

# Space-Time Processing for Co-channel Interference Rejection and Channel Estimation in GSM/DCS Systems

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## ABSTRACT

In this paper it is proposed a space-time algorithm for co-channel interference (CCI) and intersymbol interference (ISI) reduction for GSM/DCS systems. The temporal channel for the Viterbi receiver and the beam-former weights for CCI rejection are estimated jointly by optimizing a suitable cost function for low-rank space-time channels.

Compared to the solutions proposed in the literature, the advantages are: i) the reduction of the CCIs still using, for the equalization, a scalar Viterbi receiver and ii) the convergence of the estimates within few symbols of the training sequence. Performances are evaluated by simulations.

## 1 INTRODUCTION

Arrays of receivers in mobile communications allow the use of the spatial dimension to achieve co-channel interference (CCI) impairment reduction, or equivalently an increase in spectral efficiency, as capacity is mostly limited by CCI. Spatial (angular) dimension in wireless systems has already been exploited, both with a switched-beam approach [1] and with direction-of-arrival (DOA) based approaches [2]. The computational power available nowadays makes feasible the use of techniques that exploit and optimize the receivers jointly (not sequentially) in space and time domains [3].

The algorithm presented herein is based upon a new space-time (ST) receiver which jointly optimizes the estimation of the beam-former weights and of the channel response for a MLSE receiver [4][5]. First a reduction of the CCI is obtained with a sort of optimum combining performed by the spatial filter, then a conventional MLSE receiver is used, even if the residual interference is only approximately white and in general non Gaussian. The key idea for the cost function is the maximization of the signal to interference plus noise ratio (SINR). Furthermore, the separable character of the algorithm is particularly attractive as it yields to a computationally efficient structure.

The paper is organized as follows: space-time channel model that extends the temporal channel standardized in [6] is described in Section 2, the new

ST receiver based on the maximization of the SINR is in Section 3, examples and simulation results that demonstrate the performance in terms of BER are in Section 4.

## 2 ARRAY AND CHANNEL MODEL

The mobile radio channel is usually described in terms of its temporal features: path loss, fast and slow fading, Doppler spread. When dealing with antenna array systems the spatial dimension must be taken into account. In a multipath environment the spatial features of the channel, caused by the relative positions between the array elements and the signals' sources, heavily affect the shape of the overall channel response. Such a response can be conveniently treated as a random process.

### 2.1 The Vector Channel Response

For an antenna array of  $M$  elements the base-band equivalent channel of the signal received by the  $k$ -th array element is  $\tilde{h}_k(t)$  (for GMSK modulation the linearized model is assumed by considering the main pulse of the AMP decomposition [7]). All the signals received by the array can be conveniently arranged into an  $M$ -dimensional vector

$$y(t) = \sum_{n=-\infty}^{+\infty} x_n \tilde{h}(t - nT), \quad (1)$$

$\{x_n\}$  is the transmitted sequence. In general, more independent sources (users) are present (or can be considered to have a meaningful power level) in a cellular system with low reuse distance. The signal received by the antenna array will be

$$y(t) = \sum_{n=-\infty}^{+\infty} x_n \tilde{h}(t - nT) + \sum_{q=1}^Q \sum_{n=-\infty}^{+\infty} i_{n,q} \tilde{h}_q(t - nT) + n(t) \quad (2)$$

where  $i_{n,q}$  are the interferers' sequences and  $n(t)$  is spatially and temporally uncorrelated Gaussian noise ( $E[n(t)n^H(t + \tau)] = \sigma^2 \mathbf{I} \delta(\tau)$ ).

