Parameter Tracking of STE for IS-136 TDMA Systems with Rapid Dispersive Fading and Co-channel Interference

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Abstract— **In this paper, we investigate parameter tracking of spatial-temporal equalization for IS-136 TDMA cellular/PCS systems. We present three parameter tracking algorithms in this paper: the *diagonal loading minimum mean-square-error algorithm*, which uses the diagonal loading to improve tracking ability, the *2-stage tracking algorithm*, which uses diagonal loading in combination with a reduced complexity architecture, and the *simplified 2-stage tracking algorithm*, which further reduces complexity to one $M \times M$ and one 3×3 matrix inversion for weight calculation with M antennas.**

Topics: (B3) equalization, (B5) diversity, and (B9) interference rejection

I. Introduction

Antenna arrays can be used in mobile wireless systems to mitigate rapid dispersive fading, suppress co-channel interference, and improve communication quality. For flat fading channels with antenna arrays, the *direct matrix inversion* (DMI) [1], [2] or the *diagonal loading DMI* (DMI/DL) [3] algorithm can be used to enhance desired signal reception and suppress interference effectively. In this paper, we study parameter tracking of spatial-temporal equalization (STE) for rapid dispersive fading channels with antenna arrays. Our investigation focuses on equalizer parameter tracking for IS-136 TDMA cellular/PCS mobile radio systems with rapid fading and strong co-channel interference.

Since the channel can change within an IS-136 time-slot, training sequences are used to determine the initial setting of the STE and then the decided (or sliced) signals are employed to track the equalizer parameters. Even though for time-invariant channels with additive white Gaussian noise, the maximum-likelihood sequence estimator (MLSE) is superior to the DFE and LE, the MLSE becomes extremely complicated for multiple-antenna systems with co-channel interference if spatial and temporal correlations for both the desired signal and interference are used. Hence, to reduce computational complexity, the MLSE in [4], [5] uses temporal correlation for the desired signal only, which degrades its performance. On the other hand, with reasonable complexity, the STE uses spatial and temporal correlation for both the desired signal and interference, and therefore may provide superior performance with lower complexity. Therefore, we investigate the STE for IS-136 TDMA systems.

This paper is organized as follows. In Section II, we briefly describe system model. Then, we develop the *diagonal loading MMSE* (DLMMSE) and *2-stage tracking algorithms* in Section III and IV respectively. Finally, we presents computer simulation results to evaluate the performance of the STE in various environments in Section V.

II. System Model

For mobile wireless communication systems with M antennas, the received signal can be expressed in vector form as

$$\mathbf{x}(t) = \sum_{l=0}^{L} \sum_{n=-\infty}^{\infty} \mathbf{h}_l(t - nT)s_l[n] + \mathbf{n}(t),$$

with

$$\mathbf{x}(t) \triangleq [x_1(t), \cdots, x_M(t)]^T,$$

$$\mathbf{h}_l(t) \triangleq [h_l^{(1)}(t), \cdots, h_l^{(M)}(t)]^T,$$

and

$$\mathbf{n}(t) \triangleq [n_1(t), \cdots, n_M(t)]^T.$$

In the above expressions, T is the symbol period, $x_m(t)$ is the received signal from the m-th antenna, $h_0^{(m)}(t)$ is the combined channel and signal impulse response at the m-th antenna corresponding to the desired data and $h_l^{(m)}(t)$ is the combined impulse response of the m-th antenna corresponding to the l-th interferer, and $\{s_0[n]\}$ is the desired data from transmitter and $s_l[n]$, $l = 1, \cdots, L$ is the complex data of the l-th interferer. We will assume that both the transmitted and the interference data are *independent, identically distributed* (i.i.d.) complex, zero-mean random variables with variance σ_s^2.

