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Localization of Near Field Radio Controlled Unintended Emitting Sources

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Abstract**—**Locating Radio Controlled (RC) devices using their unintended emissions has a great interest considering security concerns. Weak nature of these emissions requires near field localization approach since it is hard to detect these signals in far field region of array. Instead of only angle estimation, near field localization also requires range estimation of the source which makes this method more complicated than far field models. Challenges of locating such devices in a near field region and real time environment are analyzed in this paper. An ESPRIT like near field localization scheme is utilized for both angle and range estimation. 1-D search with symmetric subarrays is provided. Two 7 element uniform linear antenna arrays (ULA) are employed for locating RC source. Experiment results of location estimation for one unintended emitting walkie-talkie for different positions are given.

Keywords**—**Localization, angle of arrival (AoA), range estimation, array signal processing, ESPRIT, uniform linear array (ULA).

I. Introduction

SUPER-HETERODYNE or super-regenerative receivers are mostly used in Radio Controlled (RC) devices and they are sensitive to radio frequency (RF) stimulation [1], [2]. RC devices emit unintended radiations due to this stimulation and these emissions are used to detect the RC device [2], [3].

In order to locate an RC device using stimulated emissions near field methods are required since these emissions are weak and affected by environmental effects like noise and fading. Various techniques have been developed in the past decades for source localization in far field region [4], [5] where impinging waves on the antenna array are considered as plane waves. On the other hand, if the sources are in the near field region of the antenna array, wave fronts of these sources are spherical instead of planer. Both angle and range should be estimated for localization in such situations which is challenging than only angle estimation.

Bearing estimation techniques with plane wave approximation, where arrival angles to each element of array are assumed to be same, show unsatisfactory performances when waves have spherical wave fronts. Major challenge in near field angle of arrival (AoA) estimation is nonlinear wave front shape.A good approximation for this nonlinearity is second order Taylor expansion (Fresnel approximation) if sources are placed in Fresnel region for uniform linear array [6].

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Recently some near field source localization methods are proposed in the literature such as 2-D MUSIC [7], which searches both angle and range, however it requires two dimensional search. Higher order statistics are used to develop ESPIRIT like methods in [8], [9] where rotation invariance property is applied with help of cumulants of received signal covariance matrix. Instead of these eigen decomposition methods, maximum likelihood estimation is presented in [10] where Expectation/Maximization iterative method used for estimating signal parameters. Polynomial rooting [11] is proposed as another technique in near field localization. Reference [12] minimizes the 2-D MUSIC cost function with path following method to eliminate two dimensional search.

Research in localization area mostly study theoretic aspects and computer simulations or experiments are performed in a controlledand shielded medium [13], [14]. Furthermore majority of the work is objectedfor locating active devices and there is not enough work in the literature for locating a passive device with its unintended emissions. Thus the main contribution of proposed work is 1) real time application and 2) performance analysis of near field location estimation of a passive, unintededly emitting device.

The rest of this paper is organized as follows. Section II outlines the near field signal model and methodology of the technique that utilized in the experiment. Measurement results in a real time environment is given in Section III and finally Section IV concludes the paper with future directions.

II. Methodology

A. Near Field Signal Model

Consider M near-field, narrowband passive radiating sources is observed by an $(2K+1)$ element uniform linear array with inter element spacing d and letarray center be the phase reference point. Received signal by k^{th} sensor is written as

$$x_k(t) = \sum_{m=1}^{M} e^{j\tau_k(\theta_m, r_m)} s_m(t) + n_k(t) \quad , k \qquad K, ..., K \tag{1}$$

where $s_m(t)$ is the received power of m^{th} source , $n_k(t)$ is the white Gaussian additive noise and $\tau_k(\theta_m, r_m)$ is phase shift due to propagation delay between reference sensor and sensor k for the m^{th} passive source In near field, this phase shift is a nonlinear function of range r_m, angle θ_m and wavelength λ of source signal, written as

$$\tau_k(\theta_m, r_m) = \frac{2\pi}{\lambda}\left(\sqrt{r_m^2 + (kd)^2 - 2r_m kd \sin\theta_m} - r_m\right) \qquad k = -K, \ldots, K \quad (2)$$