By sampling the received signal at symbol rate  $T$  and collecting  $N$  snapshots into a single matrix, the

received signal (2) can be equivalently rewritten as

$$Y = HX + \sum_{q=1}^Q H_q I_q + N;$$

$H$  is an  $M \times L$  matrix that represents the channel samples ( $L$  is the memory length of the channel):

$$H = [\tilde{h}(nT) \quad \tilde{h}((n-1)T) \quad \dots \quad \tilde{h}((n-L+1)T)]; \quad (3)$$

$X = [x(1) \quad x(2) \quad \dots \quad x(N)]$  denotes the non-symmetric Toeplitz structured data matrix, where  $x(n)$  are  $L$  symbols of the transmitted sequence sorted into a vector:

$$x(n) = \begin{bmatrix} x_n \\ \vdots \\ x_{n-L+1} \end{bmatrix} \quad (4)$$

Equivalent relationships hold true for  $H_q$  and  $I_q(n)$ . It is important to point out that the structured noise  $\sum_{q=1}^Q H_q I_q + N$  is temporally and spatially correlated, correlation being given by the CCI.

### 2.2 Generalized ETSI Models

The temporal characteristics of the mobile radio channel have been extensively modelled, while only recently space-time features have been investigated and few experimental results are available. In any case, for the GSM/DCS system, there are no commonly agreed models for testing.

The space-time model considered is an extension of the standardized ETSI temporal channel chosen to have a valid model (somewhat arbitrary) for a multi-antenna receiver that collapses to the standard one in the one-antenna receiver case. Therefore we simply added the spatial dimension to the channel models in [6], by considering, for each delay  $\tau_i$ , a corresponding DOA  $\theta_i$ . The vector channel is then

$$\tilde{h}(t) = \sum_{i=1}^{N_{\text{paths}}} a(\theta_i) A_i e^{-j\phi_i} h_0(t - \tau_i) \quad (5)$$

where  $a(\theta_i)$  is the array response vector in the direction  $\theta_i$ , while the temporal terms  $A_i e^{-j\phi_i} h_0(t - \tau_i)$  are inferred from the ETSI specifications [6]. By properly choosing the probability density functions of DOAs  $\theta_i$ , we can model different propagation environments depending on the mobile-base station distance, the antenna array height, the cell urbanization level. With this approach we can also simulate scenarios in which rays arriving close in time are not necessarily originated from scatterers close in space (specular multipath).

## 3 JOINT CO-CHANNEL INTERFERENCE REDUCTION AND CHANNEL ESTIMATION

For single antenna systems the maximum likelihood sequence estimator (MLSE) receiver represents the

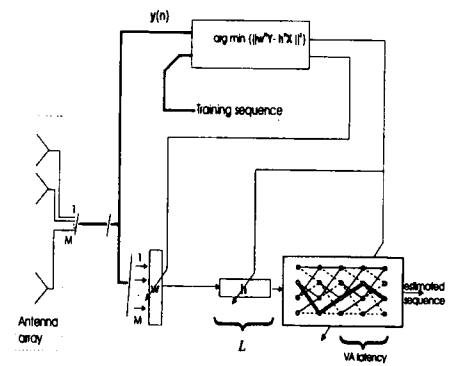


Figure 1: JST receiver structure

widespread receiver for mobile communication system, namely for GSM/DCS standard. For antenna array systems the receivers can exploit the spatial dimension. Based on the optimization criteria, space-time (ST) or vector receivers can be grouped into two main classes [3]: the multichannel MLSE (MMLSE) and the minimum mean square error (MMSE).

The MMLSE needs the estimation of the full rank channel matrix  $H$  and of the covariance matrix of the CCI. Although these parameters can be estimated during a (long) training sequence, problems would arise for non-stationary CCI and/or fast Doppler. The MMSE algorithm allows the equalization of the channel and the rejection of the CCI but this also implies the estimation of an high number of parameters (higher than the dimensions of  $H$ ).

For long training sequences the MMLSE achieves the better performance (compared to MMSE) as far as the vector Viterbi is based on a consistent estimate of the channel and interference parameters. However, for a short training sequence (i.e., the 26 symbols of the GSM/DCS midamble), the estimation of an high number of parameters could become data-sensitive and error flooring can easily occur.

