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COMBINED SPATIAL AND TEMPORAL EQULIZATION USING AN ADAPTIVE ANTENNA ARRAY AND A DECISION FEEDBACK EQUALIZATION SCHEME

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ABSTRACT

The purpose of this paper is to investigate the use of combined spatial and temporal equalization, in particular for short training sequences. The motivation for combining spatial and temporal equalization is the existence of multipath propagation and co-channel interference. Our main concern is to obtain good performance yet low complexity. We will suggest a low complexity algorithm utilizing a circular antenna array. Although it has inferior performance in an asymptotic sense, it turns out to be superior to the general solution for short training sequences. This conclusion is supported by simulations where a number of algorithms are evaluated for different scenarios involving co-channel interference.

1. INTRODUCTION

A motivation for the methods presented in this paper is the expansion of digital mobile radio communications. Here, data are transmitted in bursts, and attached to each burst is a training sequence of short duration. The channel is characterized by multipath propagation and co-channel interference. Therefore the received signal needs to be processed in some way, in order to retrieve the transmitted message.

One way of doing this is to use a decision feedback equalizer (DFE). The decision feedback equalizer consists of a feed-forward filter that filters the received signals and a feedback filter which filters previously received symbols and cancels their impact on the output of the feed-forward filter. The feed-forward and feedback filtered signals are combined and fed into a decision device which makes decisions on a symbol by symbol basis. This is an example of *temporal equalization.*

In the case of multipath propagation it is reasonable to expect that different signal paths impinge on the receiver antenna from different angles. This fact can be utilized to perform equalization in the spatial domain, i.e. we use an antenna array to separate different signal paths from each other. We can then use either only one of the signal paths, the strongest one, or we can use a combination of all the signal paths. This is an example of *spatial equalization.*

In this paper we will consider the case of combined spatial and temporal equalization by means of a combination of an antenna array and a DFE equalization scheme. The DFE is confined to have feed-forward and feed-back filters of finite impulse response type (FIR) and can be of multiple-input-single-output type (MISO).

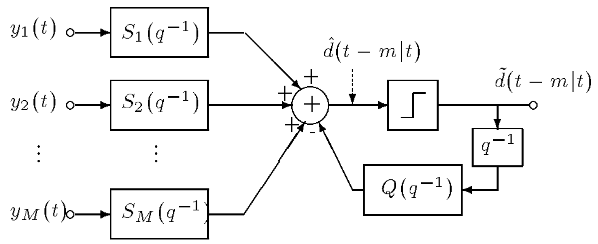

Figure 1: Structure of the general MISO FIR decision feedback equalizer

Given the above restrictions, the general structure to be considered is illustrated in Figure 1. $S_i(q^{-1})$ and $Q(q^{-1})$ are polynomials in the delay operator q^{-1} $(q^{-1}y(t) = y(t-1))$, of order ns and nq respectively. The number m is the smoothing-lag in the filtering. To each received antenna signal, y_i, a feed-forward FIR filter is connected. The outputs of these filters are summed and the output of the common feed-back FIR filter is subtracted. The resulting signal, $\hat{d}(t-m|t)$, is then fed in to the decision device to form the decided symbol estimate $\tilde{d}(t-m|t)$. A possible disadvantage with the general structure, depicted in Figure 1, is that if we chose to optimally compute all the coefficients jointly, this may require many arithmetic operations. If the training sequence is short, it could be difficult to obtain a correct tuning of the parameters because, there is not enough tuning data. For these reasons it is of interest to look for suboptimal solutions.

In [1], an algorithm is proposed that uses an LMS based adaptive array to train sets of weights to optimally receive the reference signal with different amounts of delay. The outputs corresponding to the different sets of weights are then delayed appropriately, multiplied with a coefficient and summed. It is proposed to adjust the coefficients so that maximum ratio combining is achieved. This combining is not optimal if there is some correlation left between the signals to be combined. The algorithm also lacks a decision feedback, which can improve the equalizing capability.

In [2], a structure is proposed which combines one antenna array with one FIR filter. The signals from the different antennas are weighted, summed and then passed through the FIR filter. Two different algorithms are proposed for adaptation of the antenna weights and the FIR filter coefficients. Implicitly, the algorithm utilizes delayed versions of the desired signals but it lacks a decision feedback filter.

In [3], a reduced-complexity multichannel DFE is proposed. P sets of beamforming weights are connected to the antennas. Each beamformer output is then fed through a feed-forward FIR filter. The outputs from these filters are then summed and old decisions, filtered through a FIR feedback filter, is subtracted. Symbol decisions are then formed on this signal. The beamformer and filter coefficients are adapted simultaneously but not jointly. This algorithm has a quite general structure and can be used with different levels of complexity.