In IS-136 TDMA systems, the baud-rate is $R_b = 24.3$ ksymbols/sec and $T = 1/R_b$, the shaping pulse $c(t)$ is a square-root raised-cosine with rolloff parameter $\beta = 0.35$. Therefore, the combined channel impulse response can be expressed as

$$h_l^{(m)}(t) = c(t) * g_l^{(m)}(t),$$

where $*$ denotes convolution, and $g_l^{(m)}(t)$ represents the multipath fading of wireless channel.

According to [7], the optimum STE in IS-136 TDMA systems can be implemented as shown in Figure 1. We develop parameter tracking algorithms for the STE in the following two sections.

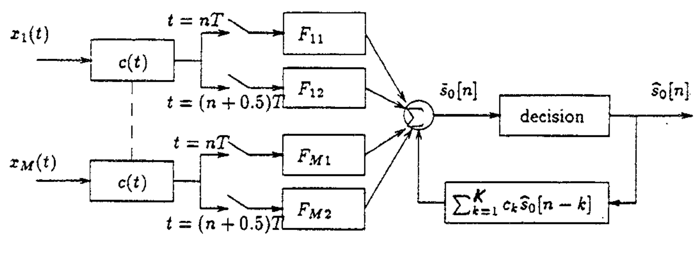

Fig. 1. General configuration of MMSE-STDFE for systems with cyclostationary interference.

III. Diagonal Loading MMSE-STE

As shown in Figure 1, in our MMSE-STDFE, a square-root raised-cosine *continuous* filter filters the received signal at each antenna, and then discrete filters enhance the signal and suppress interference. Practical communication systems use only finite length forward filters $F_{m,i}$ and feedback filter. The parameters of the forward and feedback filters are updated by decision-directed algorithms.

Let $\mathbf{u}[n]$ denote the *observation vector* at time $t = nT$, consisting of oversampled outputs from the square-root raised-cosine *continuous* filters and the previous decided symbols $\hat{s}_0[k]$ for $k < n$, and $\mathbf{w}[n]$ denote the *parameter vector* at time n consisting of the forward and the feedback filter parameters.

The classical weight generation algorithm in given by (see, e.g. [3])

$$\mathbf{w}[n] = \mathbf{R}_u^{-1}[n]\mathbf{r}_{us}[n],$$

where

$$\mathbf{R}_u[n] \triangleq \frac{1}{N}\sum_{k=1}^{N} \mathbf{u}^H[n-k]\mathbf{u}[n-k]\},$$

and

$$\mathbf{r}_{su}[n] \triangleq \frac{1}{N}\sum_{1}^{N} \mathbf{u}[n-k]\}\hat{s}_0^*[n-k].$$

Here, N is the window length. In IS-136 TDMA systems, the training sequence contains 14 symbols. Hence, the window length N is usually less than or equal to 14. This algorithm finds the $\mathbf{w}[n]$ that minimizes

$$C(\mathbf{w}[n]) = \frac{1}{N}\sum_{k=1}^{N} |\mathbf{w}^H[n]\mathbf{u}[n-k] - s_0[n-k]|^2\}.$$

However, as shown in [3], improved tracking performance can be achieved by the use of diagonal loading, i.e.,

$$\mathbf{w}[n] = [\mathbf{R}_u[n] + \gamma\mathbf{I}]^{-1}\mathbf{r}_{us}[n],$$

where

$$\gamma = \sigma \mathrm{tr}\{\mathbf{R}_u[n]\}. \quad (1)$$

Here, $\mathrm{tr}\{\mathbf{R}_u[n]\}$ denotes the trace of $\mathbf{R}_u[n]$, which is the summation of the diagonal elements. In [3], diagonal loading was used with spatial equalization only. Here, however, we consider its use with joint spatial-temporal processing.

The regularization factor σ in (1) is a positive parameter that depends on the delay spread and the strength of the noise and interference, but good performance is typically achieved for σ between 0.001 and 0.01. The above algorithm is called the *diagonal loading MMSE (DLMMSE) algorithm*, which is one form of the DMI/DL for spatial processing in [3]. Note that if the interference-to-noise ratio is known *a priori* or can be determined, better performance can generally be obtained with γ determined by (31) in [3], rather than (1).

