TRAINING AND TRACKING OF ADAPTIVE DFE ALGORITHMS UNDER IS-136

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ABSTRACT

The performance of wireless systems is severely corrupted under randomly time-varying channels. Efficient algorithms suitable to implement for fixed point DSPs are required to compensate for this degradation. The IS-136 standards define channel conditions under which wireless TDMA systems are required to work. Adaptive equalizers are unavoidable in order to satisfy these requirements. We consider training and tracking behavior for adaptive DFE structures under IS-136. It turns out that the essential difference between the performance of RLS and LMS algorithm is due to the training phase rather than the tracking behavior. For most of the conditions in IS-136, an LMS algorithm can track almost as well as an RLS algorithm when applied to a decision feedback equalizer, assumed that an RLS algorithm was run during the training phase. Simulations defined by the IS-136 standards corroborate our assumptions and validate theoretical results.

1. PROBLEMATIC

The transmission of data through frequency and time selecting fading channels requires fast and efficient adaptive signal processing techniques. The corruption of the data is due to high Doppler speeds and large delay spreads. Thus efficient digital receiver algorithms are required to ensure optimal decoding of the transmitted symbols even under low signal to noise ratios. Although it is known how a communication system with additive noise performs for an ideal equalizer, the tracking effects of the equalizer itself with a randomly time-varying channel have not been investigated. Usually, slow fading channels are assumed so that the effect of the equalizer is much smaller than the BER caused from the Rayleigh channel.

The training process of adaptive filters in a system identification problem is well understood and there exists ample literature about this field. Tracking analyses, however, is not largely unknown and relatively few literature can be found (see[1,2]). In particular for the case of equalization no general results are available yet.

The IS-136 standards[3] define the transmission modulation (offset 4DPSK) and conditions under which a wireless system (900MHz) is supposed to work. For one and two-paths Rayleigh fading channels, for example, the standard requires that the Bit-Error-Rate (BER) for a Signal-to-Noise Ratio (SNR) at the antenna of about 30dB does not exceed 3%. Although it is known how a transmission system with this modulation reacts for an ideal equalizer, the tracking effects of the equalizer itself have not been investigated. Usually, slow fading channels are assumed so that the effect of the equalizer is much smaller than the BER caused from the Rayleigh channel. The IS-136 standards however, require the 3% BER also for Doppler speeds up to 100Km/h. In this case the tracking noise of the equalizer becomes much larger than the error caused by the Rayleigh channel.

2. MAIN CONCLUSIONS

- Our theoretical investigations (see [6,7]) as well as our simulations indicate that the LMS and the RLS algorithm do not show any preference in their tracking behavior for the training of an adaptive decision feedback equalizer when the rms-delay spread of the channel is insignificant under IS-136 conditions. Only for delay spreads larger than $10\mu s$ the RLS solution provides slightly better behavior.
- The 3% BER bound as required for IS-136 can be guaranteed for Doppler speeds up to 100Km/h even with a simple and low complex LMS algorithm. However, better performance is achieved with an RLS solution.
- A proposed hybrid solution with RLS in the training and LMS in the data mode combines high performance with low complexity.
- The proposed hybrid algorithm is suitable for 16 bit fixed point solution. A current implementation requires 4MIPs.

3. THE CHANNEL MODEL

The performance of the algorithms are very much dependent on the channel they are applied to. In IS-136 a two path Rayleigh model is assumed for modeling the channel. Thus, we can describe the channel impulse response $\mathbf{c}_k = [c(0), c(1), .., c(N)]$ as

$$\mathbf{c}_k = c_1(k)\mathbf{h}_1 + c_2(k)\mathbf{h}_2 \,, \qquad (1)$$

the vectors $\mathbf{h}_1$ and $\mathbf{h}_2$ being the transfer functions of the actual paths and $c_1(k), c_2(k)$ the random, complex valued coefficients with Rayleigh distribution. We assume a linear AR model

$$c_i(k) = \sum_{l=1}^{L} f_l \, c_i(k-l) + \zeta_i(k) \; , i = 1, 2,$$

that describes their statistical properties. The driving processes $\zeta_i(k)$ are assumed to be white complex Gaussian and independent of each other. The filter coefficients $\{f_l\}$ define the correlation of the process and are determined by the Doppler speed. A few manipulations show that the channel can be written in terms of previous channel states no longer showing the assumed structure of (1) explicitly

$$\mathbf{c}_k = \sum_{l=1}^{L} f_l \mathbf{c}_{k-l} + \mathbf{h}_1\zeta_1(k) + \mathbf{h}_2\zeta_2(k) . \tag{2}$$