Given the drawbacks of the limited training sequence length, the number of degrees of freedom in ST receiver has to be parsimoniously handled in order to achieve convergence of the estimates at the expense of moderate loss of (asymptotical) performance. The approach proposed herein separates the space and time processing (also referred to as rank-one receiver since it relies on the separability of the channel  $H$ ) while the optimization is performed jointly on space and time parameters.

### 3.1 The JST Receiver

The receiver have to be designed to cope with strong CCI and to equalize severely distorted channels. According to the scheme in Fig.1 the algorithm relies

on the beam-former weights  $\mathbf{w} = [w_1, w_2, \dots, w_M]^T$  that reduce the CCI and the scalar MLSE receiver that demodulates the sequence  $\{x_n\}$ . The receiver structure can be made adaptive to handle the non-stationarity of CCI or the time-variance of the channel. The joint estimates  $\mathbf{w}$  and  $\mathbf{h}$  for the joint space-time (JST) receiver can be evaluated by the maximization of the signal to interference plus noise ratio (SINR) after the spatial filter (or equivalently after CCI reduction):

$$\begin{aligned} (\mathbf{w}_{opt}, \mathbf{h}_{opt}) &= \arg \max_{\mathbf{w}, \mathbf{h}} \text{SINR} \quad (6) \\ &= \arg \max_{\mathbf{w}, \mathbf{h}} \frac{\|\mathbf{w}^H \mathbf{Y}\|^2}{\|\mathbf{w}^H \mathbf{Y} - \mathbf{h}^H \mathbf{X}\|^2}. \end{aligned}$$

It can be shown that this optimization can be carried out with respect to  $\mathbf{h}$ :

$$\mathbf{h}_{opt} = \arg \max_{\mathbf{h}} \frac{\mathbf{h}^H \hat{\mathbf{R}}_{xx} \mathbf{h}}{\mathbf{h}^H (\hat{\mathbf{R}}_{xx} - \hat{\mathbf{R}}_{xy} \hat{\mathbf{R}}_{yy}^{-1} \hat{\mathbf{R}}_{yx}) \mathbf{h}} \quad (7a)$$

$$\mathbf{w}_{opt} = \hat{\mathbf{R}}_{yy}^{-1} \hat{\mathbf{R}}_{yx} \mathbf{h}_{opt}, \quad (7b)$$

here  $\hat{\mathbf{R}}_{xx} = \mathbf{X}\mathbf{X}^H/N$  denotes the sample covariance matrix ( $\hat{\mathbf{R}}_{xy}, \hat{\mathbf{R}}_{yy}$  are similarly defined). The time channel (7a) can be found as the generalized eigenvector associated to the maximum generalized eigenvalue of  $(\hat{\mathbf{R}}_{xx}, \hat{\mathbf{R}}_{xx} - \hat{\mathbf{R}}_{xy} \hat{\mathbf{R}}_{yy}^{-1} \hat{\mathbf{R}}_{yx})$ .

If the training sequence is white (PN sequence), the sample covariance matrix is asymptotically  $\hat{\mathbf{R}}_{xx} \rightarrow \mathbf{I}$  and the Rayleigh quotient (7a) can be modified accordingly. The objective function is thus obtained by minimizing  $\|\mathbf{w}^H \mathbf{Y} - \mathbf{h}^H \mathbf{X}\|^2$  and by constraining  $\mathbf{h}$  to have unit norm:

$$\begin{aligned} (\mathbf{w}_{opt}, \mathbf{h}_{opt}) &= \arg \min_{\mathbf{w}, \mathbf{h}} \|\mathbf{w}^H \mathbf{Y} - \mathbf{h}^H \mathbf{X}\|^2 \quad (8) \\ &\text{subject to } \|\mathbf{h}\|^2 = 1. \end{aligned}$$