If source m is in the Fresnel region [6], which is given by $0.62\left(D^3/\lambda\right)^{1/2} < r_m < 2D^2/\lambda$, where D is the aperture of the array, $x_k(t)$ can be approximated with Fresnel approximation [8] as

$$x_k(t) = \sum_{m=1}^{M} e^{j\left(-\frac{2\pi d}{\lambda}\sin\theta_m\right)k + j\left(-\frac{\pi d^2}{\lambda r_m}\cos^2\theta_m\right)k^2} s_m(t) + n_k(t) \quad k = -K, \ldots, K \quad (3)$$

The received signals vector, $\mathbf{X}(t) = \left[x_{-K}(t), \; ..... \;, x_K(t)\right]^T$, T denoting transpose, can be expressed in matrix form,

$$\mathbf{X}(t) = \mathbf{AS}(t) + \mathbf{N}(t) \quad (4)$$

$\mathbf{S}(t) = \left[s_1(t), \cdots, s_M(t)\right]^T$ is signal vector, $\mathbf{N}(t) = \left[n_{-K}(t), \ldots, n_K(t)\right]^T$ is the noise vector and $\mathbf{A} = [\mathbf{a}(r_1, \theta_1), \cdots, \mathbf{a}(r_M, \theta_M)]$ is the array matrix where the steering vector $\mathbf{a}(r_m, \theta_m)$ for m^{th} source being represented as

$$\mathbf{a}(r_m, \theta_m) = \begin{bmatrix} a_{m,-K} \\ \vdots \\ a_{m,K} \end{bmatrix} = \begin{bmatrix} e^{j\left(-\frac{2\pi d}{\lambda}\sin\theta_m\right)K + j\left(-\frac{\pi d^2}{\lambda r_m}\cos^2\theta_m\right)K^2} \\ \vdots \\ e^{-j\left(-\frac{2\pi d}{\lambda}\sin\theta_m\right)K + j\left(-\frac{\pi d^2}{\lambda r_m}\cos^2\theta_m\right)K^2} \end{bmatrix} \quad m = 1, \ldots M \quad (5)$$

B. Localization of Passive Sources

It is obvious from (5) that, the elements in $\mathbf{a}(r_m, \theta_m)$ are symmetric with respect to second term. Using this property, if the ULA is divided into two subarrays, these subarrays will be symmetric respecting second terms. First subarray is built with first L sensors in ascending order and second subarray is built with the last L sensors in descending order [15]. Received signal from these two subarrays is written as

$$\mathbf{X}_1(t) = \mathbf{A}_1\mathbf{S}(t) + \mathbf{N}_1(t), \qquad \mathbf{X}_2(t) = \mathbf{A}_2\mathbf{S}(t) + \mathbf{N}_2(t) \quad (6)$$

with $M < L < 2K + 1$, $\mathbf{N_1}$ and $\mathbf{N_2}$ are noise vectors of first and second subarray respectively. $\mathbf{A}_1$ is constructed with first L rows of $\mathbf{A}$ and $\mathbf{A}_2$ is built with last L rows of $\mathbf{A}$ in reverse order. Affiliation between subarray manifolds and $\mathbf{A}$ is

$$\mathbf{A} = \begin{bmatrix} \mathbf{A}_1 \\ \text{last } (K - L) \text{ rows} \end{bmatrix} = \begin{bmatrix} \text{first } (K - L) \text{ rows} \\ \mathbf{JA}_2 \end{bmatrix} \quad (7)$$

with $\mathbf{J}$ is the anti-identity matrix satisfying $\mathbf{J^2} = \mathbf{I}$.

$$\mathbf{A}_1 = \left[\mathbf{a}_1(r_1, \theta_1), \cdots, \mathbf{a}_1(r_M, \theta_M)\right] \quad (8)$$

