# Target Detection Using Dynamically Reconfigurable Sensor Arrays

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## ABSTRACT

This paper addresses the problem of target detection with multiple dynamically reconfigurable sensor arrays (DRSAs). The limited spatial coherence of the signal wavefront and dynamic nature of the interference seriously limit target detection performance. Traditional approaches to improve target detection include the use of large arrays with adaptive beamforming (ABF) or matched field processing (MFP) with static configurations. However, both these approaches suffer performance degradation in uncertain multipath environments when the training data is limited. Herein, we propose to improve the target detection performance by dynamically choosing the optimal orientation designed to maximize the array gain over a prescribed sector of bearing space for a DRSA based on the noise field directionality. Simulation results demonstrate the performance improvement obtained using the reconfiguring system as compared to a fixed uniform linear array (ULA) configuration with conventional or adaptive beamforming.

## 1 Introduction

The two major challenges faced by sensor arrays used for target detection are the suppression of highly dynamic interference and signal wavefront mismatch resulting from complex multipath propagation in uncertain channels, both of which limit gain against diffuse noise. The conventional way to overcome the above difficulties has been to use larger array configurations which, in principle, can provide both greater gain against diffuse noise and more degrees of freedom for interference suppression. In practice, however, large static arrays often require even more accurate environmental information and greater noise field stationarity to minimize signal wavefront mismatch and facilitate the adaptation of more degrees of freedom. Moreover, in highly complex multipath environments the spatial correlation length limits the array aperture that can be processed coherently. Another serious drawback using a fixed linear array with limited backlobe rejection is that interferers located close to the target backlobe can severely limit the array gain along the target direction due to the inherent left-right ambiguity associated with this configuration. In this paper, DRSAs are proposed as a way of achieving the detection benefit of using more sensors without incurring the above difficulties. In this work, we propose a network of DRSAs which continually re-orient and translate themselves so as to collaboratively maintain maximum detection performance in an interference dominated uncertain multipath environment. Each DRSA is optimized for array gain for a hypothesized sector of bearing space as a function of the continually predicted noise directionality and detection performance. The target sectors to be optimized by the individual DRSAs depends upon the number of DRSAs deployed and modeled propagation conditions. Simulation results indicate that up to 30 dB improvement in array gain is possible using a single DRSA for cases when the interferers are present close to the target back beam.

## 2 Signal Model

Consider an $N$ element uniform linear array (ULA) with inter-sensor spacing $d$ which samples the 2-$D$ wavefield with components in $k_x$ and $k_y$. Let the orientation of the ULA defined by the $\theta_{rot}$ in the horizontal plane with the $x$ axis so that the coordinates of the $n^{th}$ sensor are given by

$$\begin{aligned} x_n(\theta_{rot}) &= (n-1)d\cos(\theta_{rot}) \\ y_n(\theta_{rot}) &= (n-1)d\sin(\theta_{rot}) \end{aligned}$$

Letting $\mathbf{x} \in \mathbb{C}^{N\times 1}$ represent the column vector of sensor outputs at a given wavelength $\lambda$, we have

$$\mathbf{R}_{xx} = \sigma_s^2 \mathbf{R}_s(\theta_s,\theta_{rot}) + \underbrace{\sigma_n^2 \mathbf{R}_n(\theta_{rot})}_{\text{noise covariance}},$$

data covariance

signal power

noise covariance

$$\mathbf{R}_{xx} = E\left\{\mathbf{x}\mathbf{x}^H\right\},\ \mathbf{R}_s = \mathbf{d}(\theta_s,\theta_{rot})\mathbf{d}(\theta_s,\theta_{rot})^H,$$

$$\left[\mathbf{d}(\theta_s,\theta_{rot})\right]_n = e^{jd\left(k_x^s x_n(\theta_{rot}) + k_y^s y_n(\theta_{rot})\right)} \longleftarrow \text{signal steering vector}$$

$$\left.\begin{aligned} k_x^s &= 2\pi\sin(\theta_s)/\lambda \\ k_y^s &= 2\pi\cos(\theta_s)/\lambda \end{aligned}\right\} \longleftarrow \text{spatial frequencies}$$

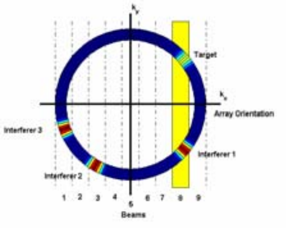
The noise covariance is normalized such that $tr\left(\mathbf{R}_n(\theta)\right) = N$

$$\mathbf{R}_n = \frac{1}{\sigma_n^2}\left(\sigma_\varepsilon^2 \mathbf{I} + \sigma_e^2 \mathbf{R}_e + \mathbf{D}(\boldsymbol{\theta}_i,\theta_{rot})\mathbf{P}\mathbf{D}(\boldsymbol{\theta}_i,\theta_{rot})^H\right),$$

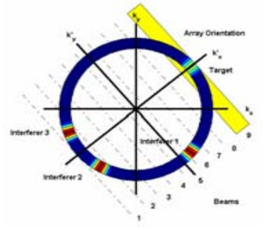
$$\mathbf{D}(\boldsymbol{\theta}_i,\theta_{rot}) = \left[\mathbf{d}(\theta_1,\theta_{rot}) \ \cdots \ \mathbf{d}(\theta_p,\theta_{rot})\right] \in \mathbb{C}^{N\times p}, \longleftarrow \text{interferer responses}$$

$$\mathbf{R}_e = \sigma_e^2 \mathbf{d}(\pi/2-\theta_{rot},\theta_{rot})\mathbf{d}(\pi/2-\theta_{rot},\theta_{rot})^H \longleftarrow \text{endfire noise}$$

## 3 Limitations of a Static Configuration



Static ULA.