The optimum channel  $\mathbf{h}_{opt}$  follows to be the eigenvector  $\mathbf{q}_{min}$  associated to the minimum eigenvalue ( $\lambda_{min}$ ) of  $\hat{\mathbf{R}}_{xx} - \hat{\mathbf{R}}_{xy} \hat{\mathbf{R}}_{yy}^{-1} \hat{\mathbf{R}}_{yx}$ :

$$\mathbf{h}_{opt} = \mathbf{q}_{min}, \quad (9a)$$

$$\mathbf{w}_{opt} = \hat{\mathbf{R}}_{yy}^{-1} \hat{\mathbf{R}}_{yx} \mathbf{q}_{min}, \quad (9b)$$

$$\|\mathbf{w}_{opt}^H \mathbf{Y} - \mathbf{h}_{opt}^H \mathbf{X}\|^2 = \lambda_{min}. \quad (9c)$$

It should be stressed that in a GSM/DCS scenario, as angular or delay spread are small compared to the resolution of the system, a rank one (or separable) solution has a variance of the estimates lower than any higher rank solution. Further, this approach could lead to an adaptive extension.

### 3.2 Partial Cholesky Factorization

The JST optimization needs the evaluation of the eigenvector corresponding to the smallest eigenvalue of the matrix  $\mathbf{R}_s^+ = \hat{\mathbf{R}}_{xx} - \hat{\mathbf{R}}_{xy} \hat{\mathbf{R}}_{yy}^{-1} \hat{\mathbf{R}}_{yx}$ , which is the Schur complement of  $\hat{\mathbf{R}}_{yy}$  in  $\mathbf{R}$ , where the matrix  $\mathbf{R}$  is

$$\mathbf{R} = \begin{bmatrix} \hat{\mathbf{R}}_{yy} & \hat{\mathbf{R}}_{yx} \\ \hat{\mathbf{R}}_{xy} & \hat{\mathbf{R}}_{xx} \end{bmatrix}. \quad (10)$$

The solution proposed here is based on a partial Cholesky factorization [8] as it allows the control of the numerical stability together with a good computational efficiency.  $\mathbf{R}_s^+$  can be carried out by a partial ( $M$  steps) triangularization via fast Schur reduction:

$$\mathbf{R} = \begin{bmatrix} \mathbf{L} \\ \mathbf{U} \end{bmatrix} \begin{bmatrix} \mathbf{L}^H & \mathbf{U}^H \\ \mathbf{0} & \mathbf{R}_s^+ \end{bmatrix} \quad (11)$$

$\mathbf{R}_s^+$  is then computed without inverting the spatial covariance matrix  $\hat{\mathbf{R}}_{yy}$ . From (11) we have

$$\begin{aligned} \hat{\mathbf{R}}_{yy} &= \mathbf{L}\mathbf{L}^H \\ \hat{\mathbf{R}}_{xy} &= \mathbf{U}\mathbf{L}^H \end{aligned} \quad (12)$$

that allows (7b) to be rewritten as  $\mathbf{L}^H \mathbf{w}_{opt} = \mathbf{U}^H \mathbf{h}_{opt}$ . Given  $\mathbf{h}_{opt}$ ,  $\mathbf{w}_{opt}$  can be found through a simple back-substitution due to the lower-triangular structure of  $\mathbf{L}$ .

The eigenvector corresponding to the smallest eigenvalue of  $\mathbf{R}_s^+$  can be obtained from the inverse power method. This follows from the iterative solution of

$$\mathbf{h}_n = (\mathbf{R}_s^+)^{-1} \mathbf{h}_{opt}(n-1) \quad (13)$$

$$\mathbf{h}_{opt}(n) = \frac{\mathbf{h}_n}{\|\mathbf{h}_n\|},$$

the normalization  $\|\mathbf{h}_n\|$  is introduced to attain the unitary energy constraint on channel vector  $\mathbf{h}$ . This problem can be similarly solved without matrix inversion. Completing the Schur reduction, we may write  $\mathbf{R} = \overline{\mathbf{L}}\overline{\mathbf{L}}^H$ ; here

$$\overline{\mathbf{L}} = \begin{bmatrix} \mathbf{L} & \mathbf{0} \\ \mathbf{U} & \mathbf{L}_s \end{bmatrix} \quad (14)$$