Using the symmetric property $\mathbf{A}_2$ is represented as

$$\mathbf{A}_2 = \left[\mathbf{C}(\theta_1)\mathbf{a}_1(r_1, \theta_1), \cdots, \mathbf{C}(\theta_M)\mathbf{a}_1(r_M, \theta_M)\right] \quad (9)$$

with

$$\mathbf{C}(\theta_m) = diag\left[e^{-j\left(\frac{4\pi d}{\lambda}\sin\theta_m\right)K}, \ldots, e^{-j\left(\frac{4\pi d}{\lambda}\sin\theta_m\right)(K-L+1)}\right] \quad (10)$$

which is a function of angle θ_m only, not r_m. Covariance matrix of received signal is $\mathbf{R} = E\left[\mathbf{X}(t)(\mathbf{X}(t))^H\right]$ and eigen decomposition of it can be written as

$$\mathbf{R} = \mathbf{U}_s\mathbf{\Lambda}_s(\mathbf{U}_s)^H + \mathbf{U}_n\mathbf{\Lambda}_n(\mathbf{U}_n)^H \quad (11)$$

with $\mathbf{U}_s$ stands for M eigenvectors in signal subspace, and $\mathbf{U}_n$ denotes $2K + 1 - M$ eigenvectors of noise subspace. $\mathbf{\Lambda}_s$ contains signal eigen values and $\mathbf{\Lambda}_n$ denotes the noise eigen values. H symbolizes complex-conjugate transpose. Generalized ESPRIT method is applied to covariance matrix for angle estimation. There exists a $M \times M$ full rank matrix $\mathbf{D}$ with $\mathbf{U}_s = \mathbf{AD}$, i.e.

$$\mathbf{U}_s = \begin{bmatrix} \mathbf{U}_{s1} \\ \text{last } (M - L) \text{ rows} \end{bmatrix} = \begin{bmatrix} \text{first } (M - L) \text{ rows} \\ \mathbf{U}_{s2} \end{bmatrix} \quad (12)$$

where

$$\mathbf{U}_{s1} = \mathbf{A}_1\mathbf{D}, \qquad \mathbf{U}_{s2} = \mathbf{JA}_2\mathbf{D} \quad (13)$$

Moreover

$$\mathbf{JU}_{s2} = \mathbf{J}^2\mathbf{A}_2\mathbf{D} = \mathbf{A}_2\mathbf{D} \quad (14)$$

Introducing a diagonal matrix as in generalized ESPRIT [5]

$$\mathbf{\Delta}(\theta) = diag\left[e^{-j\left(\frac{4\pi d}{\lambda}\sin\theta\right)K}, \; \cdots \;, e^{-j\left(\frac{4\pi d}{\lambda}\sin\theta\right)(K-L+1)}\right] \quad (15)$$

According to (12) and (14),

$$\mathbf{JU}_{s2} - \mathbf{\Delta}(\theta)\mathbf{U}_{s,1}^{S1} = [\left(\mathbf{C}(\theta_1) - \mathbf{\Delta}(\theta)\right)\mathbf{a}_1(r_1, \theta_1), \ldots, \left(\mathbf{C}(\theta_M) - \mathbf{\Delta}(\theta)\right)\mathbf{a}_1(r_M, \theta_M)]\mathbf{D} \quad (16)$$

Note that k^{th} column of matrix $\mathbf{JU}_{s2} - \mathbf{\Delta}(\theta)\mathbf{U}_{s1}$ will become zero when $\theta = \theta_k$. Therefore, with an arbitrary $K \times M$ full rank $\mathbf{F}$ matrix, $\mathbf{F}^H\mathbf{JU}_{s2} - \mathbf{F}^H\mathbf{\Delta}(\theta)\mathbf{U}_{s1}$ becomes singular

Next, the spectrum function below can be utilized to find the angles for multiple passive devices as

$$P(\theta) = \frac{1}{\det\left|\mathbf{F}^H \mathbf{J}\mathbf{U}_{s2} - \mathbf{F}^H \boldsymbol{\Delta}(\theta)\mathbf{U}_{s1}\right|} \tag{17}$$

After bearing estimation, estimated $\hat{\theta}_m$ is substituted in steering vectors and 1-D MUSIC is established for range estimation.

