Sequential Blind Beamforming Algorithm Using Combined CMA/LMS for Wireless Underground Communications

Salma AIT FARES, Tayeb A. DENIDNI and Sofiène AFFES
INRS- EMT and LRCS
Place Bonaventure, 800 de la Gauchetiere Ouest, suite 6900
Montreal, Qc, Canada, H5A1K6
Tél.: (514) 875-1266 ext. 2017. Fax: (514) 875-0344.
{aitfares, denidni, affes}@ inrs-emt.uquebec.ca

***Abstract*—In this contribution, we propose a new smart antenna array (SAA) structure using sequential blind beamforming for multipath correlated signals in an underground mining environment. This adaptive receiver is dedicated to underground environments, where the multipath problem is more severe than the co-channel interference. In this confined area, the received path arrivals are not only highly correlated but actually belong to the same signal source. Consequently, we exploit the idea that these arrival paths are delayed replicas from an identical source. Simulation results confirm the effectiveness of the proposed blind beamformer. It outperforms the CMA beamformer by approximately 2.5 dB and 4.1 dB for Gaussian and Raleigh channels, respectively.**

Keywords- Adaptive antenna array, beamforming, CMA, LMS, fading channel, adaptive signal processing.

I. INTRODUCTION

A major problem in wireless communications in confined areas, such as indoor or underground environments is the inter-symbol interference due to selective fading arising from multipath propagation. To reduce its impact on the antenna performance, adaptive antenna array (AAA) techniques have been recently proposed. Most of the research in this area has been developed for outdoor and indoor communication systems [1], [2], and few works have been devoted to underground wireless communications [11], [12]. These techniques offer new directions for exploiting spatial diversity using multiple antennas. They have the potential of achieving high data-rates and increasing the capacity of mobile services.

In adaptive array signal processing, there are two major tasks: estimating the signal direction of arrival (DoA) and antenna beamforming. The former estimates the direction of signal arrivals, and the latter determines the best receiver processor for the antenna array to capture a desired signal. Due to the significant presence of multipath in underground environments, DoA estimation seems however to be inefficient. Adaptive antenna beamforming has been shown to be an effective mean for combating co-channel interferences (CCI) and multipath propagation. Recently many different types of antenna beamforming have been developed. The design of the beamformer requires some information about the desired signal. The use of a training sequence not only complicates the system but also reduces the system capacity. Therefore, there is a strong demand to use blind algorithms. For instance, the constant modulus algorithm (CMA), applied in blind AAA, is considered a promising method in mobile communications for mitigating multipath fading and for suppressing CCI signals. Unlike the least-mean-square (LMS) algorithm [13], CMA adaptive antenna arrays (CMA-AAA) do not need synchronization between the incident desired signal and the reference signal. In [3], a combined CMA/SMI (Sample Matrix Inversion) beamformer has been proposed to improve the SINR. The SMI method has been used to determine the initial weights for CMA operation. However, this method requires a training sequence to be transmitted, which implies a loss in spectral efficiency. For correlated signal sources, a cascade and parallel multi-stage constant modulus beamformers based on the DoA information obtained from the first-stage of the CMA beamformer, has been reported [4], [14]. As the first stage CMA may not be able to correctly estimate the DoA in a coherent environment, this approach largely depends on the performance of the first CMA beamformer and tends to be unreliable in multipath environments. However, due to the significant presence of multipath in underground environments [6], this approach seems to be inefficient. To separate the correlated signal sources from different paths, in [5] the CMA algorithm has been used to adapt the weights of the different beamforming filters under orthogonality constraints. The high correlated nature of the received signal in the mining environments makes the use of CMA with orthogonal filter constraints less efficient.

In this paper, we propose an efficient and yet simple new sequential blind beamformer (SBB) to estimate the desired signal in a multipath correlated underground environment. This underground communication system will be built around the standard IEEE 802.11b, which uses a carrier sense multiple access with collision avoidance that minimizes the CCI problem.

II. CMA ADAPTIVE ANTENNA ARRAY: BACKGROUND

Consider an N-element AA with $(L+1)$ narrow-band signals impinging on sensors. The received signal at the antenna elements consists of the desired signal, the interference signals and noise, and is given by:

$$\mathbf{x}(k)=s(k).\mathbf{a}_s+I(k)+\boldsymbol{\eta}(k)\ , \tag{1}$$

where $s(k)$ is a desired source sequence, drawn from alphabet members $A=\{a_1,\dots,a_m\}$, $I(k)$ is the sum of interferering signals, $\mathbf{a}_s$ is the propagation vector for the desired signal and $\boldsymbol{\eta}(k)$ is the additive white Gaussian noise vector.