IV. Two-Stage Tracking Algorithms

The DLMMSE algorithm requires inversion of a matrix which has a length given by the total number of spatial-temporal parameters, and therefore can be computationally intensive. For example, if the forward filter at each antenna has 2 taps and the feedback filter has 1 tap in Figure 1, then for 4-antenna systems, a 9×9 matrix inversion is required to compute the filter parameters, which can be difficult for real-time implementation.

In [8], a space-time decomposition algorithm was proposed for the STE to reduce the computational complexity when interference is not presented. With interference, we propose a modified version of the STE of [8] as shown in Figure 2, and combine it with DLMMSE algorithm.

In this STE, $\tilde{\mathbf{x}}(nT - T/2)$, $\tilde{\mathbf{x}}(nT)$, and $\tilde{\mathbf{x}}(nT + T/2)$ are combined at the 1st, 2nd and 3rd combiners, respectively. The weighting vector $\mathbf{w}_i[n]$ is estimated

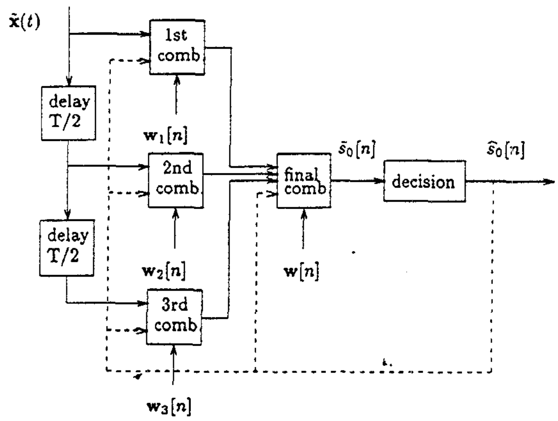

Fig. 2. Two-stage STE for systems with cyclostationary interference.

for each combiner by the DLMMSE algorithm using $\tilde{\mathbf{x}}(nT+(i-2)T/2)$ as the observation vector and $\hat{s}_0[n]$ as the reference signal. That is, $\mathbf{w}_i[n]$ is calculated by

$$\mathbf{w}_i[n]=(\mathbf{R}_i[n]+\gamma\mathbf{I})^{-1}\mathbf{r}_i[n],$$

where

$$\mathbf{R}_i[n] = \frac{1}{N}\sum_{k=1}^{N}\tilde{\mathbf{x}}(nT-kT+(i-2)T/2)\,\tilde{\mathbf{x}}^H(nT-kT+(i-2)T/2),$$

and

$$\mathbf{r}_i[n]=\frac{1}{N}\sum_{k=1}^{N}\tilde{\mathbf{x}}(nT-kT+(i-2)T/2)\hat{s}_0^*[n-k]$$

Hence, the outputs of the first stage combiners are

$$y_i[n]=\mathbf{w}_i^H[n]\tilde{\mathbf{x}}(nT+(i-2)T/2),$$

The weighting vector $\mathbf{w}[n]$ at the final combiner is calculated by

$$\mathbf{w}[n]=(\mathbf{R}[n]+\gamma\mathbf{I})^{-1}\mathbf{r}[n],$$

where

$$\mathbf{R}[n]=\begin{pmatrix} R_{11}[n] & R_{12}[n] & R_{13}[n]\\ R_{21}[n] & R_{22}[n] & R_{23}[n]\\ R_{31}[n] & R_{32}[n] & R_{33}[n]\end{pmatrix},$$

$$R_{ij}[n] \triangleq \frac{1}{N}\sum_{k=1}^{N}\mathbf{w}_i^H[n]\tilde{\mathbf{x}}[nT-kT-(i-2)T/2]\,\tilde{\mathbf{x}}^H[nT-kT-(j-2)T/2]\mathbf{w}_j[n]), \quad (2)$$

and

$$\mathbf{r}[n]=(r_1[n],\ r_2[n],\ r_3[n])^T,$$

$$r_i \triangleq \frac{1}{N}\sum_{k=1}^{N}\mathbf{w}_i^H[n]\tilde{\mathbf{x}}[nT-kT+(i-2)T/2]\hat{s}_0^*[n-k].$$

