# The Constrained Conjugate Gradient Algorithm

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*Abstract*—Based on the condition for equivalence between linearly constrained minimum-variance (LCMV) filters and their generalized sidelobe canceler (GSC) implementations, we derive the new constrained conjugate gradient (CCG) algorithm. We discuss the use of orthogonal and nonorthogonal blocking matrices for the GSC structure and how the choice of this matrix may affect the relationship with the LCMV counterpart. The newly derived algorithm was tested in a computer experiment for adaptive multiuser detection and showed excellent results.

*Index Terms*—Conjugate gradient algorithm, constrained adaptive filtering.

## I. INTRODUCTION

LINEARLY constrained adaptive filters have been used in many applications including adaptive beamforming with sensor arrays and blind adaptive interference cancellation in multiuser mobile communication systems. The constrained version of the least mean square (LMS) algorithm (CLMS) was proposed in [1] for the minimization of the output-error energy of a finite impulse response (FIR) filter subject to a set of known linear constraints, i.e., $\min_{\mathbf{w}} E[e^2]$ subject to $\mathbf{C}^T\mathbf{w} = \mathbf{f}$, where $\mathbf{w}$ is the length $M$ coefficient vector, $e$ is the filter output error, $\mathbf{C}$ is the $M \times p$ constraint matrix, and $\mathbf{f}$ is the length $p$ gain vector. In [2], an alternative structure was presented whereby only a smaller set of coefficients are updated, which are confined to the subspace orthogonal to the space spanned by the constraint matrix $\mathbf{C}$. This structure, known as the generalized sidelobe canceler (GSC), is able to transform the linearly constrained minimization problem into an unconstrained minimization problem, and therefore can accommodate virtually any adaptation algorithm. Although the constrained algorithm and its GSC implementation are assumed to present identical steady-state performance [2] in a stationary environment, different choices of the blocking matrix $\mathbf{B}$ such that $\mathbf{B}^T\mathbf{C} = \mathbf{0}$ leads to different results. Moreover, this matrix determines the computational complexity of the adaptation algorithm implemented in the GSC structure. This paper revisits the condition of equivalence between a constrained adaptive filter and its GSC counterpart and uses this condition to introduce a new constrained algorithm, the constrained conjugate gradient (CCG) algorithm.

## II. PRELIMINARIES

The CLMS solution to the linearly constrained minimum-variance (LCMV) problem is given by [1]

$$\mathbf{w}(k+1) = \mathbf{P}\mathbf{w}(k) - \mu y(k)\mathbf{P}\mathbf{x}(k) + \mathbf{F} \qquad (1)$$

where

$\mathbf{F} = \mathbf{C}(\mathbf{C}^T\mathbf{C})^{-1}\mathbf{f}$;

$\mathbf{P} = \mathbf{I} - \mathbf{C}(\mathbf{C}^T\mathbf{C})^{-1}\mathbf{C}^T$ projection matrix onto the subspace orthogonal to the subspace spanned by the constraint matrix, and the output signal;

$y(k) = \mathbf{w}^T(k)\mathbf{x}(k)$, output signal.

$\mathbf{x}(k)$ is the input-signal vector containing present and past input-signal samples $[x(k)\,x(k-1)\,\cdots\,x(k-M+1)]^T$. We recall the fact that although $\mathbf{P}\mathbf{w}(k) + \mathbf{F}$ corresponds to $\mathbf{w}(k)$ in infinite precision, the computation as in (1) is necessary in a limited-precision-arithmetic machine in order to avoid any drift from the constraint plane [1].

The GSC decomposes the coefficient vector by using a transformation matrix given by $\mathbf{T} = [\mathbf{C} \vdots \mathbf{B}]$ where $\mathbf{B}$ is called blocking matrix, and it spans the null space of the constraint matrix $\mathbf{C}$. The GSC-transformed coefficient vector in $\mathbf{w}(k) = \mathbf{T}\mathbf{w}(k)$ is partitioned as $\mathbf{w}(k) = [\mathbf{w}_U^T \vdots -\mathbf{w}_L^T]^T$, where the upper part is constant and chosen such that $\mathbf{C}\mathbf{w}_U$ corresponds to $\mathbf{F} = \mathbf{C}(\mathbf{C}^T\mathbf{C})^{-1}\mathbf{f}$, and $-\mathbf{w}_L = \mathbf{w}_{GSC}(k)$ is updated according to an unconstrained adaptive filter such that the overall coefficient vector corresponds to $\mathbf{w}(k) = \mathbf{F} - \mathbf{B}\mathbf{w}_{GSC}(k)$.

The inverse of the GSC transformation matrix (guaranteed by linearly independent columns of $\mathbf{B}$ and $\mathbf{C}$, and by $\mathbf{B}^T\mathbf{C} = \mathbf{0}$ [3]) can be partitioned as $\mathbf{T}^{-1} = [\mathbf{A}_1^T \vdots \mathbf{A}_2^T]^T$ where $\mathbf{A}_1 = (\mathbf{C}^T\mathbf{C})^{-1}\mathbf{C}^T$ and $\mathbf{A}_2 = (\mathbf{B}^T\mathbf{B})^{-1}\mathbf{B}^T$.

By replacing $\mathbf{A}_1$ and $\mathbf{A}_2$ in $\mathbf{T}^{-1}$ and then in $\mathbf{T}\mathbf{T}^{-1} = \mathbf{I}$ we find another expression for the projection matrix $\mathbf{P}$, as obtained in [4]

$$\mathbf{P} = \mathbf{B}(\mathbf{B}^T\mathbf{B})^{-1}\mathbf{B}^T. \qquad (2)$$

## III. EQUIVALENCE CONDITION REVISITED

In this section, we obtain the CLMS algorithm from its GSC implementation in order to find under which circumstances they are equivalent in infinite precision. The GSC coefficient-vector update equation using the LMS algorithm relates to the coefficient-vector update equation for the constrained LMS algorithm according to

$$\mathbf{w}(k+1) = \mathbf{F} - \mathbf{B}[\mathbf{w}_{GSC}(k+1)]$$
$$= \mathbf{F} - \mathbf{B}[\mathbf{w}_{GSC}(k) + \mu e_{GSC}(k)\mathbf{x}_{GSC}(k)] \qquad (3)$$

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