LOW COMPLEXITY BLIND SPACE-TIME IDENTIFICATION OF PROPAGATION PARAMETERS

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ABSTRACT

The radio electrical transmissions often have multiple paths due to reflections on physical objects or due to the inhomogeneity of the propagation medium for example the ionospheric layers in a HF communication.

This work presents a new algorithm for the blind estimation of the physical parameters in a multipath channel (direction of arrival, time delay and fading). The results exposed are useful for tactical applications such as HF radiolocalization, or for radio communication systems, to combat the degradations due to the channel. The present study is based on the recent work done on blind deconvolution which estimates the channels impulse responses. Based on a physical path parametric model, a spatio-temporal parametric blind identification of the front wave is performed. These parameters are direction of arrival : DOA θ, relative time delay τ and complex gain ϕ (fading).

1. INTRODUCTION

This paper focuses on blind spatio-temporal identification of multiple path channels. Space-time identification means here that we are estimating time delays τ, DOA θ and fading ϕ of multiple reflections of an unknown signal. This is a central problem in many fields including radar-sonar and communication systems.

In papers [1], a blind spatio-temporal identification of multipath channels has been presented. The purpose was already to estimate the physical parameters of the channel (θ_m, τ_m). The proposed algorithms proceed in two steps and are based on the exploitation of the properties of the correlation matrix of successive independent estimates of the channel impulse response $\widehat{\mathbf{h}}$. These estimates can be obtained with blind methods such as those proposed in papers [3], [4]. Exploitation of the parametric relation between $\mathbf{h}$ and (θ, τ, γ) allows to apply a 2D subspace method (MUSIC) in order to obtain jointly time delay and DOAs in a 2D spectrum. In [2] a direct estimation of the space-time parameters is proposed. The drawback of such methods is that they require either several channel estimations and/or work on large matrices. The difference in this work compared to [5] where a similar channel representation is used, is that in [5] the pulse shape is supposed to be known and several channel estimations are necessary.

The originality of the present work is that it requires a single channel estimation an works on reduces dimension matrices. An other contribution of this study is the resolution enhancement that can bring the knowledge of one of the space-time parameters to solve the other.

This paper is organized as follows : In **section 2**, we formulate the problem and give a parametric model for the ionospheric propagation channel impulse response. The model includes time delay, azimuth and elevation angle and path gain. In **section 3** the proposed algorithm is described and in **section 4** simulations are made. Finally we will conclude in **section 5**.

Notations

We will use the following notations :

x : scalar,

$\mathbf{x}$: vector,

$\mathbf{X}$: matrix,

^{T} : transpose,

* : conjugate,

† : transpose conjugate,

$*$: convolution product.

2. PROBLEM MODELISATION

The signal arrives on the antenna by different paths, and as the antenna is made of several sensors, the signal arriving on each sensor has been through a different channel. Thus we have one impulse response $h_n(t)$ per sensor. Each impulse response is the combination of several paths having different time delays, direction of arrival, gains and phases.

2.1. Data representation

The physical model of the signal at the output of a N sensor array is :

$$x_n(t) = \sum_{m=1}^{M} a_n(\theta_m)\alpha_m e^{i\phi_m} s(t-\tau_m) + n_n(t) \quad (1)$$

with $x_n(t)$ the output of the n^{th} sensor, $s(t)$ the source signal, $a_n(\theta)$ the n^{th} sensors response in the direction θ, $\alpha_m e^{i\phi_m}$ the complex amplitude of the m^{th} $(1 \leq m \leq M)$ path, τ_m the delay of the m^{th} path and $n_n(t)$ the noise on the n^{th} sensor.

The physical model can be represented by the convolution of the source signal by the channel $h_n(t)$:

$$x_n(t) = (h_n * s)(t) + n_n(t) \quad (2)$$

The propagation characteristics $(\tau, \theta, \alpha, \phi)$ are all confined in the channel impulse response. As we work with discrete and causal models the output of the n^{th} antenna is at the instant k :

$$x_n[k] = \sum_{l=-L}^{L} h_n[l] s[k-l] + n_n[k] \quad (3)$$

where $2L+1$ is the length of the channel.

In the last years, several blind spatio-temporal methods to estimate the channels impulse response have appeared [3], [4]. Once that the impulse response is found, a parametric estimation can be performed.