Hence, the output signal is given by

$$\tilde{s}_0[n]=\mathbf{w}^H[n]\begin{pmatrix} y_1[n]\\ y_2[n]\\ y_3[n]\end{pmatrix}.$$

We call the equalizer that uses the above *2-stage tracking algorithm* a *2-stage STLE.* Decision-feedback can be used at either the first stage combiners or the second stage combiner. Hence, we refer to as the *first-stage STDFE* and the *second-stage STDFE*, respectively.

For an M-antenna system, a 2-stage STLE requires two $M \times M$ and one 3×3 matrix inversions, since $\mathbf{R}_1[n]=\mathbf{R}_3[n-1]$. However, the computation in the 2-stage STLE can be further reduced if we calculate $\mathbf{w}_2[n]$ by

$$\mathbf{w}_2[n]=\frac{1}{2}[(\mathbf{R}_3[n]+\gamma\mathbf{I})^{-1}+(\mathbf{R}_3[n-1]+\gamma\mathbf{I})^{-1}]\mathbf{r}_2[n],$$

which eliminates the calculation of $\mathbf{R}_2[n]$, which we call this equalizer a *simplified 2-stage STLE,* since it requires only one $M\times M$ and one 3×3 matrix inversion.

V. Performance Evaluation through Computer Simulations

The performance of the STE has been evaluated through computer simulation, which focused on its application in IS-136 TDMA systems. The simulation uses the system model described in Section 2. Each time slot contains a 14 symbol training sequence followed by 134 symbols randomly drawn from $\{\frac{1+j}{\sqrt{2}}, \frac{1-j}{\sqrt{2}}, \frac{-1+j}{\sqrt{2}}, \frac{-1-j}{\sqrt{2}}\}$. DQPSK modulation is used with coherent detection. The 4-antenna system has white Gaussian noise and a single co-channel interferer, whose powers are given by the signal-to-noise ratio (SNR) and the signal-to-interference ratio (SIR), respectively. The channel for both the desired signal and interference is the two-path model with the same average power for each path and f_d = 184 Hz. The signal received by each antenna is first passed through a squared-root raised-cosine filter and then oversampled at a rate of $2/T$ for STE. To give insight into the average behavior of the STE in various environments, we have averaged the performance over 1,000 frames.

Figure 3 shows the required SIR for a BER=10^{-2} of different length DLMMSE-STE's for channels with

SNR= $20dB$ and different t_d's. From the figure, without delay spread, both the 5-tap DLMMSE-DFE and 4-tap DLMMSE-LE, *i.e.*, spatial processing only, operate up to -2.5dB SIR. With increasing t_d, the equalizer's interference suppression ability is reduced. The equalizer performance is generally improved by increasing the number of taps. However, for rapid dispersive fading channels, a too long equalizer does not necessarily have the good performance because the parameter tracking performance degrades with increasing equalizer length, even through the longer equalizer always performs better than the shorter one with the optimum equalizer parameters. Hence, in Figure 3, the 5-tap DLMMSE-DFE and 4-tap DLMMSE-LE have the best performance if $t_d \leq T/8$, while the 13-tap DLMMSE-STDFE and 12-tap DLMMSE-STLE have the best performance if $t_d > T/2$. Usually $t_d < T/2$ in IS-136 TDMA systems, therefore, the 9-tap DLMMSE-STDFE and 8-tap DLMMSE-STLE are two of the best STE's

Figures 4 and 5 show the BER of a 9-tap DLMMSE-DFE for different SNR's, SIR's and t_d's. In particular, for channels with $t_d = 0.25T$, the 9-tap STDFE attains a 10^{-2} BER when SIR= $5dB$, SNR= $17dB$ or SIR= $2.5dB$, SNR= $20dB$.