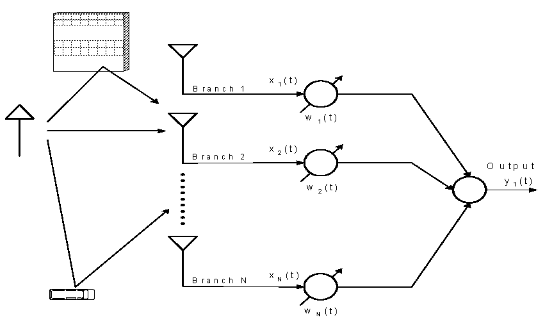

Figure 1. An adaptive antenna array.

Given a beamformer weight vector $w(k)$, the output of the beamformer is:

$$y_1(k)=\mathbf{w}^H(k)\cdot\mathbf{x}(k)\ , \tag{2}$$

The CMA-AAA aims to eliminate the amplitude fluctuations of the array output signal due to the incidence of interferences. Therefore, the cost function to be minimized is normally represented as [7], [8]:

$$J(\mathbf{w})=E\left[(\left|y_1(k)\right|^2-R_{CMA})^2\right]. \tag{3}$$

where $E[\bullet]$ denotes the ensemble mean and R_{CMA} is a constant which depends on the input symbols a. This constant is defined by [9]:

$$R_{CMA}=\frac{E\left[\left|a\right|^4\right]}{E\left[\left|a\right|^2\right]},\qquad \text{for } a\in A\ . \tag{4}$$

A stochastic gradient search method can be used to minimize the CMA cost function by adaptively adjusting the weight vector w according to:

$$\mathbf{w}(k+1)=\mathbf{w}(k)-\mu_1\cdot e^*(k)\cdot\mathbf{x}(k)\ , \tag{5}$$

where μ_1 is a small positive step size, * indicates complex conjugate, and $e(k)$ is the error signal given by:

$$e(k)=y_1(k)\cdot(\left|y_1(k)\right|^2-R_{CMA})\ . \tag{6}$$

Since CMA is phase blind, the array output will have an arbitrary phase rotation at the convergence, therefore a Modified CMA (MCMA) is proposed in [9], [10]. In this algorithm, the cost function is divided into real and imaginary parts, as follows:

$$J(\mathbf{w})=E\left[(\left|y_R(k)\right|^2-R_R)^2\right]+E\left[(\left|y_I(k)\right|^2-R_I)^2\right], \tag{7}$$

where

$$R_R=\frac{E\left[a_R^4(n)\right]}{E\left[a_R^2(n)\right]},\ R_I=\frac{E\left[a_I^4(n)\right]}{E\left[a_I^2(n)\right]} \tag{8}$$

$$a(k)=a_R(k)+j.a_I(k) \tag{9}$$

$$y_1(k)=y_{1R}(k)+j.y_{1I}(k)\ . \tag{10}$$

Again, application of a stochastic gradient algorithm to minimize the CMA cost function, in (7), gives the following tap-weight updating equation:

$$\mathbf{w}(k+1)=\mathbf{w}(k)-\mu_1\cdot e^*(k)\cdot\mathbf{x}(k) \tag{11}$$

where, in this case, the error function is given by:

$$e(k)=e_R(k)+j.e_I(k)\ , \tag{12}$$

$$e_R(k)=y_{1R}(k)\cdot(y_{1R}^2(k)-R_R)\ , \tag{13}$$

$$e_I(k)=y_{1I}(k)\cdot(y_{1I}^2(k)-R_I)\ . \tag{14}$$

We will use MCMA later, but we will refer to it as CMA for simplicity.

However, the presence of multipath tends to result in multiple correlated signals arriving at the antenna array (AA), and since a CMA-AAA assumes no a priori-information on the desired signal, it is difficult to separate and combine the multipath rays of the desired signal. Therefore, when CMA-AAA is only applied, the input signal power of the multipath rays cannot be efficiently used. Consequently, in this work, we use multiple beamformings that maximize the output power by looking for all dominant multipaths. This method does not require any orthogonality constraint on the beamforming filters. Instead, sequential beamforming is realized.

III. SEQUENTIAL BLIND BEAMFORMING – CMA

As mentioned above, we take advantage of the received signal characteristics in mining environments, where the multipath problem is more severe than CCI. So, the received path arrivals are not only highly correlated but actually belong to the same signal source. Consequently, we exploit the idea that these arrival paths are delayed replicas from an identical source. This method is implemented in two steps. First, the beamforming weights for the strongest path are estimated using CMA. Then, the delayed replicas from this estimated signal are used as references to construct the beamformers for the remaining paths using LMS algorithm. Fig. 2 illustrates the concept of the initial proposed SBB-CMA method.