2.2. Channel model

From the physical model described in (1) and the formulation made in (2) we deduce the channel model :

$$h_n(t) = \sum_{m=1}^{M} a_n(\theta_m)\alpha_m e^{i\phi_m} \delta(t-\tau_m) \quad (4)$$

We suppose from now on that the channel has a finite frequency band B. The discrete corresponding filter becomes from (4) :

$$\begin{aligned} h_n[j] &= F_e \sum_{m=1}^{M} a_n(\theta_m)\alpha_m e^{i\phi_m} sinc(B(jT_e - \tau_m)) \\ & \quad with \quad j \in \mathbb{Z} \end{aligned} \quad (5)$$

where $sinc(x) = \frac{sin(\pi x)}{\pi x}$. As we work causally, the channel will be modelised by a FIR channel :

$$\begin{cases} h_n[j] = F_e \sum_{m=1}^{M} a_n(\theta_m)\alpha_m e^{i\phi_m} sinc(B(jT_e - \tau_m)) \\ h_n[j] = 0 \; for \; j < -L \; or \; j > L \end{cases} \quad (6)$$

A more general model including non ideal filters can be directly included in the same way as in (4). Without loss of generality we will keep the model (6).

Once the channel estimation performed, $\mathbf{h}$ can expressed in such ways to separate the different contributions of the DOAs, the time delays and the complex amplitudes. Indeed, from eq(6) we get :

$$\mathbf{h}_n = \sum_{m=1}^{M} a_n(\theta_m)\alpha_m e^{j\phi_m} \mathbf{m}(\tau_m) \quad (7)$$

where

$$\mathbf{m}(\tau) = [sinc((-LT_e - \tau)B), \cdots, sinc((LT_e - \tau)B)]^T \quad (8)$$

By considering the complex amplitudes $\gamma_m = \alpha_m e^{j\phi_m}$, we can write :

$$\mathbf{H} = [\, \mathbf{h}_1, \mathbf{h}_2, \cdots, \mathbf{h}_N \,] = \mathbf{M}\Omega\mathbf{A}^T \quad (9)$$

with

$$\mathbf{M} = [\mathbf{m}(\tau_1), \cdots, \mathbf{m}(\tau_M)], \quad (10)$$

$$\Omega = \begin{bmatrix} \gamma_1 & 0 & \cdots & 0 \\ 0 & \gamma_2 & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & \gamma_M \end{bmatrix} \quad (11)$$

and

$$\begin{aligned} \mathbf{A} &= [\mathbf{a}(\theta_1), \cdots, \mathbf{a}(\theta_M)] \quad (12) \\ where \; \mathbf{a}(\theta) &= [a_1(\theta), \cdots, a_N(\theta)]^T \quad (13) \end{aligned}$$

Based on this factorization, we can now propose new low cost high-resolution estimators for the physical characteristics of the channels.

3. SPACE-TIME PARAMETER ESTIMATION

With the introduced model, we can estimate the spatio-temporal parameters in different ways for instance a blind algorithm as [3]. Indeed we can work on the different products of the channel matrix $\mathbf{H}$ or if one set of the parameters is known (angles or delays), we can estimate the other set of parameters directly by M mono-dimensional researches.

The two next subsection treat of the case of totally unknown parameters. Then the case where one estimated parameter is known is treated.

3.1. Time parameters estimation

From equation (9), we obtain

$$\mathbf{H}\mathbf{H}^\dagger = \mathbf{M}\Gamma\mathbf{M}^\dagger \quad (14)$$

$$where\ \Gamma = \Omega \mathbf{A}^T \mathbf{A}^* \Omega^\dagger$$

From (14) we can apply any parametric estimation method (MUSIC, ML,...). For example, we can estimate Π_1, the projector on the noise subspace of $\mathbf{HH}^\dagger$. The rank of the matrix $\mathbf{M}$ is M if the time delays are all different. If the antenna is unambiguous and that the fadings are different, the matrix Γ is full rank M. Thus with these conditions, the matrix $\mathbf{HH}^\dagger$ is of rank M. From construction we see that we must have less paths than the length of the channel to be able to identify the parameters thus $M < 2L+1$. The noise projector Π_1 can be estimated by taking the $2L+1-M$ eigen vectors corresponding to the lowest eigen values of $\mathbf{HH}^\dagger$. Then we apply a normalized MUSIC type algorithm looking for the minimas of :

$$f_1(\tau) = \frac{\mathbf{m}(\tau)^\dagger \Pi_1 \mathbf{m}(\tau)}{\mathbf{m}(\tau)^\dagger \mathbf{m}(\tau)} \tag{15}$$

where $\mathbf{m}(\tau)$ is as in (8), or a maximum likelihood like algorithm with a criteria like :

$$\mathbf{J}(\tau_1, \cdots, \tau_M) = tr\left(\left(\mathbf{I}_{L+1} - \mathbf{M}\left(\mathbf{M}^\dagger \mathbf{M}\right)^{-1} \mathbf{M}^\dagger\right) \mathbf{HH}^\dagger\right) \tag{16}$$

and finding the minimums of $\mathbf{J}(\tau_1, \cdots, \tau_M)$.

