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STRUCTURE OF A MULTIBEAM ADAPTIVE SPACE-TIME PROCESSOR

L. H. Sibul and Guy R. L. Sohie

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It is shown that an adaptive multi-input, multi-output space-time processor (beamformer and filter) consists of a multi-input, multi-output adaptive processor and a nonadaptive beamsteering operator. The adaptive processor is determined by the spatial and temporal properties of the noise field; whereas, the beamsteering operator is determined a priori by the desired beamsteering directions. In this structure, the multichannel adaptive processor is common to all the desired beamsteering directions.

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ABSTRACT

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I. INTRODUCTION

A number of papers on the adaptive beamforming literature have considered a multi-input, single output adaptive beamformer as shown in Figure 1 [1]-[6]. The comment is usually made that this postulated structure can be used to study adaptive beamformers that have off-broadside beamsteering directions by placing a beamsteerer between the sensors and adaptive beamformer. The difficulty with this approach is that for each new beamsteering direction, the adaptive filter coefficients must be recomputed. If multiple simultaneous beamsteering directions are desired, simultaneous adaptation for all the beamsteering directions becomes intractable.

An alternative approach to the previously cited work is not to postulate a structure in advance, but to let the space-time processor structure evolve from the mathematics for the optimum processor. This approach has been taken by Stocklin [7], Bryn [8], Middleton and Groginsky [9], Adams and Nolte [10], Cox [11], and Bangs and Schultheiss [12] to name a few. The purpose of this note is to point out that the theory of multichannel maximum likelihood processor yields a processor structure that appears to be attractive for adaptive implementation. We shall show that the structure shown in Figure 2 follows naturally from the theory of multichannel maximum likelihood processors. This structure has the advantage that the adaptive part of the processor is determined by the spatial and temporal properties of the noise field and it is common to all beamsteering directions. The adaptive processor is followed by a beamsteering operator which can simultaneously form a

