. Due to sensor position error, the impinging angle is estimated as 43°. Also it suppresses the required signal and provides a distorted version of the original received signal. This response is shown in Figure 5.

In the case of LCMV method, it provides better output for the same conditions. Figure 6 shows the LCMV output, which clearly indicates the recovery of the original signal even in the case of signal direction mismatch. A comparison of beam former responses is shown in Figure 7.

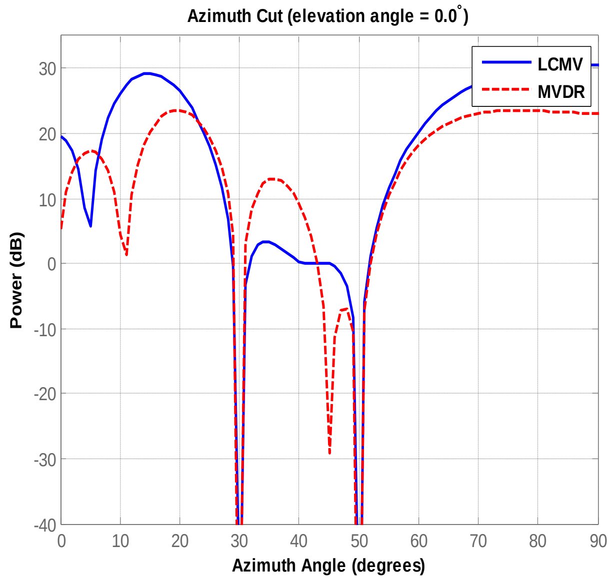

Fig 7: LCMV and MVDR beamformer response pattern

From the analysis, it is inferred that, LCMV is a better choice as it places nulls only at the interferences and does not suppress the required signal at 45°, despite a signal direction mismatch. Thus, LCMV method is a better choice for receiver array signal processing. The optimal DOA technique is root-MUSIC algorithm as it is more accurate than ESPRIT algorithm.

4. CONCLUSIONS

Different DOA and adaptive beamforming techniques for target tracking in a Wi-Fi environment were analyzed in this work. The merits and demerits of various DOA schemes are identified. An RSS based position determination is first carried out, which is followed by DOA and adaptive beam forming techniques. Root-MUSIC algorithm provides better DOA estimates than ESPRIT algorithm, for the system considered in the study. It is observed that LCMV performs better as it avoids self nulling and recovers the required signal even under the presence of interfering signals.

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