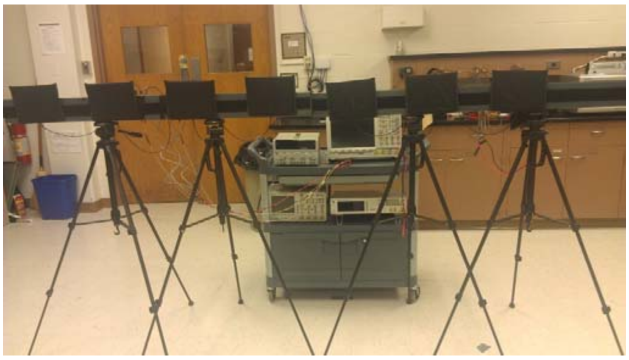

Fig. 1 Measurement setup for the experiment

III. Experiment Results and Discussion

Channel 8 (FRS) of a walkie-talkie is utilized for the experiment. A continuous, -40 dB stimulating signal at 467.5625 MHz is provided with Agilent MXG-N5182A signal generator. Walkie-talkie is standby mode and cycles on-off. It is placed on ground and RF stimulating signal keeps walkie-talkie on [1].

Measurement hardware setup for this experiment has two 7-element uniform antenna array which built with broadband, omnidirectional (UHF BW 350-450MHz, (Pharad lightweight wearable)) antennas. Antenna elements are connected to 40 dB low noise amplifiers (LNA) to amplify weak signal from the source and also to decrease the effect of noise, then connected to 4-channel Agilent MSO6104A and Agilent MSO7104B oscilloscopes for data collection. Measurement setup is depicted in Fig. 1. Fresnel region for 7 element ULA is $6\,ft < r_k < 36\,ft$. Accuracy of localization is increased by engaging two antenna arrays in both x and y directions.

Fig. 2 illustrates effectiveness of locating one walkie-talkie with information from near field bearing and range estimation. Antenna centers are placed at (12,0) and (0,12) positions from the origin where each point represent 1 ft. Experiment is performed in a 25x25 ft^2 area. Walkie-talkie is placed different positions, root mean square (RMS) localization error is calculated for each position and represented in each bar of Fig. 2. RMS localization error less than 0.5 ft. when device is at (6,6) position and it goes up to 3.7 ft. if the device is placed at (18,12). Inaccurate number of multipath estimation and hardware imperfections cause error in localization.

In order to make a comparison with far field assumption, localization result using multiple signal classification (MUSIC) is given in Fig. 3. As illustrated in figure, minimum localization error is 1ft and it reaches to 7ft. in the same localization area with near field method. In far field assumption, AoA for each sensor assumed to be same and range effect is discarded. On the other hand, performance of near field localization technique overcomes far field approximation when the source is placed in near field region of the ULA.

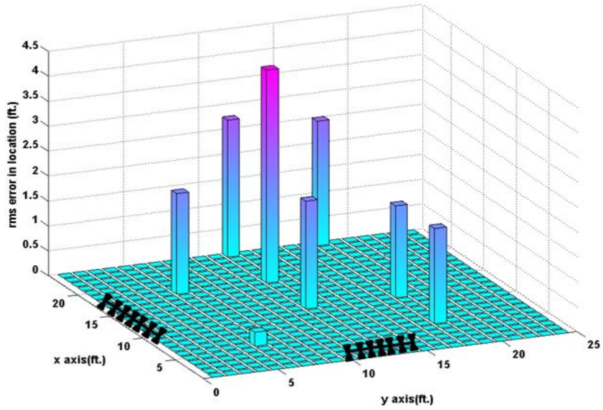

Fig. 2 Localization results of one unintended emitting RC device with near field DOA estimation technique