DRSA.

- The field directionality measured at a line array is a projection of a 2-D spatial spectrum with wavenumbers ($k_x$,$k_y$) onto the $k_x$ line.
- Mainlobes for a set of contiguous beams for a ULA oriented along the x-axis are shown (top left) are illustrated by vertical stripes. Observe that the target is masked by intereferer-1 in the back beam.
- For a DRSA oriented by π/4, the target appears distinct and moreover the interferers 2 and 3 fall into the same beam, thereby increasing the usable bearing space fraction (UBSF).

## 4 DRSA Design

**OBJECTIVE:** To find the best orientation of a DRSA in order to maximize the passive detection performance in a littoral underwater acoustic environment, over a desired sector of surveillance.

**Idea** : We propose DRSAs that dynamically orient themselves and optimally sample the 2-D wavefield so as to maximize array gain (AG).

- Finding the best orientation can be viewed as finding the best 1-D projection of the 2-D (or 3-D) wavenumber spectrum, in terms of target detection.
- Array gain which is indicative of passive detection performance is defined by:

$$g(\theta_s,\theta_{rot}) \triangleq \frac{\left|\mathbf{w}^H\mathbf{d}(\theta_s,\theta_{rot})\right|^2}{\mathbf{w}^H\mathbf{R}_n(\theta_s,\theta_{rot})\mathbf{w}}$$

- An estimate of the noise field directionality can obtained from multiple DRSAs with different orientations

$$\hat{\mathbf{R}}_n(\theta_{rot}) = \int_{\theta\in\Theta_{\rm int}} \hat{\sigma}_i^2(\theta)\mathbf{d}(\theta_{rot},\theta)\mathbf{d}(\theta_{rot},\theta)^H\,d\theta + \hat{\sigma}_e^2\,\mathrm{R}_e + \hat{\sigma}_\varepsilon^2\mathbf{I}$$

- The optimum orientation is chosen to be one that maximizes the average estimated array gain over the desired source sector in bearing is

$$\theta_{opt} = \arg\max_{\theta_{rot}} \int_{\theta\in\Theta_s} \hat{g}(\theta,\theta_{rot})\,d\theta.$$

- This technique can easily be generalized to the case of multiple DRSAs covering different sectors in bearing space.

### Conclusions

◆ **An approach to use dynamically reconfigurable sensor arrays to improve detection performance compared to using conventional and adaptive beamforming with static configurations is presented.**

◆ **The orientation of the DRSA is determined by optimizing the array gain over a desired target sector in bearing space.**

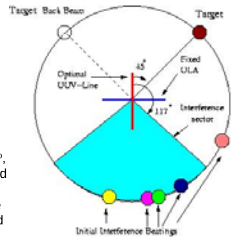
◆ **Simulation results indicate significant improvement in terms of array gain as well as usable bearing space fraction for target detection can be obtained using this approach.**

## 5 Simulation Results

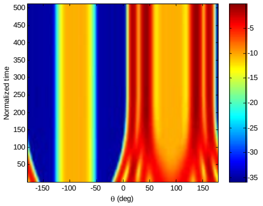
- The scenario considered (right) is one wherein a weak target is present along with 5 moving interferers. The target and noise powers were chosen so that

$$\frac{\sigma_s^2}{\sigma_n^2} = -24\text{dB},\ \frac{\sigma_\varepsilon^2}{\sigma_n^2} = -30\text{dB},\ \frac{\sigma_\varepsilon^2}{\sigma_e^2} = 20\text{dB},\ \frac{tr\left(\mathbf{R}_{\rm int}(\theta_{rot})\right)}{N\sigma_\varepsilon^2} = 30\text{dB}.$$

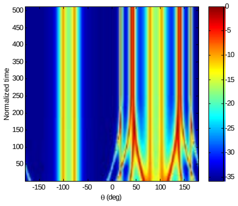
The array comprises of 20 elements spaced d=0.4λ apart. The true initial bearings are of the interferers are {112º, 143º, 162º, 169º, 189º}, while the interference sector was assumed to be Θ∈[117º,243º]. All interferers have an elevation angle spread of Φ∈[-15º,0º], unknown to the DRSA algorithm. The target sector chosen for DRSA optimization is the entire field of view (0,2π] and the target elevation was set at 7.5º.



Experimental scenario.

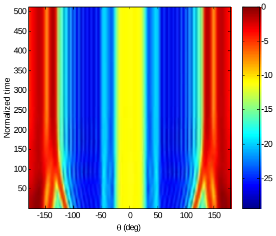


ULA (CBF)

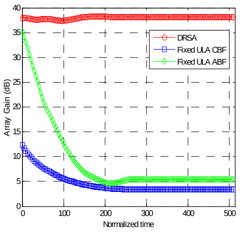


ULA (ABF)

- Bearing-time record (BTR) for conventional beamforming (CBF) using a hamming window (left) and adaptive beamforming (clairvoyant) for a fixed array along x-axis. Observe that the target is completely masked by the interference in the back beam for the CBF case at all times due to its wide mainlobe width. Although the ABF provides a greater UBSF, it cannot prevent against target masking.



DRSA



Array gain vs time

- The BTR for the DRSA (optimal orientation was found to be $\theta_{rot}$=89º is shown (top-left) wherein the target appears distinct at all times. Moreover, due to the DRSA orientation the interferers are clustered in bearing between 130º and 180º , thereby increasing the (UBSF).
- The array gain along the target bearing for CBF, ABF and the DRSA (optimal orientation was found to be $\theta_{rot}$=89º is shown (top-right). As the interferers move closer to the target back beam, the array gain for the CBF and ABF cases drops, while the DRSA maintains an array gain that is about 30 dB greater than these methods.

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