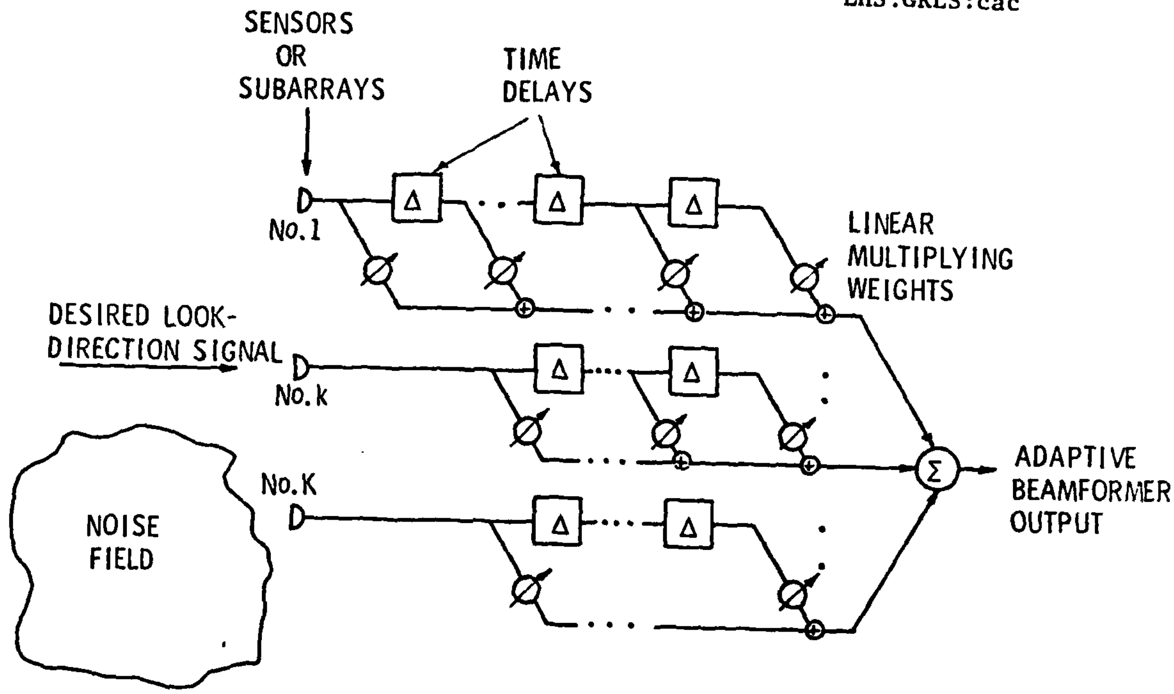

Figure 1. Single beam adaptive array processor

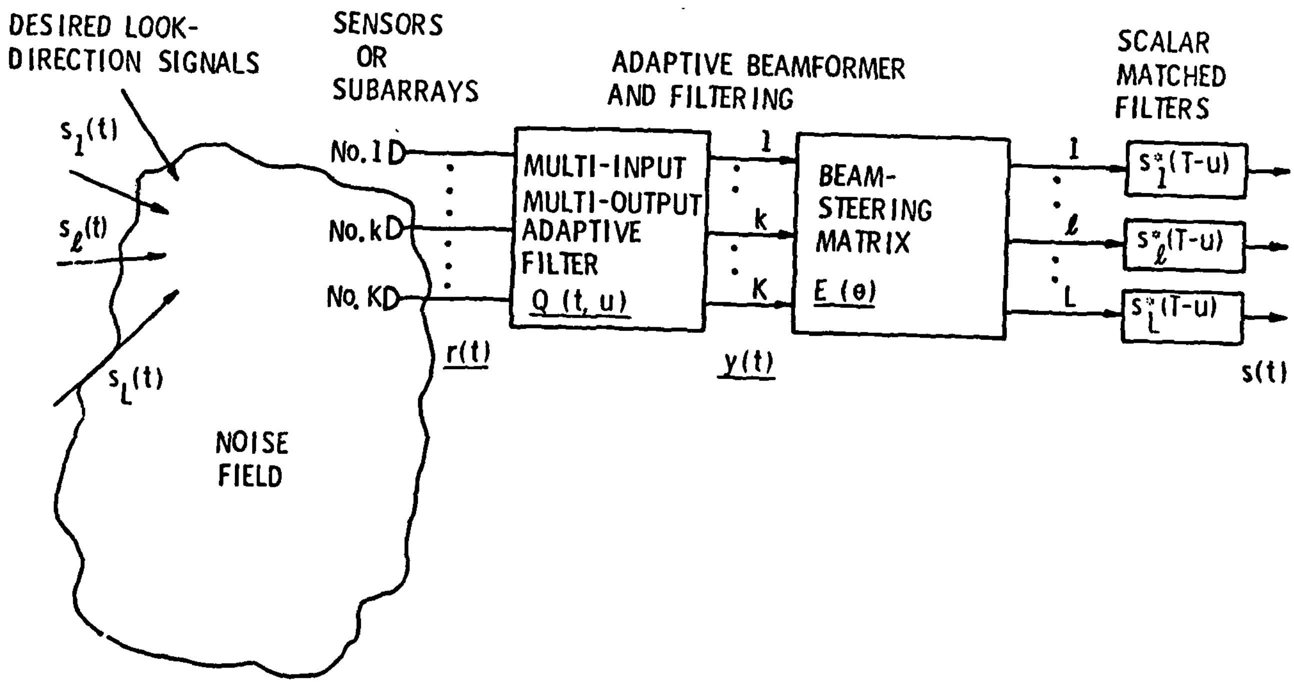

Figure 2. Multibeam adaptive space-time processor

set of beams in all the desired beamsteering directions. The beam-steering operator consists of a set of time delays.

In this paper, lower case letters denote scalars, underlined lower case letters denote vectors, and underlined capital letters denote matrices. The superscripts T, H, and * denote transpose, Hermitian transpose, and complex conjugate. All integrations are carried out over the signal duration T of the active reception interval. $\underline{I}$ denotes identity matrix and $\delta(t - z)$ denotes a delta function. Other symbols are defined in the text.

II. MULTICHANNEL LIKELIHOOD RATIO PROCESSOR

The structure of a multibeam processor for active detection of slowly fluctuating point target in anisotropic, nonstationary, colored Gaussian noise is a generalization of multi-input, single output likelihood ratio processor. The likelihood function for an input vector $\underline{r(t)}$ is

$$\ell_1 = \int_T \underline{v_1^H(u)} \int_T \underline{Q(u,t)}\ \underline{r(t)}\, dt\, du \tag{1}$$

where $v_1(u)$ is the desired signal vector arriving from the direction θ_1, $\underline{Q}(t,u)$ is the matrix inverse kernel that satisfies the integral equation

$$\int_T \underline{R_n(t,u)}\ \underline{Q(u,z)}\, du = \underline{I}\, \delta(t-z), \tag{2}$$