The IS-136 standard defines one path (flat) and two path Rayleigh fading channels with various delay spreads. The correlation of the alterations in the channel coefficients is caused by vehicle movements and the Doppler effect within. Applying Jakes' channel model (see [8]), it is assumed that the spectral density function of these alterations is given by

$$S_c(f) = \begin{cases} \frac{1}{\pi\sqrt{f_D^2 - f^2}} & \text{for } |f| \le f_D \\ 0 & \text{for } |f| > f_D \end{cases} , \tag{3}$$

f_D denoting the Doppler frequency. The corresponding autocorrelation function (acf) $s_c(t)$ can be found via Fourier transform (see [9] 3.387.2)

$$s_c(\tau) = J_0(2\pi f_D \tau) . \tag{4}$$

Figure 1 shows how (4) can be approximated by simpler models. The first order model is hereby an AR(1) model, i.e., a recursive filter model with one pole as in (5). Oscillations can only be modeled with at least two poles. The provided oscillation however, deceases rather quickly. Although not a perfect fit these simple models describe the essential behavior of the channel alteration quite sufficiently and will provide a simple model that allows to study the effect of these channels on the estimation algorithms. Note that for lower speeds even the first order model can be very precise for larger periods.

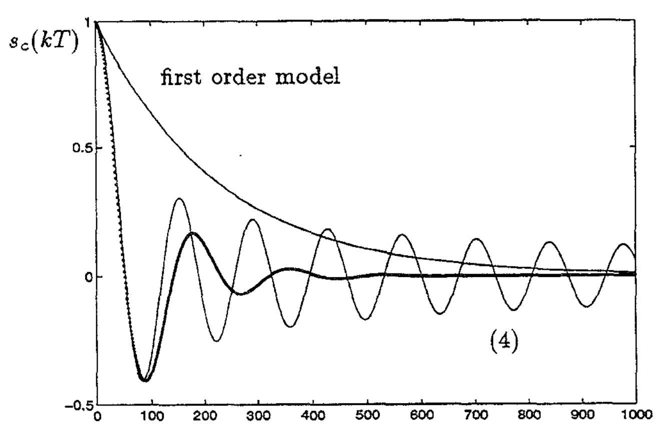

Figure 1: *Simple filter models for the acf of the channel alterations.*

Assumption (Channel Model) In order to simplify matters in our analysis we assume $L = 1$ and combine the driving terms into one new white noise term.

$$\begin{aligned} \mathbf{c}_k &= f\,\mathbf{c}_{k-1} + \sqrt{1-f^2}\,\mathbf{q}_k & (5) \\ u(k) &= \mathbf{s}_k\mathbf{c}_k + v(k) & (6) \end{aligned}$$

where $\mathbf{q}_k$ is a white complex-valued Gaussian vector random process of unit variance, i.e., $E[\|\mathbf{q}_k\|_2^2] = 1$ for a one path model or twice that amount for a two path model. The row vector $\mathbf{s}_k = [s(k), s(k-1), ...s(k-L)]$ consists of the transmitted symbol sequence $s(k)$.

4. THE DIFFERENTIAL DETECTOR PERFORMANCE

Figure 2 depicts the obtained BER for a pure differential detector (DD) at a Doppler speed of 100Km/h. It is assumed here and in the following that the receiver has a noise figure of 8dB which adds to the external SNR at the antenna. The shown SNR is thus to understand as an equivalent baseband value. For 3% BER at 22dB a little square is depicted as reference. As the figure demonstrates, the differential decoder is able to satisfy the standards only for the flat fading condition. Even for a small delay spread the differential decoder is performing very poorly and for larger delay spreads the BER goes up to 25%.

