In Proceedings of Nordic Radio Symposium seminar, Linköping, Sweden, 1994.

COMBINED SPATIAL AND TEMPORAL EQULIZATION FOR MOBILE RADIO APPLICATIONS

Erik Lindskog, Anders Ahlén and Mikael Sternad
Systems and Control Group, Uppsala University
P.O. Box 27, S–751 03 Uppsala, Sweden
tel: +46-18-183071 e-mail: el@syscon.uu.se

Abstract: A motivation for the method presented in this paper is the expansion of mobile radio communications. Here data are transmitted in bursts, where attached to each burst is a training sequence of short duration. The purpose is to investigate what can be gained by combining 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. The suggested algorithm can also be extended to multi-user detection.

1. INTRODUCTION

In radio transmission with multipath propagation which causes intersymbol interference 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 in to 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).

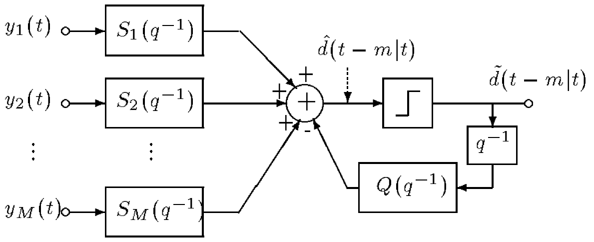

Figure 1: Structure of the general MISO FIR decision feedback equalizer

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}, 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, it 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 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. They propose to choose the coefficients so that maximum ratio combining is achieved. This combining is not optimal if the noise is correlated between the sensors as in the case of co-channel interference. 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. Unfortunately, the better one turns out to involve a minimization problem having local minimas. Implicitly the algorithm utilizes delayed versions of the wanted 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 output 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. The algorithm proposed in this paper can however not be realized within this structure.

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 also to an even simpler scheme. 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, $d(t)$, t=1,2,...,N, which is used to tune the equalizer parameters. The so obtained equalizer is then used to equalize the remaining data of the package. The transmitted sequence, $d(t)$, is assumed to be binary with the values 1 or -1. The different algorithms are presented next.

General Beam Decision Feedback Equalizer (GB-DFE):

To get an analogy between the algorithms we call 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 chosen to minimize $\sum_{t=m+nq+2}^{N} |\hat{d}(t-m|t)-d(t-m)|^2$. The resulting equalizer is then used to equalize the signal resulting from the data sequence.

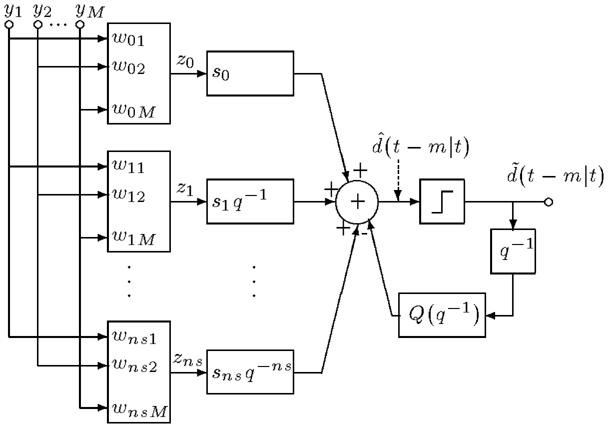

Figure 2: Structure of the MIB-DFE

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

The MIB-DFE can easily be generalized to cope with multiuser detection provided that the training sequences are different. It is also possible to convert the MIB-DFE into an adaptive algorithm that can continue to adapt during the data sequence in a decision directed mode.

It should be noted that the GB-DFE can be interpreted in terms of the MIB-DFE. However the resulting beam pattern will be different since the GB-DFE will perform spatial and temporal equalization jointly.

Single Beam Decision Feedback Equalizer (SB-DFE):

The SB-DFE uses only *one* set of antenna weights computed to minimize $\sum_{t=ns+1}^{N}|z(t)-d(t)|^2$ where $z(t)$ is the output from the antenna array. It is assumed that the reflection of $d(t)$ with no delay is the strongest one. This can be viewed as if in Figure 2 the same set of weights were to be used in all the weight vectors. The output signal, $z(t)$, from the antenna array is then computed and in a second step the DFE filter coefficients are calculated in order to minimize $\sum_{t=m+nq+2}^{N}|\hat{d}(t-m|t)-d(t-m)|^2$ using $z(t)$ (and $d(t-m-1)$) as input.

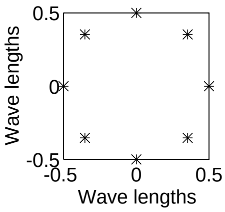

Figure 3: Antenna configuration

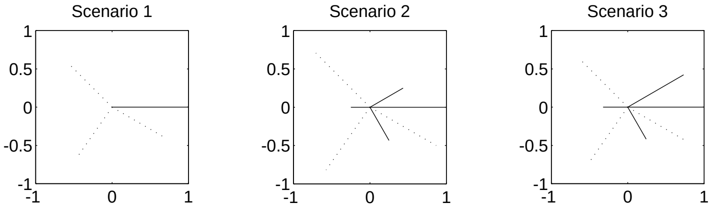

Figure 4: Scenario 1,2 and 3. Desired signals (solid) and co-channel interferers (dotted). The line lengths are proportional to the square root of the power impinging from each direction. The antenna is located at the origin.