$\underline{R_n(t,u)}$ is the noise covariance matrix [13][14]. The vector of maximum likelihood functions $\underline{\ell}$ is given by

$$\underline{\ell} = \int_T \underline{V^H(u)} \left(\int_T \underline{Q(t,u)}\ \underline{r(t)}\, dt \right) du \tag{3}$$

where $\underline{\ell}^T = [\ell_1, \ell_2 \ldots \ell_L]$ and the matrix $\underline{V(u)}$ is given by:

$$\underline{V(u)} = [\underline{v_1(u)}, \underline{v_2(u)} \ldots \underline{v_L(u)}].$$

The inner integral in Equation 3 is an optimum spatial and temporal smoothing filter where the kernel $\underline{Q(t,u)}$ is determined through Equation 1 from the noise covariance matrix $\underline{R_n(t,u)}$. The covariance matrix $\underline{R_n(t,u)}$ describes the spatial and temporal properties of the anisotropic, colored, and nonstationary noise field. The very essence of the adaptive processing is to "learn" the covariance matrix $\underline{R_n(t,u)}$ from the real data and to find a suitable approximation to the inverse kernel $\underline{Q(u,t)}$. These two steps are the most difficult and computationally most demanding operations in the adaptive processing. Hence, these steps should be done once for all the beamsteering directions. The multiple beamsteering and matched filtering operation is performed by the operator

$$\int_T \underline{V^H(u)} \cdot du$$

A typical term of the vector of likelihood function is

$$\ell_\ell = \int_T \underline{v_\ell^H(u)} \cdot \underline{y(u)}\, du$$

$$= \int_T [v_{\ell 1}^*(u)\, y_1(u) + v_{\ell 2}^*(u)\, y_2(u) \ldots$$

$$\ldots + v_{\ell K}^*\, y_K]\, du \tag{4}$$

where $\underline{y(u)}$ is the output vector of the adaptive matrix filter. Equation 4 indicates that a typical likelihood function is computed by a vector correlation receiver. The meaning of the processor structure becomes clearer if we convert the vector correlation receiver to the vector matched filter form:

$$\ell_\ell = \int_T \underline{h_\ell^H(T-u)}\, \underline{y(u)}\, du \tag{5}$$

where

$$\underline{h_\ell^H(u)} = \underline{v_\ell^H(T-u)} \tag{6}$$

If we now make the usual assumption that the received signals impinging on the sensors or subarrays are identical, except for the relative propagation delays from sensor to sensor*, the ℓ-th received signal vector becomes:

$$v_\ell^T(u) = [s_\ell(u-\tau_1)\ldots s_\ell(u-\tau_k)\ldots s_\ell(u-\tau_K)] \tag{7}$$

*This is not an overly restrictuve assumption because one can easily compensate for different sensor characteristics in the beamformer. Many problems of practical interest fall into this category.

or the vector matched filter can be implemented by a set of delays that will bring the ℓ-th look-direction signal into time coincidence at the ℓ-th output of the beamsteering operator. That is, the beamsteering operator forms a set of uniformly shaded beams in each of the desired look-directions. As it is shown in Figure 2, the outputs of the beamsteering operator are processed by a set of scalar matched filters.

III. ADAPTIVE IMPLEMENTATION OF THE LIKELIHOOD RATIO PROCESSOR

From the previous discussion, it is obvious that the matrix inverse kernel $\underline{Q}(t,u)$ is the only part of the likelihood ratio (LR) processor that is based on information which is not available a priori: the matched filters are uniquely determined by the (known) signals, and the beamsteering is only dependent on the desired look-directions. The matrix inverse kernel $\underline{Q}(t,u)$, on the other hand, is exclusively dependent on the physical properties of the interference and these cannot, in general, be assumed to be known in advance. This clearly suggests an adaptive implementation of this part of the processor.

In order to derive an adaptive realization of the operator $\underline{Q}[\cdot]$ as defined by:

$$(\underline{Q}\ \underline{r})(t) \triangleq \int_T \underline{Q}(t,u)\ \underline{r}(u)\, du \tag{8}$$

where $\underline{Q}(t,u)$ is the solution to the integral Equation 2, it is more convenient to consider the "dual" problem, i.e., the operator:

$$(\underline{H}\,\underline{r})(t) = [(\underline{I} - \underline{Q})\underline{r}](t) \triangleq \int_T [\underline{I}\,\delta(t-u) - \underline{Q}(t,u)]\underline{r}(u)\,du$$

$$\triangleq \int_T \underline{H}(t,u)\,\underline{r}(u)\,du \tag{9}$$

where $\underline{H}(t,u)$ satisfies the integral equation (substituting 9 into 2)

$$\int_T \underline{H}(t,u)\underline{R}_n(u,z)\,du = \underline{R}_c(t,z) \tag{10}$$

where $\underline{R}_c(t,z)$ is the correlation function of a "colored" noise component.*