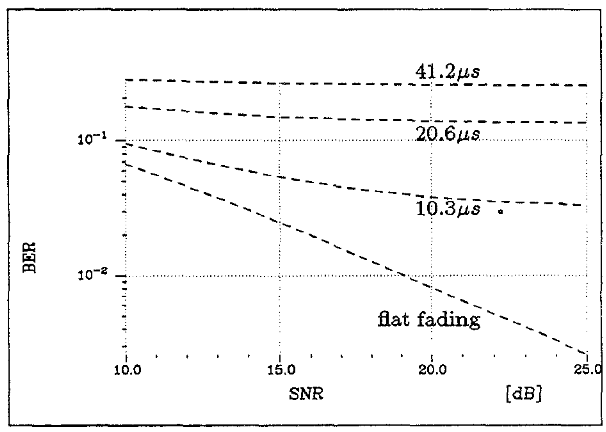

Figure 2: *BER curves for pure differential detector at Doppler speed of 100Km/h.*

Little is known about the theoretical BER that are to expect. Only for flat Rayleigh fading the theoretical BER curve for differential decoding is known. For DQPSK it is given by

$$\text{BER} = \frac{1}{2 + \text{SNR}} .$$

This equation describes a monotone mapping from the additive noise to the obtained BER. Compared to the flat Rayleigh fading curve in Figure 2 our result is about 1dB better than the theoretical line. This is due to a feedforward AGC that helps compensating for extremely deep fades. Since no theoretical information is available for differential detectors under delay spread and/or the effect on the equalizers, simulations for the various situations are helpful. A theoretical approach describing the equalizer performance in flat fading conditions has also been developed and is reported in [6,7].

5. THE DFE STRUCTURE

In [6,7] it has been demonstrated how the equalization problem can be reformulated to an equivalent system identification problem. In order to do so the existence of an optimal equalizer (model reference) with the structure depicted in

Figure 3 is required. The reference model consists of a linear filter that performs an equalization of the channel. Since a general channel can be perfectly equalized only by a filter of (double) infinite length, a finite (and general small) filter order can only achieve a rough equalization. The nonlinear decision device (slicer) following the equalizer guarantees that the outcome of the reference model equals the transmitted signal $s(k-D)$, where we allow for a delay of D samples. The difference of the reference model output $s(k-D)$ and the estimate $\hat{z}(k)$ leads to the error $e(k)$ that is used for updating the estimates $\hat{\mathbf{w}}_k$. A final decision device delivers estimates $\hat{s}(k-D)$ of the transmitted sequence. The outcome of the linear part is denoted $z(k) = \mathbf{u}_k\mathbf{w}_k + \mathbf{s}_{k-1}\mathbf{a}_k$ where the sampled receiver values have been combined in a row vector $\mathbf{u}_k$ and the filter taps in a column vector $\mathbf{w}_k$ for the feedforward and $\mathbf{a}_k$ for the feedback part. The results reported in the following assume a T/2-spaced DFE structure with three coefficients in the forward and one in the backward path. Thus only four coefficients need to be estimated. In [6,7] it is shown how to compute an equivalent SNR for this structure so that the mapping (4.) can be applied to it to calculate the BER. Comparisons for flat Rayleigh fading showed a good agreement between theory and simulation.