3. SIMULATION RESULTS

The algorithms where tested on three different scenarios described below. In all cases the antenna array consisted of eight antennas in a circular array as shown in Figure 3. The orders ns=3 and nq=2 where used for all algorithms (In Scenario 3 below, the best choice for nq is however nq=3).

Scenario 1:

The desired signal is impinging on the array from one single direction $\alpha=0$ degrees with the channel in that direction described by $B(q^{-1})=1+0.5q^{-1}+0.5q^{-2}-0.25q^{-3}$. 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 chosen such that the SIR, averaged over all the antenna elements, became 3 dB. Independent white noise giving a SNR of 3dB, averaged over the antenna elements, where also added to the signals at the antenna elements. See Figure 4.

Scenario 2:

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 $-0.25q^{-3}$. Co-channel interferers and noise as in Scenario 1. See Figure 4.

Scenario 3:

The desired signal is impinging on the array in the same directions as in Scenario 2 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 4. This scenario is motivated because it may be impossible to sample in such a way that each sample contains only one symbol.

For each scenario, and for different lengths of the training sequence, 100 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[1] was estimated over a data sequence of 10000 symbols. The resulting BER[1] can be seen for the different scenarios in Figure 5.

In Scenario 1, asymptotically, as the training sequence length goes to infinity, all algorithms are approximately equally good. This is because all the signals are impinging from the same direction and the possible spatial equalization capability of the MIB-DFE and the GB-DFE is not exploited.

In Scenario 2, when the different delayed signals are impinging from different directions it can be seen that the MIB-DFE and the GB-DFE perform better than the SB-DFE. This is because these algorithms can now make use of their power to equalize in the spatial domain. For long training sequences the GB-DFE outperforms the MIB-DFE as can be expected. However, for short training sequences, the MIB-DFE outperforms the GB-DFE. The reason for this is that there is not enough data for the GB-DFE to tune properly in this case.

In Scenario 3, when from each direction there is a mixture of two adjacent symbols impinging on the array,

---

[1] Assuming correct past decisions

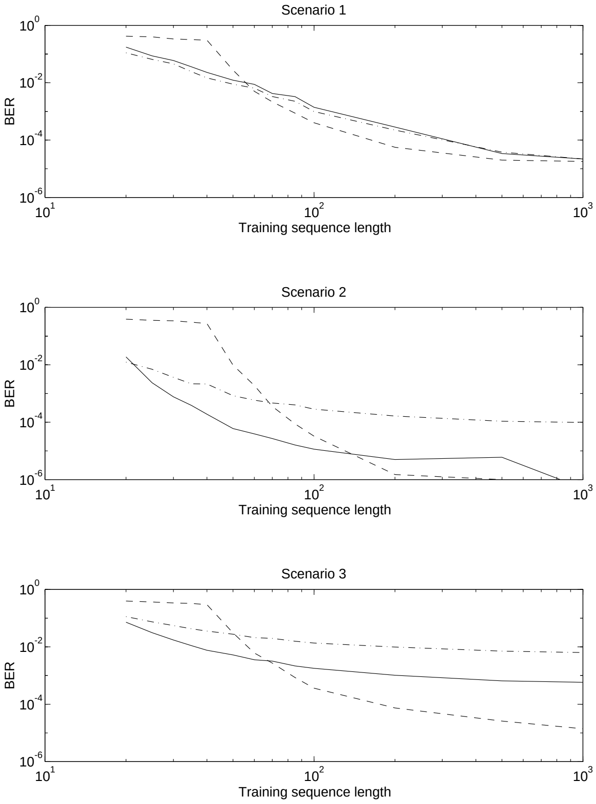

Figure 5: BER[1] for scenario 1,2 and 3: MIB-DFE(solid), GB-DFE(dashed) and SB-DFE(dash-dotted). SNR=SIR= 3dB. When the estimate of the BER becomes zero the corresponding curve is not plotted further.

the GB-DFE outperforms the MIB-DFE even more at long training sequences. This is because the MIB-DFE is not as good as the GB-DFE in doing joint spatial and temporal equalization. However, for short training sequences the MIB-DFE still outperforms the GB-DFE. In both Scenario 2 and 3 the SB-DFE is worse than the MIB-DFE as it only uses one beam.

Apart from being able to handle short training sequences, the MIB-DFE requires much less computation than the GB-DFE in the case of large number of antennas and large filter lengths. The computational complexity, C=the number of multiplications, of the MIB-DFE and the direct GB-DFE asymptotically behave as

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

and

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

respectively.

5. CONCLUSIONS

Different ways of doing joint spatial and temporal equalization has 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, will in general outperform the GB-DFE, for short training sequences.

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 the number of symbols mixed in each path is small.

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

Work aiming to compare the MIB-DFE to other methods presented in the litterature is currently underway.

References

[1] Y. Ogawa, Y. Nagashima and K. Itoh, "An adaptive antenna system for high-speed digital mobile communications". *IEICE Trans. Commun*, Vol. E75-B, No. 5, pp. 413-421, may 1992.

[2] R.P. Gooch and B.J. Sublett, "Joint spatial and temporal equalization in a decision-directed adaptive antenna system". *Proc. 22nd Asilomar Conference on Signals, Systems and Computers*, pp. 255-259, 1988

[3] M. Stojanovic, J. Catipovic and J. Proakis, "Reduced-complexity simultaneous beamforming and equalization for underwater acoustic communications". *Proc Oceans'93*, pp. III-426-431, IEEE, New York.