EFFICIENT SEQUENTIAL BLIND BEAMFORMING FOR WIRELESS UNDERGROUND COMMUNICATIONS

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***Abstract*— In this paper, a new technique enabling path diversity Maximum Ratio Combining (MRC) is proposed to leverage the performance of the previously proposed Sequential Blind Beamforming (SBB) method. The latter mitigates the inter-symbol and intra-symbol interferences and recovers the signal and its integer and non-integer (fractional) multiple replicas using jointly CMA, LMS and adaptive fractional time delay estimation. While implementing EGC at the combining step can give an acceptable performance in the SBB, since the resolved paths have common phase ambiguity, more substantial improvement can be obtained by implementing coherent MRC with hard decision feedback identification. Simulations results in different scenarios validate the superiority of the SBB using the proposed MRC compared to the EGC path combiner.**

Keywords- Adaptive antenna array, CMA, LMS, fractional delay, adaptive signal canceller, multipath fading channel, EGC, MRC, path diversity.

I. INTRODUCTION

Multipath fading represents the main cause of quality degradation in wireless communications applied in confined environments such as underground areas [1-2]. To provide a solution, adaptive antenna arrays (AAA) have been proposed [3-9]. For instance, the constant modulus algorithm (CMA) [7-9], applied in AAA, has been considered as a promising method in mobile communications for mitigating multipath fading. This method is attractive since it is blind and no off-line training sequence is needed. On the other hand, CMA suppresses the integer and non-integer rays of the desired signal, which wastes a substantial part of the available power. Since these arrival paths are delayed replicas of the desired signal, it is desirable to separate and to combine these paths instead of suppressing them for received power maximization.

Recently, a Sequential Blind spatial-domain path-diversity Beamforming (SBB) has been proposed using jointly M-CMA (Modified-CMA) [10-12], LMS and adaptive Fractional Time Delay Estimation (FTDE) filtering [11-12] to recover the desired signal and its integer and non-integer multiple replicas. In this proposed method, the M-CMA filter output is used as a reference signal to extract separately the remaining paths of the desired signal. Therefore, these estimated paths possess a common phase ambiguity. As a result, a combination based on a simple addition of the estimated paths can only be constructive and it represents a coherent EGC as presented in the previous work [11-12]. Relying on the common phase ambiguity characteristic presented in the extracted paths, additional enhancement remains to be exploited in the combining stage. Therefore, in this paper, an improvement of the SBB is presented when a coherent detection Maximum Ratio Combining (MRC) with hard decision feedback identification [13-14] is developed. This additional approach allows for optimal and constructive combination of the different received paths for signal-to-noise ratio (SNR) maximization.

The paper is organized as follows. In Section 2, a review of the SBB method is described briefly, and the proposed enabling path diversity MRC is presented. Section 3 presents the performance of the SBB using the proposed MRC compared to EGC. Section 4 concludes this paper.

II. PROPOSED PATH DIVERSITY COMBINING IN SBB

A. Signal Model and SBB Overview

Consider an N-element antenna array receiving L multipath signals. The received signal $x_m(k)$ at the m-th antenna can be expressed as:

$$x_m(k) = \sum_{i=1}^{L} \alpha_i s(k-\tau_i).e^{-j\pi(m-1)sin(DoA_i)} + \eta_m(k) \tag{1}$$

where,

- $\alpha_i(k)$ are the complex gains of the Rayleigh fading rays (with uniformly distributed phases φ_i between 0 and 2π) of the i-th path;
- $s(k)$ is the desired source sequence, drawn from alphabet members $A=\{a_1,\dots,a_j\}$;
- L is the number of multipath signals;
- $\eta_m(k)$ are additive white Gaussian noise processes with variance σ_n^2 at the m-th receive antenna;
- τ_i is the time path arrival (TPA) for the i-th path;
- and DoA_i is the direction of arrival of the i-th path.

For convenience, the array is assumed to be uniform and linear with inter-element spacing $d=\lambda/2$, where λ is the wavelength at the operating frequency.