It can be shown from Equation 10 that the linear system $\underline{H}[\cdot]$ corresponds to a minimum mean-square error estimate of this "colored" component based on observation of the input signal $\underline{r}(t)$ over the observation interval (in other words, so-called optimal "smoothing"), since the "orthogonality" condition (Papoulis [15]):

$$E\{[\underline{c}(t) - (\underline{H}\,\underline{r})(t)] \cdot \underline{r}^H(u)\} = 0 \qquad t,u \in T \tag{11}$$

reduces to condition (10).

Various interpretations can now be made. While the operator H[•] can be implemented as a MMSE estimator ("smoother") using a multi-

---

*It can be shown (Van Trees [13]) that the relation between this "generalized" colored component and the usual definition of the colored noise c'(t) (where $\underline{R}_{c'}(t,u)$ does not contain any singularities) is given by:

$$\underline{R}_c(t,u) = \underline{R}_{c'}(t,u) + (\underline{N} - \underline{I})\,\delta(t-u)$$

where $\underline{N}$ is the matrix of (cross) spectral heights of the temporally uncorrelated noise components.

dimensional version of Widrow's unconstrained LMS algorithm (Widrow [16]), the actual "inverse" filter $\underline{Q}[\cdot]$ which is given by:

$$[\underline{Q}\,\underline{r}](t) = \underline{r}(t) - [\underline{H}\,\underline{r}](t) \triangleq \underline{r}(t) - \underline{\hat{c}}(t) \qquad (12)$$

(see Figure 3) is obviously a "noise" canceller (Widrow, et al. [4]).

It is to be noted that under general interference conditions, the LMS algorithm may have unacceptable convergence properties due to the eigenvalue spread of the input correlation matrix (Widrow, et al. [17]). Other structures that have been proposed more recently for noise cancelling applications (Griffiths [18][19]) are the so-called "lattice" or "ladder" configurations, which seem to have efficient convergence behavior as well as interesting roundoff-noise characteristics (Crochiere [20]). While these structures have been primarily used for linear prediction, the smoothing case is only a straightforward extension (Friedlander [21]; Lee, et al. [22]).

As an additional comment, we can add that in the adaptive realization of $\underline{Q}[\cdot]$, only those data should be used which are known to be interference data only. Since, of course, it is unknown a priori whether or not a target is present, those data corresponding to the range in question should be excluded from the data used in the implementation. This obviously limits the application to the case of active sonar or radar.

Finally, we should mention that exactly the same structure as in Figure 2 can be used for maximum likelihood parameter estimation (Van Trees [13]). Thus, parameter estimation does not require different algorithms nor a higher computational load.

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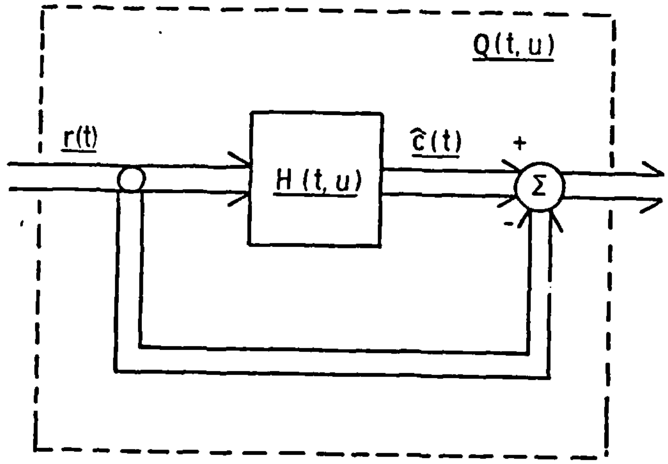

Figure 3. Implementation of the inverse kernel Q(t,u)

IV. CONCLUSION

A structure for the implementation of a likelihood-ratio detector is derived. This structure consists of a "noise canceller" which can be implemented by unconstrained adaptive algorithms, followed by a fixed beamformer and a set of (scalar) matched filters. This structure seems to be more interesting than previous applications where adaptive constrained algorithms were used as adaptive beamformers. Since no constrained algorithms have to be used and the space-time adaptive processor is common to all "look directions", it is suggested that this implementation will be more computationally efficient. Furthermore, since noise cancelling has been extensively studied, various forms for the implementation of the adaptive part of this likelihood-ratio processor are available.

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