Figure 6 shows the performance of a 2-stage STLE. Compared with the 5-tap, 9-tap, or 13-tap DLMMSE-STDFE, the 2-stage equalizer has less sensitive required SIR curves. Considering the computation complexity and noise and interference suppressing performance, the 2-stage STLE is preferred over the DLMMSE-STDFE.

Figures 7 and 8 show the BER of the 2-stage STLE under various conditions. Compared with Figures 4 and 5, the 2-stage STLE has stronger noise suppressing ability, but weaker interference suppressing ability than the 9-tap STDFE.

Figure 9 compares the required SIR for a 10^{-2} BER for the original and simplified 2-stage STLE. Compared with the original 2-stage STLE, the simplified STLE has only about a 0.5 dB degradation when $t_d \leq 0.5T$. However, it has almost the same performance when $t_d > 0.5T$.

VI. Conclusions

In this paper, we have investigated STE in IS-136 TDMA systems with antenna arrays to mitigate intersymbol interference and suppress co-channel interference, and thereby enhance system performance. In order to track the the parameters of STE, we developed the *diagonal loading MMSE-STE* and the *two-stage tracking STE*. Furthermore, to reduce the computational complexity, we developed a *simplified two-stage tracking STLE*, which requires only one $M \times M$ and one 3×3 matrix inversion for M-antenna systems, but can attain a 10^{-2} BER for $t_d = T/2$, $f_d = 184$ Hz, and SIR=5dB. Hence, considering performance and complexity, the simplified 2-stage STLE is a promising technique for IS-136 TDMA systems.

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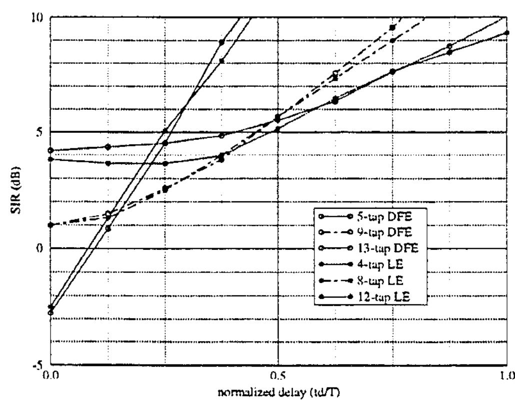

Fig. 3. Performance of DLMMSE-STDFE and DLMMSE-STLE: required SIR for BER= 10^{-2} versus t_d with $f_d =$ 184 Hz and SNR= $20dB$.

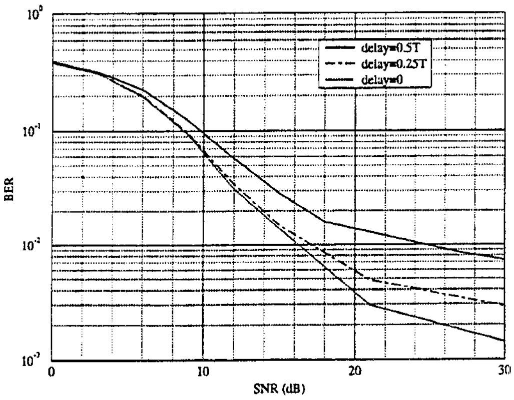

Fig. 4. Effect of SNR on BER of 9-tap DLMMSE-STDFE with $f_d = 184$ Hz, SIR=5dB, and different t_d's.

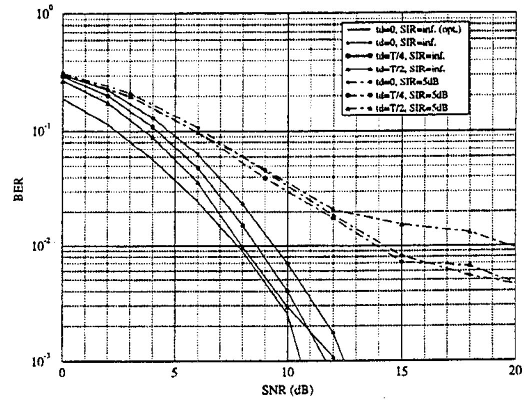

Fig. 7. Effect of SNR on BER of 2-stage STLE ($\sigma = 0.009$) with $f_d = 184$ Hz, different t_d's and SIR's.