The received signal vector representation is given by:

$$\mathbf{x}(k) = \mathbf{A}_s(k).\mathbf{s}(k) + \boldsymbol{\eta}(k) \tag{2}$$

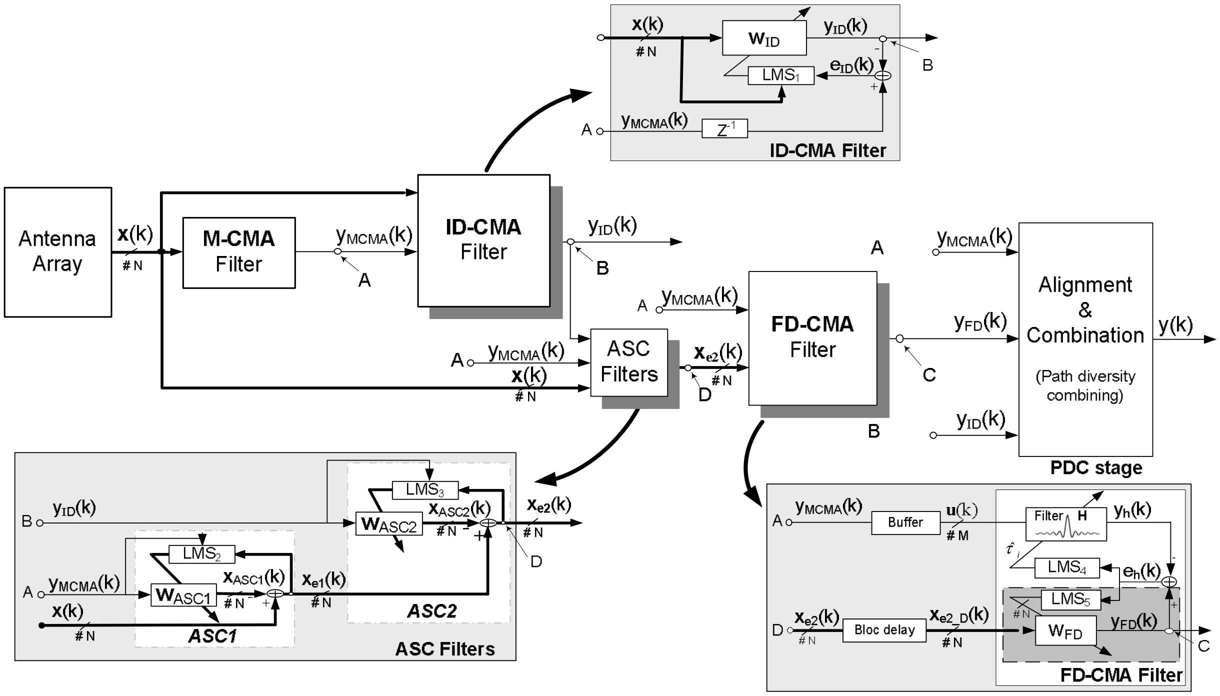

Figure 1. Proposed SBB Algorithm.

where $\boldsymbol{A_s}$ is an NxL matrix whose colums $\{\mathrm{a}_s(\theta_k)\}$ for k=1,…, L are determined by the propagation vectors and $\mathbf{s}(k)=[\alpha_1\cdot s(k-\tau_1)\ldots\,\alpha_L\cdot s(k-\tau_L)]^T$.

For the sake of simplicity and for illustration purposes, the following study is carried out using a three-path channel model where the TPAs are given by τ_1= 0 (assumed to be the strongest path), $\tau_2 = \tau < T_s$, and $\tau_3 = T_s$.

In summary, this method is implemented using three sequential filters, as dipected in Fig.1. The first filter (M-CMA) is used to estimate the strongest path while its weights are adapted using M-CMA [10-12]. The output of this filter is fed into both the Integer Delay-CMA (ID-CMA) [11] and Fractional Delay-CMA (FD-CMA) filters [12] to construct, respectively, the path arriving with an integer delay $\tau_3 = T_s$ and the one with a fractional delay $\tau_2 = \tau$. However, to ensure that the FD-CMA filter detects the path arriving with a fractional delay and not the others, adaptive signal cancellers (ASC) [8-9] are used to extract the other signal contributions from the received signal vector. The blow-ups of the aforementioned filters are shown also in Fig.1. A path diversity combining (PDC) stage (block 'PDC stage' in Fig.1) adjusts the delays of filters' output signals before their summation (i.e, EGC) to provide the final signal estimate [12]. However, it may be found that the EGC performance is not enough satisfactory, and some more advanced form of diversity combining is required to reach the optimal constructive combination of the different received paths. Consequently, we present below an incremental upgrade of the PDC step based on coherent detection MRC with hard decision feedback identification [13-14].

B. Coherent Detection MRC with hard Decision Feedback Identification

The paths y_{MCMA}, y_{FD} and y_{ID} estimated by the filters M-CMA, ID-CMA and FD-CMA respectively, possess a common phase ambiguity, since they are sequentially extracted using y_{MCMA} as a reference signal. In our previous work [12], a simple EGC is applied at these filters' outputs to combine the estimated paths constructively for power maximization as shown in Fig. 2.

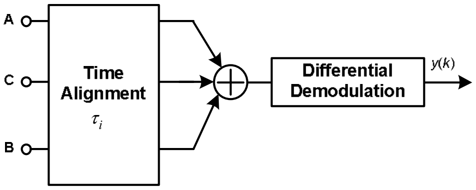

Figure 2. EGC path diversity combining stage.