We propose an algorithm with a structure equivalent to the general one of Figure 1 but with a simplified and suboptimal way of computing the filter coefficients. This algorithm is compared to the general MISO FIR decision feedback equalizer and to two versions of an algorithm similar to the one proposed in [3]. The algorithms are evaluated for a number of different scenarios.

2. ALGORITHMS

Three different algorithms, all restricted to FIR DFE:s, are compared. The algorithms are all derived using the assumption of correct past decisions in the DFE. We assume that data is transmitted in packages where the first N symbols constitute a known training sequence, $d(t) = \pm 1$, t=1,2,...,N, which is used to tune the equalizer parameters. The so obtained equalizer is then used to estimate the remaining transmitted data of the package.

2.1. General Beam Decision Feedback Equalizer (GB-DFE)

To get an analogy between the algorithms, we denote the general MISO FIR decision feedback equalizer by this name. For a given order of the filters, the coefficients in the equalizer, shown in Figure 1, are adjusted to minimize $\sum_{t=m+nq+2}^{N} |\hat{d}(t-m|t)-d(t-m)|^2$. The resulting equalizer is then used to estimate the remaining transmitted symbols.

2.2. Multiple Independent Beam Decision Feedback Equalizer (MIB-DFE)

The MIB-DFE, which is the algorithm we propose here, combines an antenna weight adaptation algorithm with a DFE scheme. The structure of the equalizer is depicted in Figure 2.

The MIB-DFE has $ns+1$ sets of M antenna weights. First, the $ns+1$ sets of antenna weights are adjusted to minimize the sum $\sum_{t=ns-i+1}^{N} |z_i(t) - d(t-(ns-i))|^2$ for i=0,1,...,ns. This means that each set forms a beam in order to optimally receive versions of the training sequence with different delays. The $ns+1$ output signals, $z_i(t)$, i=0,1,...,ns, from the antenna weighting sets are then computed over the duration of the training sequence. In a second step, the DFE filter coefficients s_0,s_1,...,s_{ns} and Q_0,Q_1,...,Q_{nq} are computed to minimize the criterion

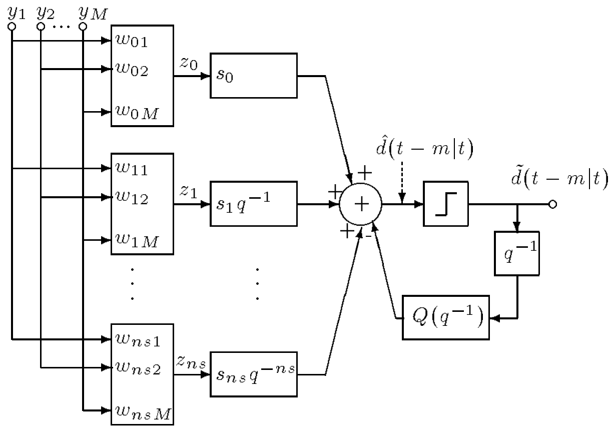

Figure 2: Structure of the MIB-DFE

$\sum_{t=m+nq+2}^{N} |\hat{d}(t-m|t) - d(t-m)|^2$ using the $z_i(t)$ signals (and $d(t-m-1)$) as filter inputs. This algorithm has lower complexity than the GB-DFE and it is believed to be new.

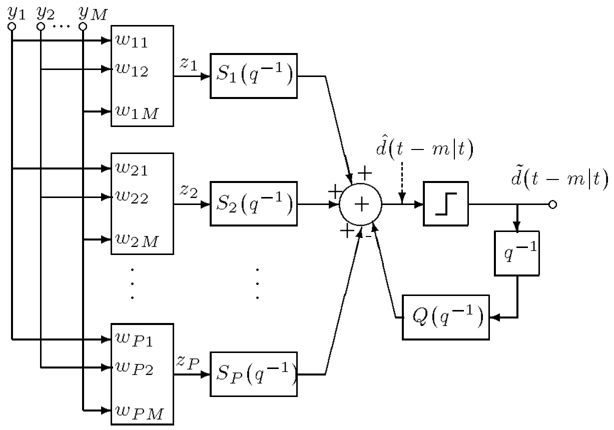

Figure 3: Structure of the Simultaneous Beamforming an Equalization algorithm (SBE).

2.3. Simultaneous Beamforming and Equalization iterating with the LS-algorithm (SBE-LS)

This algorithm is very similar to the one proposed in [3]. The major difference is that we have chosen to tune the beamformer weights and the equalizer feedforward and feedback filter coefficients by iterating with the Least Squares (LS) algorithm. The LS algorithm is first applied to the feedforward and feedback filter coefficients, with the beamformer weights fixed. It is then applied to the antenna weights, with the feedforward and the feedback filter coefficients held fixed. The iteration of these two steps then continues until convergence. In [3], this iteration is performed using two Recursive Least Squares (RLS) algorithms, taking one step in each algorithm for every new sample. In both the SBE-LS and the algorithm in [3], the initial values for the beamformer weights are non-zero, and different for each beamformer. The structure of the algorithm can be seen from Figure 3. Note that this algorithm has a full FIR-filter processing each signal z_i, whereas the MIB-DFE only use one filter parameter together with a delay.