3.2. Angle parameters estimation

In the same way as for the time parameters, we can write :

$$\mathbf{H}^\dagger \mathbf{H} = \mathbf{A}^* \Upsilon \mathbf{A}^T \tag{17}$$

$$where \Upsilon = \Omega^\dagger \mathbf{M}^\dagger \mathbf{M} \Omega \tag{18}$$

From (17) we construct a projector Π_2,the projector on the noise subspace of $\mathbf{H}^\dagger \mathbf{H}$. In this case, the rank of $\mathbf{HH}^\dagger$ is full when we have different time delays and different complex amplitudes. The dimension constraint here is that the number of sensors must be bigger than the number paths. The noise projector Π_2 can be estimated by taking the $N-M$ "smallest" eigen vectors and we then apply a normalized MUSIC type algorithm :

$$f_2(\theta) = \frac{\mathbf{a}(\theta)^T \Pi_2 \mathbf{a}^*(\theta)}{\mathbf{a}(\theta)^T \mathbf{a}^*(\theta)} \tag{19}$$

The minimums of $P(\theta)$ give the different angles of arrival. A maximum likelihood type with the following criteria can also be used :

$$\mathbf{J}(\theta_1, \cdots, \theta_M) = tr\left(\left(\mathbf{I}_N - \mathbf{A}^*\left(\mathbf{A}^T \mathbf{A}^*\right)^{-1} \mathbf{A}^T\right) \mathbf{H}^\dagger \mathbf{H}\right) \tag{20}$$

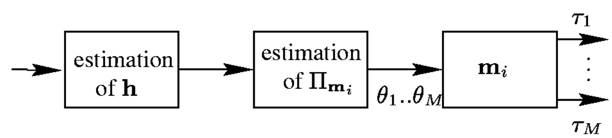
and the and finding the minimums of $\mathbf{J}(\theta_1, \cdots, \theta_M)$ give the wanted directions.

3.3. Time estimation knowing the angles

If the angles are known, we can build an estimate of the steering matrix $\mathbf{A}$ called $\hat{\mathbf{A}}$ and have an estimation of $\mathbf{M}\Omega$ called $\hat{\mathbf{M}} = \hat{\mathbf{H}}\hat{\mathbf{A}}^*(\hat{\mathbf{A}}^T\hat{\mathbf{A}}^*)^{-1}$. As Ω is diagonal, if perfect estimation was made, the columns of $\mathbf{M}$ and $\hat{\mathbf{M}}$ would be collinear. Let $\hat{\mathbf{M}} = [\mathbf{m}_1, \cdots, \mathbf{m}_M]$ thus we can estimate separately the different delays by computing on each coulomb of $\hat{\mathbf{M}}$ a mono-dimensional parametric search. For example, applying an MUSIC type algorithm, with a projector $\Pi_{\mathbf{m}_i} = \mathbf{I} - \frac{\mathbf{m}_i \mathbf{m}_i^\dagger}{\mathbf{m}_i^\dagger \mathbf{m}_i}$ with $\mathbf{I}$ the identity matrix of dimension $2L+1$ we get then pseudo-spectrum :

$$f_3^i(\tau) = \frac{\mathbf{m}(\tau) \Pi_{\mathbf{m}_i} \mathbf{m}^\dagger(\tau)}{\mathbf{m}^\dagger(\tau)\mathbf{m}(\tau)} \tag{21}$$

Again, the minimums of $f_3^i(\tau)$ will give the time delays τ.