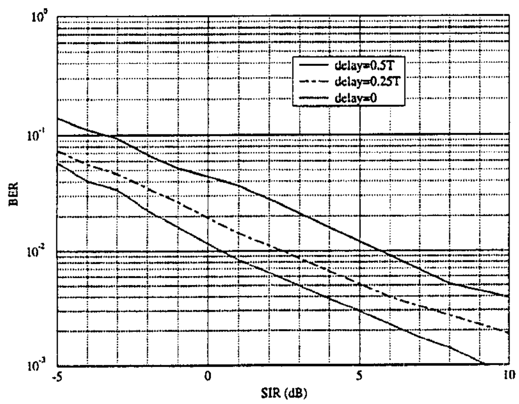

Fig. 5. Effect of SIR on BER of 9-tap DLMMSE-STDFE with $f_d = 184$ Hz, SNR=20dB, and different t_d's.

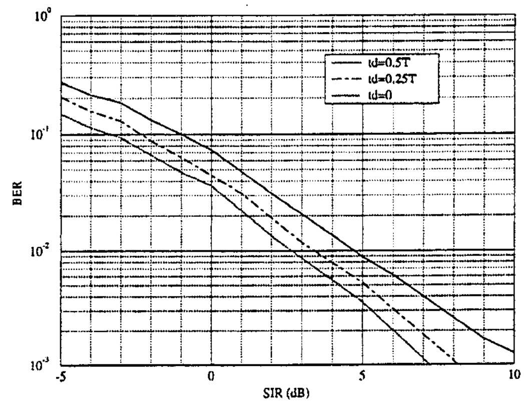

Fig. 8. Effect of SIR on BER of 2-stage STLE ($\sigma = 0.009$) with $f_d = 184$ Hz, SNR=20dB, and different t_d's.

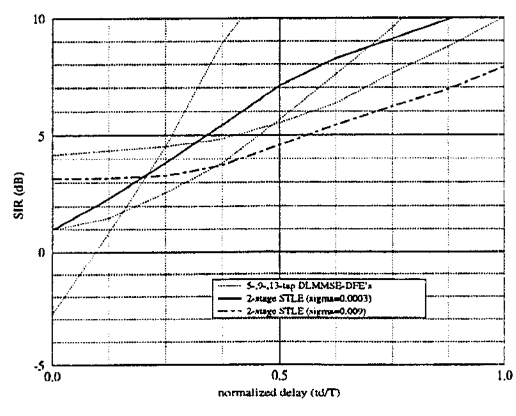

Fig. 6. Effect of t_d on required SIR of 2-stage STLE for BER= 10^{-2} with $f_d = 184$ Hz and SNR= $20dB$.

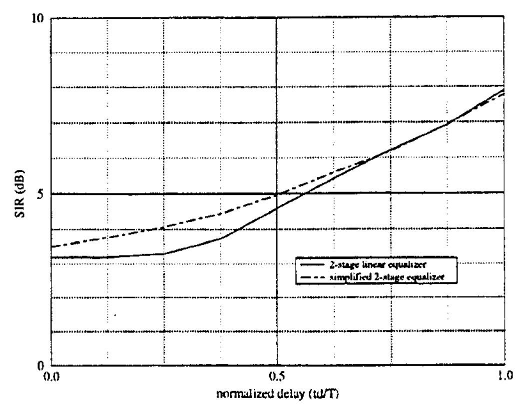

Fig. 9. Comparison of required SIR for original and the simplified 2-stage STLE with $f_d = 184$ Hz and SNR= $20dB$.