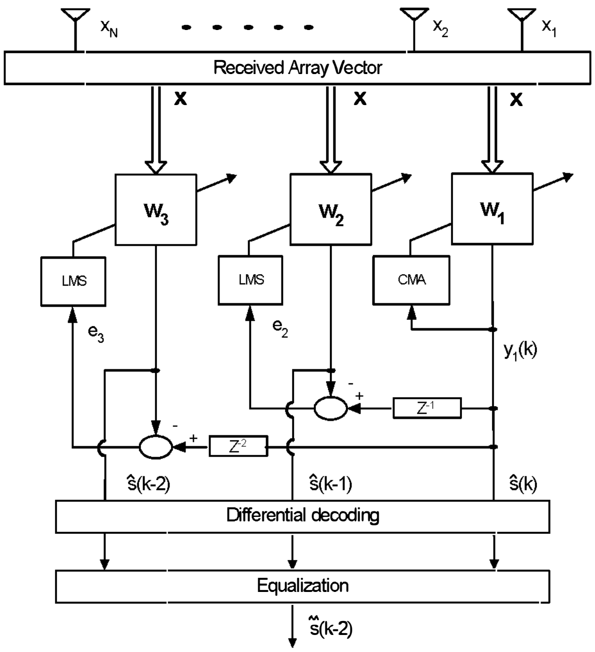

Figure 2. Concept of the initial SBB-CMA method.

Using the delayed replicas of $y_1(k)$ as reference signals, the weight vectors $\mathbf{w_2}$ and $\mathbf{w_3}$ are adjusted using LMS as follows:

$$\mathbf{w}_2(k+1) = \mathbf{w}_2(k) - \mu_2(y_1^*(k-1) - y_2^*(k)) \cdot \mathbf{x}(k), \qquad (15)$$

$$\mathbf{w}_3(k+1) = \mathbf{w}_3(k) - \mu_3(y_1^*(k-2) - y_3^*(k)) \cdot \mathbf{x}(k). \qquad (16)$$

where $\mu_i, i \in \{2,3\}$ is a small positive step size.

In cellular radio systems, all multipath signals suffer from fading fluctuations. Thus, it frequently happens that the stronger path signal between multipath incidents changes back and forth. However, CMA has a tendency to lock onto the path signal that has the greatest power [7], [8]. Consequently, the first beamformer (using CMA) estimates the strongest multipath replica of the desired signal and not necessarily the first path $\hat{s}(k)$. Fig. 3 shows a modified approach to solve this problem when the first arrival path is not necessarily the dominant one.

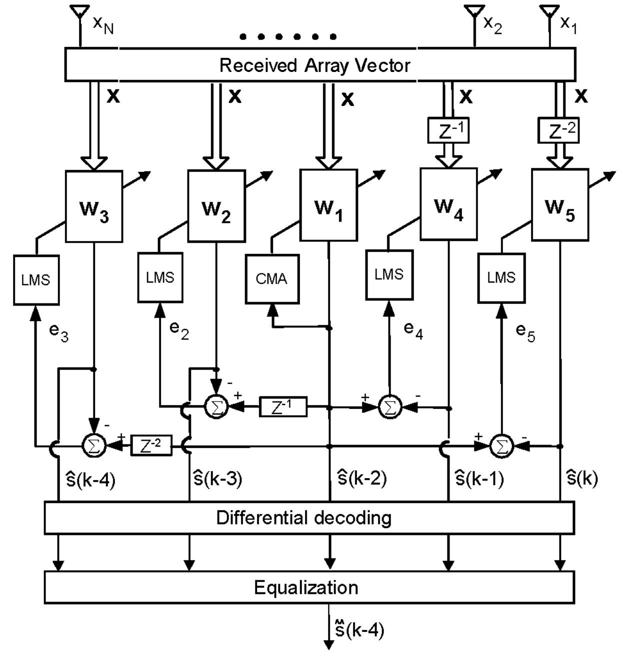

Figure 3. Concept of the modified SBB-CMA method.

The procedure is as follows. First, we start by activating the 3rd beamformer ($\mathbf{w_1}$) to estimate the strongest path, e.g., $\hat{s}(k-2)$, using CMA. Then, by feeding back this estimated signal as a reference and by delaying the received array vector $\mathbf{x}$ by one and two samples, the weights $\mathbf{w_4}$ and $\mathbf{w_5}$ are adapted using LMS to predict the signals $\hat{s}(k-1)$ and $\hat{s}(k)$. The same estimated signal from the CMA beamformer is delayed and used as a reference signal for the rest of the beamformers ($\mathbf{w_2}$ and $\mathbf{w_3}$) to estimate $\hat{s}(k-3)$ and $\hat{s}(k-4)$. A simple equalization stage finally adjusts the delays of the 5 beamformer outputs before their summation to provide the final signal estimate.