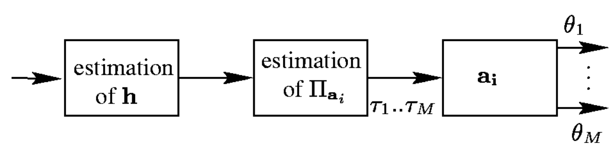


3.4. Angle estimation knowing the delays

As for the time parameters estimation, when the delays are known, the angles can be deducted easily. An estimate of the steering matrix can be performed by computing $\Omega\hat{\mathbf{A}}^T = (\mathbf{M}^\dagger\mathbf{M})^{-1}\mathbf{M}^\dagger\mathbf{H}$. As Ω is diagonal, with perfect estimates, the columns of $\hat{\mathbf{A}}$ and those of $\mathbf{A}$ are collinear. Let $\hat{\mathbf{A}} = [\mathbf{a}_1, \cdots \mathbf{a}_M]$, thus an parameter estimation method can be developed with a MUSIC type algorithm whose projector is $\Pi_{\mathbf{a}_i} = \mathbf{I} - \frac{\mathbf{a}_i \mathbf{a}_i^\dagger}{\mathbf{a}_i^\dagger \mathbf{a}_i}$ and the pseudo-spectrum is :

$$f_4^i(\theta) = \frac{\mathbf{a}(\theta) \Pi_{\mathbf{a}_i} \mathbf{a}^\dagger(\theta)}{\mathbf{a}^\dagger(\theta)\mathbf{a}(\theta)} \tag{22}$$

The minimas of $f_4^i(\theta)$ give us the angles of arrival of the different paths.



4. SIMULATIONS

In the simulations, we used a MUSIC type algorithm to estimate the different parameters. In the following figures we will show the example of a two path channel where the first and second path time delays and DOAs are $\tau_1 = -1.7$, $\theta_1 = 15$ and $\tau_2 = 1.7$, $\theta_2 = 20$. The Signal to Noise Ratio is 10dB and the temporal observation is made over 1000 snapshots. The antenna array is circular, 5 sensors,

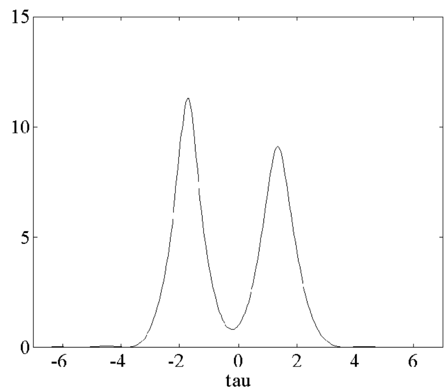


Figure 1: Direct estimation of group delay, first estimation

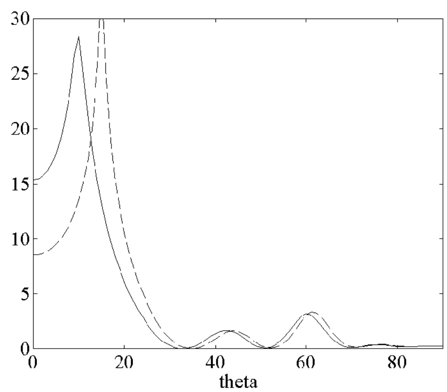


Figure 2: Estimation of incidence angle from group delay. Full line : spectrum deducted from $\tau_1 = -1.7$, 1^{st} column of $\hat{\mathbf{A}}$. Doted line : spectrum deducted from $\tau_1 = 1.7$, 2^{nd} column of $\hat{\mathbf{A}}$.

with a normalized ray of 0.8 compared to the wave length. The noise is white temporally and spatially.

The figures 1 and 2 show that it is possible to apair $\tau_1 = -1.7$ to $\theta_1 = 15$ and $\tau_2 = 1.7$ to $\theta_2 = 20$. For comparison, the figure 3 shows the spectrum of a spatial MUSIC direction finding method with the same simulation parameters. We see that the spatial MUSIC failed to separate the two paths.

5. CONCLUSION

In this paper we have proposed a low cost blind estimation of the parameters of wireless propagation channel. The advantages of the proposed method is that only needs one channel estimation to perform the parametric identification and requires less computational power than classical blind parametric spatio-temporal estimation methods. The channel model makes it possible to separate the temporal contribution and the spatial contribution and thus obtain higher performance in parametric resolution than with classical methods.

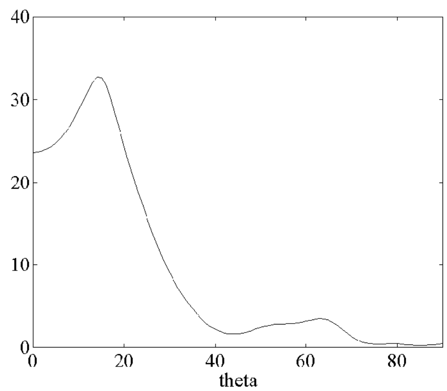


Figure 3: Spatial direction finding

6. REFERENCES

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