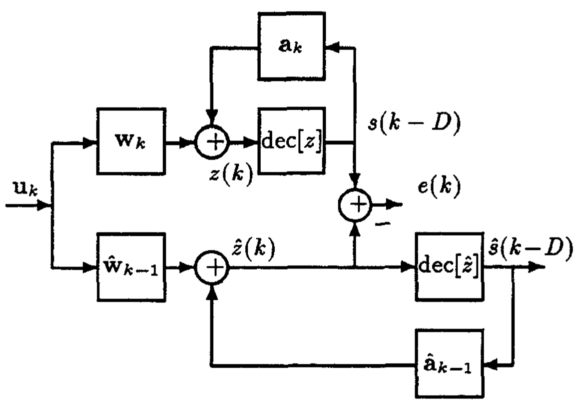

Figure 3: *Model reference structure for DFE equalizer.*

6. THE DFE PERFORMANCE

6.1. A Pure LMS Algorithm

The first experiment shows results for an LMS driven DFE structure. We use the sync word (14 symbols) at the beginning of a frame as well as the following one on the next frame in a backward mode. Also it is assumed that the CDVCC (6 symbols), that is located in the middle of the frame is known and can be used for training the equalizer. Thus the procedure for a whole frame is split up into four parts, two running forward and two backward. The two end points for the for- and backward schemes are selected by a search procedure for the fade minima. All adaptive DFE algorithms in the following will run with this scheme. Similar experiment with much simpler structure though have been reported in [4,5] where it is believed that only RLS driven equalizer can satisfy the conditions in a fast moving environment.

In a first step the LMS algorithm is run only for 20 symbols (during the training mode plus six symbols data mode) and the update of the coefficients was stopped during the remaining data mode. The LMS needs to be run twice during the traing mode in order to achieve accurate estimates. As Figure 4 reveals (continuous lines), the standards can only be satisfied for small delay spreads. For larger delay spreads than 10 μs the BER exceeds 3%. Also shown are the previous curves from the differential detector for flat fading and 10μs delay spread for reference. Even for the small delay spread of 10μs the DFE achieves a better behavior than the differential detector. If the LMS algorithm is also run during the remaining data mode, the behavior can be improved further and now the standards can be satisfied even for larger delay spreads (dotted lines). In the figure are four cases depicted for each situation: flat fading, 2-path fading with 10.3,20.6 and 41μs delay spread. The smallest BER are obtained for flat fading the largest for 20.6μs delay spread. The step-size for the LMS algorithm was selected to obtain optimal behavior for this Doppler speed. For smaller Doppler speeds a smaller step-size led to better performance.

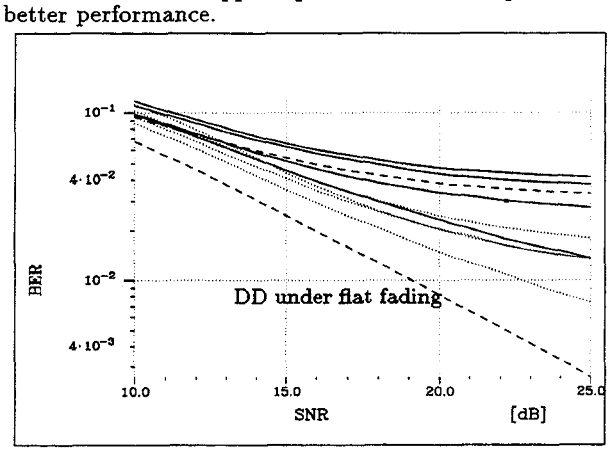

Figure 4: *BER curves for LMS driven DFE at Doppler speed of 100Km/h. Continuous lines: LMS only during training, dotted lines: LMS for training and tracking, dashed lines: differential detector (DD) for reference.*

6.2. A Pure RLS Algorithm

The first experiment is repeated but with an RLS instead of the LMS algorithm. Again, we first run the adaptation only during the first 20 symbols (a bit more than just the 14 training symbols) and then in a second step we run the RLS algorithm during the whole frame. All four curves for full adaptation mode show better performance than the set when the RLS is run only during the training mode. If we compare the results to the previous ones for the LMS algorithm, the results of the first mode (with the 20 symbols update only) show a strong improvement. On the other hand if we compare the performance of the LMS and the RLS algorithm in their tracking modes, the improvement is very similar. Starting with a much more accurate estimation from the training sequence due to an RLS algorithm, we expect the LMS algorithm to behave almost as good as the RLS when run in the data mode.