Finally, by delaying the received vector array and using the output $y_1(k)$ as a reference signal, the weight vectors $\mathbf{w_4}$ and $\mathbf{w_5}$ are updated using LMS as follows:

$$\mathbf{w}_4(k+1) = \mathbf{w}_4(k) - \mu_4(y_1^*(k) - y_4^*(k)) \cdot \mathbf{x}(k-1), \qquad (17)$$

$$\mathbf{w}_5(k+1) = \mathbf{w}_5(k) - \mu_5(y_1^*(k) - y_5^*(k)) \cdot \mathbf{x}(k-2). \qquad (18)$$

where μ_i, $i \in \{4,5\}$ is a small positive step size.

IV. COMPUTER SIMULATIONS

In this section, simulated results are presented to assess the performance of our proposed method. The figure of merit is the required SNR to achieve a Bit Error Rate of less than 0.001. A linear array consisting of 4 isotropic elements with half wavelength spacing is used. A BPSK desired signal is propagated along three multipaths to the AA, while the interference and noise are simulated as white Gaussian noise. Differential encoding is employed to overcome the phase ambiguity in the signal estimation. Two types of channel models are studied separately: Gaussian and Raleigh. The symbol rate is set to 1Mb/sec i.e. $T_s = 1\mu s$, and each frame consists of 160 DBPSK modulated symbols.

Figure 4 illustrates the simulated BER performance versus SNR for SBB-CMA and CMA over a Gaussian channel. From these results, it can be noted that the proposed approach provides a good enhancement and outperforms CMA by approximately 2.5 dB at a required BER=0.001.

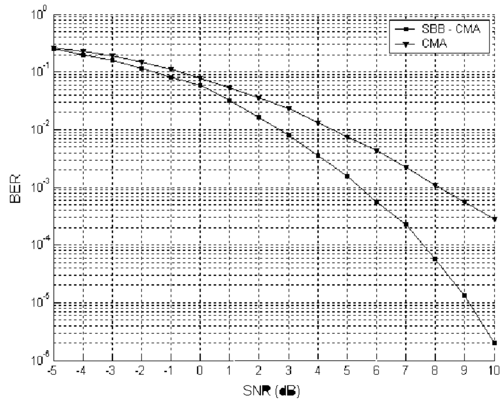

Figure 4. BER vs. SNR for a Gaussian channel.

With the same number of antenna elements -4-, the BER performance in the Raleigh fading channel for different Doppler frequency values (f_d=20 Hz, 35Hz) was studied. The use of these two Doppler frequency values reflects the typical range of the vehicle speed in our underground environment. For operations at a carrier frequency f_c=2.4GHz and vehicle speeds v_1=10km/h, and v_2=15km/h, we found approximately that $f_{d1} \cong$ 20Hz and $f_{d2} \cong$ 35Hz.

Figure 5 illustrates the simulated BER performance versus SNR of both SBB-CMA and CMA for the two Doppler values above. As expected, and for both algorithms, the BER performance decreases with increasing Doppler frequency values. It is shown also that the BER performance with the proposed method gives very good results. The SBB-CMA outperforms CMA for the two Doppler frequency values (i.e. f_{d1}=20 Hz, f_{d2}=35Hz) by approximately 3 and 4.1 dB, respectively.

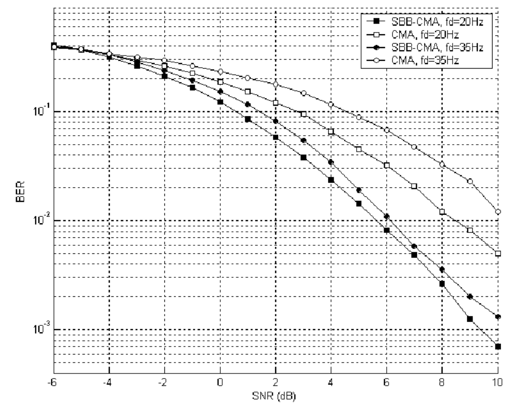

Figure 5. BER vs. SNR for a Raleigh channel

V. CONCLUSION

In order to reduce the multipath effect which causes ISI and degradation in the transmission quality of wireless communication systems, a simple new sequential blind beamformer is proposed. This adaptive receiver is dedicated to underground environments where the multipath problem is more severe than the CCI. It exploits the idea that these arrival paths are delayed replicas from an identical source and mitigates the effect of frequency-selective fading.

Simulation results with both Gaussian and Raleigh channel models show that the proposed approach provides a good enhancement in BER performance. The improvement in SNR for Gaussian and Raleigh channels are about 2.5 dB and 4.1 dB, respectively, for a Doppler frequency value f_d =35 Hz.

Also, simulations suggest that the proposed algorithm shows very satisfactory results at high SNR where the receiver is expected to operate in an underground wireless environment [6].

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