and  $\mathbf{L}_s$  is the Cholesky factor of  $\mathbf{R}_s^+$  (i.e.,  $\mathbf{R}_s^+ = \mathbf{L}_s \mathbf{L}_s^H$ ). Iterative method (13) can be rewritten as

$$\mathbf{L}_s \mathbf{L}_s^H \mathbf{h}_n = \mathbf{h}_{opt}(n-1) \quad (15)$$

and therefore can be solved with a two-step back-substitution approach using the intermediate variable  $\mathbf{u}_n$

$$\begin{aligned} \mathbf{L}_s^H \mathbf{h}_n &= \mathbf{u}_n \\ \mathbf{L}_s \mathbf{u}_n &= \mathbf{h}_{opt}(n-1) \end{aligned} \quad (16)$$

To summarize,  $\mathbf{h}_{opt}$  and  $\mathbf{w}_{opt}$  are efficiently determined by three steps: 1) Cholesky factorization of  $\mathbf{R}$  via fast Schur reduction, 2) inverse power method to obtain  $\mathbf{h}_{opt}$  through a two-step back-substitution approach, 3) a final back-substitution for  $\mathbf{w}_{opt}$ .

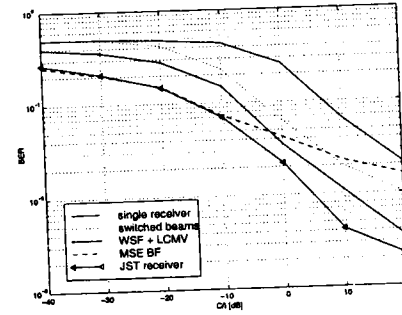


Figure 2: Stationary environment performance: BER vs C/I (three synchronous interferers, TU50, 5 degrees angle spread)

### 4 SIMULATION STUDY

The evaluation of the performances of the JST algorithm has been evaluated through Montecarlo simulations over a wide range of conditions. Performance is then evaluated in terms of Bit-Error-Rate (BER) of uncoded bits (over 2000 TDMA slots) for various carrier-to-interferer ratios (C/I). The analysis is restricted to interference limited scenarios as ST receivers are designed to increase the spectral efficiency of the system by means of a reduction of the reuse distance. Although the algorithm proposed works independently of the array geometry, here we consider the case of a uniform linear array with  $M = 8$  antennas equally spaced by half wavelength:  $[\mathbf{a}(\theta)]_k = e^{j\pi(k-1)\sin\theta}$ .

In order to demonstrate the benefit obtained by the use of the proposed algorithm, the performances of different types of ST receivers are compared in a stationary environment characterized by one useful signal and three synchronous CCIs uniformly distributed within the 120 deg sector covered by the antenna array (see Fig.2). The channel model is the generalized TU with an angular spread for all the rays of 5 deg. The receiver schemes considered in this simulation are: a single antenna MLSE system; a switched-beams structure [1]; a DOA based (WSF estimation + LCMV beamforming) approach [2]; a MMSE beamforming [9], and the JST receiver proposed in this paper. As shown in Fig.2 the JST solution provides a better performance almost on the whole range of carrier-to-interference ratios.

### 5 CONCLUSIONS AND REMARKS

The space-time processing is known to be beneficial for the reduction of the co-channel interference mobile communication systems. The joint space-time (JST) algorithm estimates jointly (not sequentially)

the beamforming and the channel response by maximizing the SINR; the main advantages being i) the reduction of the CCIs still using, for the equalization, a scalar Viterbi receiver and ii) the convergence of the estimates within few symbols of the training sequence. The parallelism of the JST algorithm can be exploited for an efficient implementation of the algorithm.

It is worthwhile to notice that the JST algorithm represents a separable receiver that is optimum only when the channel model is separable (rank-one channel matrix  $\mathbf{H}$ ); in all the other cases the JST receiver has to be considered as sub-optimum. In the examples discussed here the JST algorithm has been proved to be effective but this is mostly because the parameters of the GSM standard fit reasonably the constraints of a rank-one channel.

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