Two versions of this algorithm were tested. The first had only *one* beamformer and a decision feedback equalizer with *one* feedforward filter of length $ns+1$ and a feedback filter of length $nq+1$. The second version had $P = ns+1$ beamformers, with P DFE:s of the same orders as the one used in the first version. We choose $P = ns+1$ in order to obtain a structure somewhat similar to the MIB-DFE above.

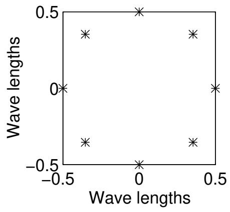

Figure 4: Antenna configuration

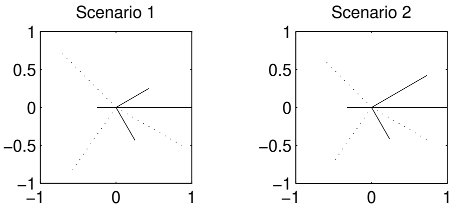

Figure 5: Scenario 1 and 2. Desired signals (solid) and co-channel interferers (dotted). The line lengths are proportional to the square root of the power impinging from each direction. The antenna is located at the origin.

3. SIMULATION SCENARIOS

The algorithms where tested on two different scenarios described below. In both cases the antenna array consisted of eight antennas in a circular array as shown in Figure 4. The orders ns=3 and nq=2 where used for all algorithms. 5 iterations were performed in the SBE-LS algorithms.

For each scenario, and for different lengths of the training sequence, 300 experiments with different noise and co-channel interferer realizations where made. In each experiment the equalizer parameters where computed by using the training sequence and then the BER was estimated over a data sequence of 10000 symbols. To simplify the simulations, the BER was estimated using correct past decisions, i.e. the effects of error bursts were not considered.

3.1. Scenario 1

The desired signal is impinging on the array from the directions $\alpha = 0$, 30 -60 and 180 degrees with the respective channels $B(q^{-1}) = 1$, $0.5q^{-1}$, $0.5q^{-2}$ and $-0.25q^{-3}$. Three co-channel interferers are impinging on the array from the directions $\alpha_{co} = 135$, -30 and 235 degrees respectively, each having a constant channel $B_{co}(q^{-1}) = b_{co}$. The constant b_{co} was in each scenario selected such that the SIR, averaged over all the antenna elements, became 4 dB. Independent white noise giving a SNR of 4 dB, averaged over the antenna elements, where also added to the signals at the antenna elements. See Figure 5.

3.2. Scenario 2

The desired signal is impinging on the array in the same directions as in Scenario 1 but now each channel is a mixture of two adjacent symbols. The respective channels are $B(q^{-1}) = 1 + 0.5q^{-1}$, $0.5q^{-1} + 0.8q^{-2}$, $0.5q^{-2} + 0.2q^{-3}$ and $0.2q^{-3} + 0.3q^{-4}$. Co-channel interferers and noise as in Scenario 1. See Figure 5. This scenario is motivated because it may be impossible to sample in such a way that each sample contains only one symbol.

4. RESULTS

The resulting BER[1] for the different scenarios can be seen in Figure 6.

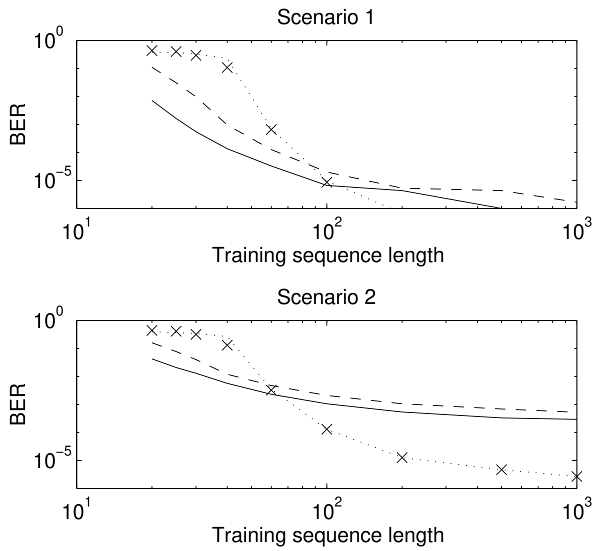

Figure 6: BER[1] for scenario 1 and 2: MIB-DFE(solid), SBE-LS with one beamformer (dashed), SBE-LS with four beamformers (x) and GB-DFE(dotted). SNR=SIR=4dB. When the estimate of the BER becomes zero the corresponding curve is not plotted further.