Having the same phase ambiguity for the estimated paths can be better exploited by implementing coherent MRC with hard decision feedback identification presented in [13-14], as shown in Fig. 3.

In the first step, all the paths estimated by the SBB are aligned by proper additional delays, then scaled by a weight vector $\boldsymbol{g}(k)$. The summation of these scaled paths, $\tilde{s}(k)$, is given by:

$$\tilde{s}(k) = \mathbf{g}^H(k)\cdot\mathbf{y}_d(k) \tag{3}$$

where, $\boldsymbol{g}(k)=[g_1(k)\ g_2(k)\ g_3(k)]^{\mathrm{T}}$ is the weighting vector and $\mathbf{y}_d(k)=[y_{MCMA}(k)\ y_{FD}(k)\ y_{ID}(k+1)]^T$.

In the next step, $\tilde{s}(k)$ is quantized by making a hard decision to match it to a tentative symbol $\hat{s}(k)$. This operation can be expressed as follows:

$$\hat{s}(k) = Hard\left\{\tilde{s}(k)\right\} = \arg \min_{c_k \in C_M} \left\{\left|\tilde{s}(k) - c_k\right|\right\} \tag{4}$$

where C_M represents the MPSK modulation constellation defined by:

$$C_M = \left\{\ldots, c_k, \ldots\right\} = \left\{\ldots, e^{j\frac{(2k-1)-\delta(M-2)}{M}\pi}, \ldots\right\}, k \in \left\{1,\ldots,M\right\}. \tag{5}$$

Since $\hat{s}(k)$ provides a selected estimate of the desired signal, it can be used as a feedback reference signal to update the weight vector $\boldsymbol{g}(k)$ using LMS-type adaptation:

$$\hat{\mathbf{g}}(k+1) = \hat{\mathbf{g}}(k) + \mu \cdot (\mathbf{y}_d(k) - \hat{\mathbf{g}}(k) \cdot \hat{s}(k)) \cdot \hat{s}^*(k) \tag{6}$$

where μ is an adaptation step-size.

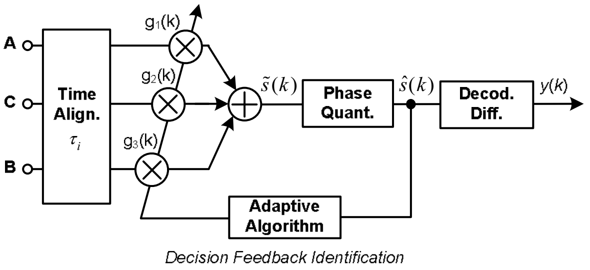

Figure 3. MRC path diversity combining stage.

Finally the desired output signal $y(k)$ is estimated from $\hat{s}(k)$ by differential decoding, as shown in Fig. 3, instead of differential demodulation needed previously with simple EGC. This final decoding step is expressed by:

$$y(k) = \hat{s}(k) \cdot \hat{s}^*(k-1). \tag{7}$$

The proposed technique enabling MRC path diversity combining offers an SNR gain of about 2 dB gain compared to simple EGC implementation.

III. COMPUTER SIMULATION RESULTS

In this section, simulation results are presented to assess the performance of the proposed MRC path diversity combiner for the SBB method and to compare it with the EGC implementation. A two-element array with half-wavelength spacing is considered. A DQPSK desired signal is propagated along 4 multipaths to the AA while the interferences and noise are simulated as white Gaussian noise. The first path is direct with time path arrival delay $\tau_1= 0$. The second and third paths arrive, respectively, with delays τ_2 and τ_3 smaller than the sampling interval. And the last path arrives with delay $\tau_4 = T_s$. The performance studies were carried out with two channel models. The type-A channel is Rayleigh fading with a Doppler shift f_{d1}=20Hz. The type-B channel is Rayleigh fading with a higher Doppler shift f_{d2}=35Hz. The use of these two Doppler frequencies reflects the typical range of the vehicle speed in our underground environment. The BER performance for different Doppler frequencies (f_{d1} and f_{d2}) was studied. The figure of merit is the SNR required to guarantee a BER below 0.001.

Figures 4 and 5 illustrate the measured BER performance versus SNR for SBB using MRC or EGC in the combining step for Type-A and -B channels with $\tau_2=0.4T_s$ and $\tau_3=0.8T_s$, respectively, at 2.4 GHz. A benchmark comparison with AAA using M-CMA is also provided.

For the type-A channel, the results show that SBB with MRC provides good enhancement and outperforms SBB with EGC and the AAA M-CMA by approximately 2.5 dB and up to 7 dB at a required BER=0.001, respectively (Fig. 4).

