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Partially adaptive beamformers use only a subset of adaptive degrees of freedom to alleviate the computational burden and improve the convergence properties of adaptive algorithms for arrays with large numbers of sensors [1,6]. However, reducing the number of adaptive degrees of freedom generally diminishes the beamformer's steady state interference cancellation capability. The goal of partially adaptive beamformer design is to choose a low dimensional adaptation space that provides acceptable steady state interference cancellation. Several design procedures have been proposed. Eigenstructure [5] and beam based designs can result in excellent steady state interference cancellation, but often require an excessive number of adaptive weights [3]. Power minimization designs [4] attempt to minimize the average interference output power over a set of likely interference scenarios Q for a given adaptive dimension. Unfortunately this optimization problem is intractable so a suboptimal solution is proposed wherein each component of the adaptation space is optimized separately over a distinct subset of Q. Although good performance is obtained with relatively small numbers of adaptive weights, the procedure is not very systematic; the subsets of Q used to design individual components are selected through a hand-crafting trial and error process in order to obtain the best performance. Here we propose an alternate perspective to the design problem. Our objective is to minimize the number of adaptive degrees of freedom subject to a constraint on the worst case interference cancellation performance loss over a set of interference scenarios Q. Each component of the adaptation space is chosen to give fully adaptive performance at a specific interference scenario. The dimension of the adaptation space is increased one at a time until the performance constraint is satisfied over the entire set of possible interference scenarios. This systematic procedure can also be used to order the components of the adaptation space according to their contributions to interference cancellation.					
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Partially Adaptive Beamformer Design with Performance Constraints

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SUMMARY

Partially adaptive beamformers use only a subset of adaptive degrees of freedom to alleviate the computational burden and improve the convergence properties of adaptive algorithms for arrays with large numbers of sensors[1,6]. However, reducing the number of adaptive degrees of freedom generally diminishes the beamformer's steady state interference cancellation capability. The goal of partially adaptive beamformer design is to choose a low dimensional adaptation space that provides acceptable steady state interference cancellation.

Several design procedures have been proposed. Eigenstructure[5] and beam based designs can result in excellent steady state interference cancellation, but often require an excessive number of adaptive weights[3]. Power minimization designs[4] attempt to minimize the average interference output power over a set of likely interference scenarios Q for a given adaptive dimension. Unfortunately this optimization problem is intractable so a suboptimal solution is proposed wherein each component of the adaptation space is optimized separately over a distinct subset of Q . Although good performance is obtained with relatively small numbers of adaptive weights, the procedure is not very systematic; the subsets of Q used to design individual components are selected through a hand-crafting trial and error process in order to obtain the best performance.

Here we propose an alternate perspective to the design problem. Our objective is to minimize the number of adaptive degrees of freedom subject to a constraint on the worst case interference cancellation performance loss over a set of interference scenarios Q . Each component of the adaptation space is chosen to give fully adaptive performance at a specific interference scenario. The dimension of the adaptation space is increased one at a time until the performance constraint is satisfied over the entire set of possible interference scenarios. This systematic procedure can also be used to order the components of the adaptation space according to their contributions to interference cancellation.

The linearly constrained minimum variance criterion[3] for choosing the beamformer weight vector w is

$$\min_w w^H R_x w \quad \text{subject to} \quad C^H w = g \quad (1)$$

where $R_x = E\{xx^H\}$ is the data covariance matrix. C is the constraint matrix and g the response vector. The generalized sidelobe canceller[2] representation decomposes

$$w = w_o - C_n w_n \quad (2)$$

where $w_o \in \text{range}(C)$ is a nonadaptive weight vector satisfying the constraint, C_n is the signal blocking matrix satisfying $C_n^H C = O$, and w_n represents the adaptive degrees of freedom. When the desired signal is statistically uncorrelated with the interference, $R_x = R_s + R_n$ where R_s is the signal covariance matrix and R_n is the interference and noise covariance matrix. Using $C_n^H R_s = O$, the optimal adaptive weight vector is $w_n = (C_n^H R_n C_n)^{-1} C_n^H R_n w_o$. The minimum interference and noise output power is

$$P_i^{\min} = w_o^H R_n w_o - w_o^H R_n C_n^H (C_n^H R_n C_n)^{-1} C_n^H R_n w_o \quad (3)$$