In Scenario 1, the different delayed signals are impinging from different directions. For short training sequences the MIB-DFE performs better than the other algorithms. The reason why the MIB-DFE performs the best is that it exploits the fact that only one symbol at a time is impinging on the antenna array from each direction. Also, the fact that it has relatively few parameters to tune simultaneously makes it potentially better for short training

[1] Assuming correct past decisions

sequences. The latter property is likely one of the resons why the first version of the SBE-LS algorithm also performs relatively well in this scenario.

In Scenario 2, there is a mixture of two adjacent symbols impinging on the array from each direction. The MIB-DFE still has the lowest BER for short training sequences. However, it is clear that in a mixture scenario, like Scenario 2, the MIB-DFE is not as good as when only one symbol at a time impinges from each direction.

The SBE-LS algorithm with one beamformer is for these scenarios comparable with the MIB-DFE, but still the MIB-DFE has lower BER.

5. COMPUTATIONAL COMPLEXITY

Apart from being able to handle short training sequences, the MIB-DFE requires less computation than the GB-DFE, especially in the case of a large number of antennas and long filter lengths. The MIB-DFE also requires less computations to tune the equalizer parameters than the SBE-LS algorithm. The reason is that usually more than one iteration has to be made in this algorithm. The computational complexity, C=the number of multiplications for tuning of the equalizer parameters, for the GB-DFE, the MIB-DFE and the SBE-LS algorithms asymptotically behave as

$$C_{\text{GB-DFE}} \sim (M(ns+1)+nq+1)^3/6+ (M(ns+1)+nq+1)^2 N/2 \quad (1)$$

$$C_{\text{MIB-DFE}} \sim M^3/6+M^2(N/2+ns+2)+ 2MN(ns+1)+(ns+nq+2)^3/6+ (ns+nq+2)^2 N \quad (2)$$

and

$$C_{\text{SBE-LS}} \sim [(MP)^3/6+(MP)^2 N/2+ ((ns+1)P+nq+1)^3/6+ ((ns+1)P+nq+1)^2 N/2] \times \text{nIt} \quad (3)$$

respectively. nIt is the number of iterations performed in the SBE-LS algorithm. The fact that the matrices to be inverted are positive definite has been taken into account when estimating the computational complexity.

6. INTERPRETATION OF THE GENERAL MISO DFE AS A BEAMFORMER

Consider a genaral MISO DFE with a feedforward filter performing the following operation

$$x(t)=(s_{10}+s_{11}q^{-1})y_1(t)+(s_{20}+s_{21}q^{-1})y_2(t) \quad (4)$$

If we rewrite

$$\begin{array}{ll} s_{10}=w_{10}s_0 & s_{11}=w_{11}s_1 \\ s_{20}=w_{20}s_0 & s_{21}=w_{21}s_1 \end{array} \quad (5)$$

then the feedforward filter can be rewritten as

$$\begin{aligned} x(t) \quad = \quad & s_0[w_{10}y_1(t)+w_{20}y_2(t)] \\ & +s_1q^{-1}[w_{11}y_1(t)+w_{21}y_2(t)] \end{aligned} \quad (6)$$

which is in the form of the MIB-DFE.

In general, the MISO DFE in Figure 1 can always rewritten into the structure of the MIB-DFE in Figure 2. Thus, the general MISO DFE can be interpretated as a multiple beamformer and combiner. If the parameters of the general MISO DFE are tuned optimally then this beamforming and combining is done optimally. The MIB-DFE performs the beamforming and the combining in a way that is suboptimal in the asymptotic sense, but works relatively well for short training sequences.

7. CONCLUSIONS

Different approaches to joint spatial and temporal equalization have been considered. The general way of computing the equalizer coefficients is not appropriate for short training sequences and it also potentially requires a large amount computations in order to tune the equalizer parameters. The proposed alternative suboptimal algorithm, the MIB-DFE, has good performance for short training sequences and requires less computations than the other algorithms considered in order to tune the equalizer parameters.

It is favorable to use the MIB-DFE, as opposed to the GB-DFE, when the training sequences are short and/or there is a large number of antenna elements and many multipaths with different delays impinging on the array from different directions. The MIB-DFE performs better if there is no mixture of symbols in the different signal paths. It should be interesting to investigate how the MIB-DFE can be modified in order to better can handle the situation when a mixture of adjacent symbols is impinging from each direction.

In mobile radio applications where short training sequences are necessary, the MIB-DFE would be interesting for multiuser detection. In mobile radio applications the channel may also be subject to non-negligible fading. Therefore, decision directed adaptation may have to be used during the burst. An adaptive variant of the MIB-DFE would be an interesting alternative as it has less degrees of freedom compared to the general algorithm, the GB-DFE, and would therefore, potentially, provide better tracking properties.

8. REFERENCES

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