6.3. A New Hybrid Structure

Since the LMS algorithm can be implemented with much lower complexity than the RLS (in particular when run on a fixed point DSP), it is of great interest not to run the RLS algorithm during the whole frame. The previous results encourage to run the RLS algorithm only during the first 20

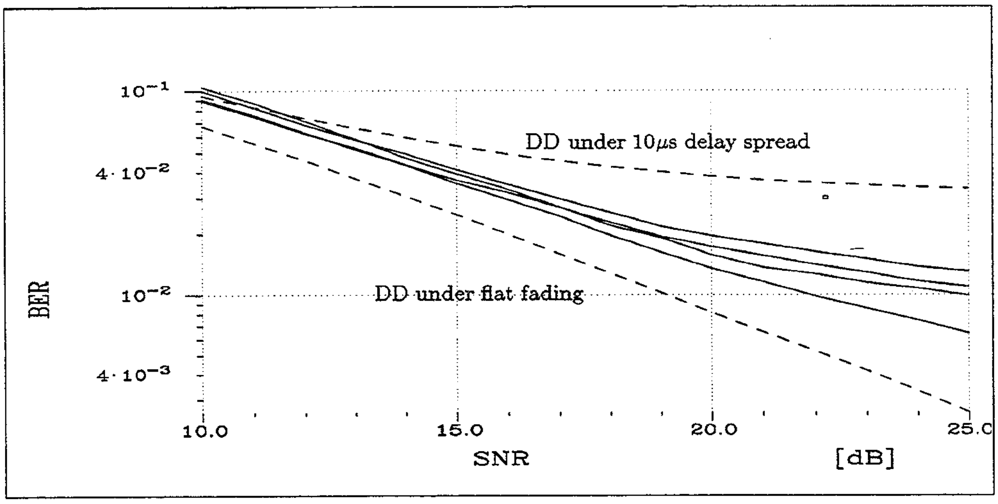

Figure 6: *BER curves for hybrid RLS/LMS driven DFE at Doppler speed of 100Km/h.*

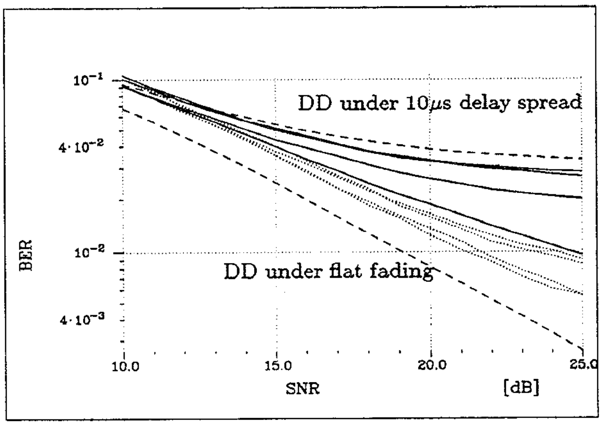

Figure 5: *BER curves for RLS driven DFE at Doppler speed of 100Km/h. Continuous lines: RLS only during training, dotted lines: RLS for training and tracking, dashed lines: differential detector (DD) for reference.*

symbols (mostly known training data) and the LMS during the remaining data mode. Figure 6 depicts the results of this hybrid algorithm. If compared to the pure RLS solution of Figure 5 (dotted lines) the achieved BER is almost the same, i.e., the differences are less than 1dB. Thus, the hybrid solution with RLS for training and LMS for data mode promises low BER combined with low complexity.

7. CONCLUSIONS AND CURRENT IMPLEMENTATION

Our theoretical investigations as well as our simulations indicate that the LMS and the RLS algorithms exhibit similar performance in their tracking behavior when used under IS-136 conditions. Both meet the 3% BER bound as required by standard for Doppler speeds up to 100Km/h and small delay spread. A new hybrid RLS/LMS algorithm has been proposed that utilizes RLS only for the first 20 symbols and switches then to LMS. This structure offers two advantages. First, it reduces the overall complexity of the algorithm. A current implementation with a DSP1627 from Lucent Technologies requires 4 MIPs. A second advantage is the improved numerical stability. When run an RLS algorithm for many iterations the entries of the estimated acf matrix tend to take very high values. A fixed point program could not satisfy these requirements and would run into saturation. Running only 20 symbols keeps these values bounded and thus the algorithm stable.

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