A partially adaptive beamformer is obtained by replacing $\text{range}(C_n)$ with a lower dimensional adaptation space $\text{range}(T_n) \subset \text{range}(C_n)$. Hence, $w = w_o - T_n w_n$. The corresponding minimal interference and noise output power is

$$P_i(T_n) = w_o^H R_n w_o - w_o^H R_n T_n (T_n^H R_n T_n)^{-1} T_n^H R_n w_o \quad (4)$$

In general, $P_i(T_n) > P_i^{\min}$; that is, the interference cancellation performance degrades. However, if the interference scenario(characterized by R_n) is known, then there exists a one-dimensional adaptation space represented by

$$t_n^{\text{opt}} = C_n (C_n^H R_n C_n)^{-1} C_n^H R_n w_o \quad (5)$$

which achieves zero performance degradation, i.e. $P_i(t_n^{opt}) = P_i^{min}$.

In practice the interference scenario is unknown; this is one of the primary motivations for using an adaptive beamformer. Hence, in order to design a T_n that provides good performance for unknown interference scenarios, we parameterize the interference environment with a vector Θ : for instance, Θ may represent the number of interferers, their power levels and directions, spectral characteristics, etc. The interference covariance matrix is assumed to be completely determined by Θ and is explicitly expressed as $R_n(\Theta)$. The set of interference scenarios over which T_n is designed is represented by a discrete set $Q = \{\Theta_k, k = 1, 2, \dots, K\}$. Multiple degrees of freedom are usually needed in order to obtain good performance over all interference scenarios in Q .

The performance of a partially adaptive beamformer is evaluated in terms of its interference and noise output power relative to that of the fully adaptive beamformer. Define the performance index

$$I(T_n, \Theta_k) = \frac{P_i^{min}(\Theta_k)}{P_i(T_n, \Theta_k)}. \quad (6)$$

The partially adaptive beamformer design criterion is to choose T_n such that

$$I(T_n, \Theta_k) \geq \delta_o, \quad 1 \leq k \leq K. \quad (7)$$

Clearly, we require $0 < \delta_o \leq 1$.

Now we propose a design procedure which yields partially adaptive beamformers satisfying the criterion (7). This procedure is based on the observation that maximum interference cancellation is obtained for a specific interference scenario with only a single degree of freedom. The basic idea is to construct T_n one column at a time where each column is chosen to provide maximum interference cancellation for a different interference scenario. A column is added at an interference scenario only if the performance loss given the already designed columns exceeds the maximum tolerance. We continue to add columns to T_n until the performance requirement is satisfied for all interference scenarios in Q . Note that each additional column will generally improve the performance for all interference scenarios even though it is optimized for a single scenario. Consequently, we generally require far fewer columns in T_n than the number of interference scenarios K .

The key issue is to decide which interference scenarios to use in designing T_n . Intuitively, we add a column corresponding to the scenario with the greatest performance degradation given the existing columns. This is accomplished in an approximate manner through the use of a sequence of L increasing performance levels $\delta_1 < \delta_2 < \dots < \delta_L = \delta_o$. At each level we add columns to T_n that provide optimum performance only for scenarios whose performance index (defined by (6)) does not satisfy the current performance constraint.

The following is a pseudo-code description of this automated design procedure.

```

 $T_{no} = \emptyset$ 
for  $l = 1$  to  $L$ 
  for  $k = 1$  to  $K$ 
    if  $I(T_{no}, \Theta_k) < \delta_l$ 
       $t_n = C_n(C_n^H R_n(\Theta_k) C_n)^{-1} C_n^H R_n(\Theta_k) w_o$ 
       $T_{no} = [T_{no} \ t_n]$ 
    endif
  end-loop-on- $k$ 
end-loop-on- $l$ 

```

Our experience suggests that good results are usually achieved with $L = 3$ or $L = 4$. Simulations indicate that the resulting beamformers exhibit better interference cancellation performance than those obtained through existing design methods while using fewer degrees of freedom.

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