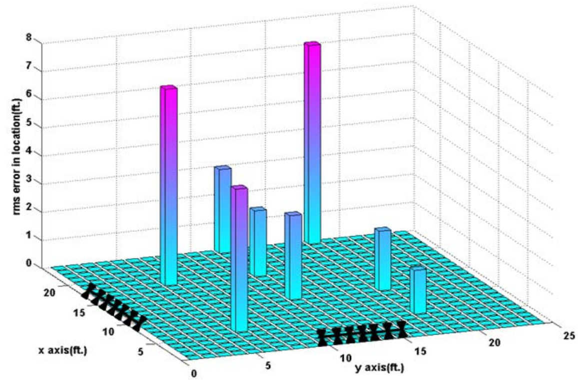

Fig. 3 Localization results of one unintended emitting RC device with far field bearing estimation technique

Similar to other eigen value decomposition methods, near field AoA and range estimation requires number of sources impinging the sensor array. There is one emitting source in this experiment; however there exist multiple paths due to obstacles in the environment. Determining number of multipath affects the accuracy of AoA and range estimation.

TABLE I
Performance Table of Near Field Localization Method

x(ft.)	y(ft.)	Measured x (ft.)	Measured y (ft.)	Error in x (ft.)	Error in y (ft.)
6	6	5.8	5.8	0.2	0.2
6	18	8	17.7	2	0.3
12	18	10.5	22	1.5	4
18	6	18.2	7.9	0.2	1.9

TABLE II
PERFORMANCE TABLE FOR FAR FIELD LOCALIZATION METHOD

x(ft.)	y(ft.)	Measured x (ft.)	Measured y (ft.)	Error in x (ft.)	Error in y (ft.)
6	6	5	11	1	5
6	18	13	18	7	0
12	18	10.5	16.2	1.5	1.8
18	6	16.9	7.1	1.1	1.1

Table I provides real coordinates with respect to a reference origin point in directions, measured distances and error in both axes is given for better understanding for near field localization process with real time data. Localization of a near field source with a far field localization process is demonstrated in Table II concerning the comparison between two methods. Furthermore, Fig. 4 depicts experiment area in Missouri S&T campus and shows localization area for each method in order to compare their effectiveness.

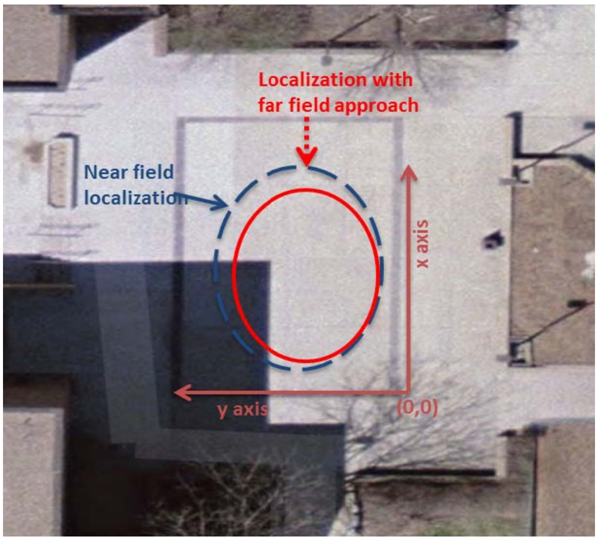

Fig. 4 Performances comparison of near field and far field localization methods when sources are in near field region

IV. CONCLUSION

Near field bearing estimation scheme is used to determine angle of arrival from one passively emitting walkie-talkie in a real life environment. Based on second order statistics of received signal covariance matrix, a 1-D search with two symmetric subarrays is performed. With far field like rotational invariance property in signal subspace of these symmetric subarrays, 2-D parameter estimation is converted to 1-D estimation. Since it does not require higher order statistics and needs only 1-D search, this method is computational cost efficient. Near field technique provides more accurate localization results than far field method, since it considers range effect on phase shift between sensors. Bearing estimation and localization of unintended emitting RC sources when number of sources and number of multipath are not known is considered as future work.

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