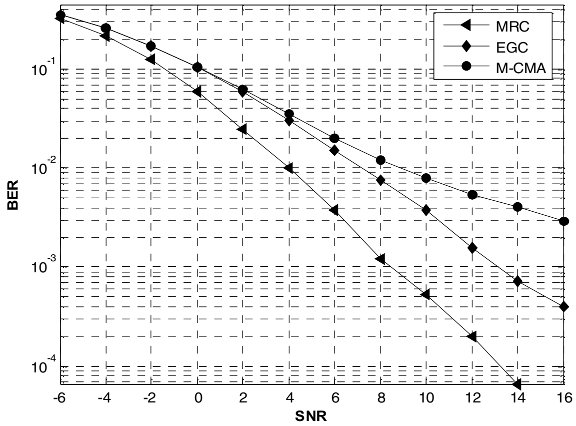

Figure 4. BER performance versus SNR in Type –A Channels for τ_2=0.4 T_s and τ_3=0.8 T_s.

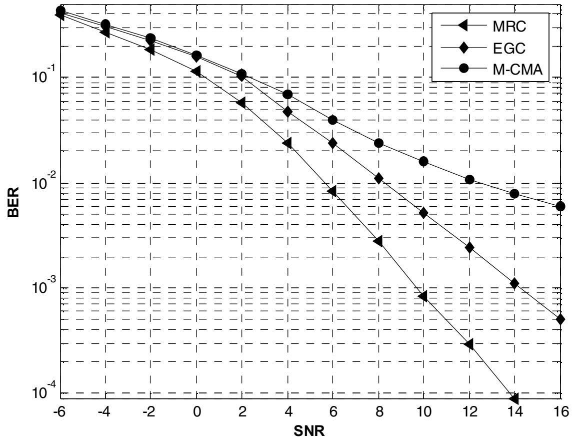

Figure 5. BER performance versus SNR in Type –B Channels for τ_2=0.4 T_s and τ_3=0.8 T_s.

In channel B enviromenet with higher doppler frequency, the measured results show that SBB with MRC maintains its advantage compared to SBB with EGC and to the AAA M-CMA where improvements of approximately 2 dB and up to 7 dB at a required BER=0.001 are obtained, respectively (Fig. 5).

Figures 6 shows the measured BER performance versus SNR for SBB using MRC or EGC in the combining step and with M-CMA AAA for Type-A channel using four antenna elements (*N*=4). Again it is clear that the SBB using the proposed MRC is more efficient than both the preivous SBB version using EGC [11-12] and the conventional M-CMA algorithm [10].

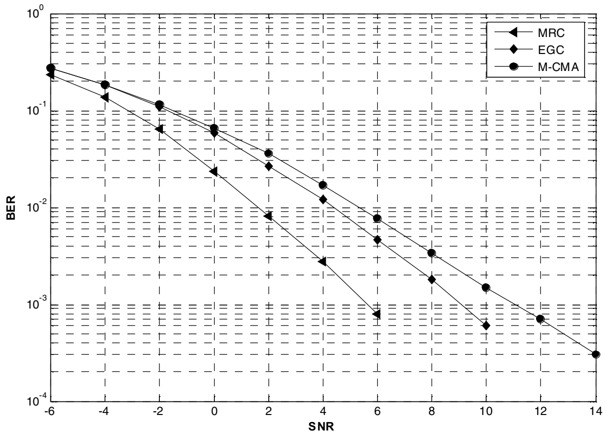

Figure 6. BER performance versus SNR in Type –A Channel for $\tau_2=0.2T_s$ and $\tau_3=0.8T_s$ using 4 antenna elements.

For BPSK modulation, the proposed MRC path diversity combining offers unnoticeable improvement compared to EGC since the symbol imaginary part does not affect the final demodulation. In contrast, MRC is necessary for higher order modulations such as QPSK, where the decision region in the symbol constellation is getting narrower and direct decoding without the proposed coherent detection with feedback identification may cause substantial error due to noise presence, especially in low SNR environments.

IV. CONCLUSION

In this paper, a new technique enabling MRC path diversity has been presented to enhance the performance of the previously proposed SBB method. Since the resolved paths in the SBB method have common phase ambiguity where a common reference signal is used to extract separately the different desired paths from the received signal, using EGC path diversity can give an acceptable performance. Using the proposed MRC with hard decision feedback identification, an additional improvement has been obtained. This additional approach allows optimal and constructive combination of the different received paths to achieve signal-to-noise ratio (SNR) maximization. Simulation results show that the proposed MRC with SBB receiver outperforms the EGC based SBB in all scenarios.

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