A LOW COMPLEXITY SEMI-BLIND CHANNEL IDENTIFICATION AND SOURCE RECOVERY METHOD FOR TRANSMISSION SYSTEMS WITH GUARD INTERVALS

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ABSTRACT

A semi-blind channel identification method is proposed for block transmission systems with guard intervals. Usually, block transmission systems append a sequence of $L-1$ zeros (where L is an upper bound on the channel length), called a guard interval, to each block before transmitting the blocks so as to prevent inter-block interference. This paper shows that by replacing the $L-1$ zeros between each block with specially chosen sequences of L known symbols, a penalty of just one extra symbol per block, it is possible to determine directly the channel coefficients from L consecutively received blocks. For non-time-varying channels, the scheme is equivalent to transmitting a training sequence every L blocks and hence it can be considered as a way of distributing a training sequence over L blocks. The benefit of the proposed method is twofold. Firstly, due to its distributed nature, it outperforms the training sequence method when the channel varies with time. Secondly, it has a lower latency delay than the traditional training sequence based method yet achieves the same or better performance. Note too that the proposed method retains all the advantages of guard intervals.

1. INTRODUCTION

A major characteristic of wireless communications is multipath transmission, or in other words, channels with memory. Because of this characteristic, the current received symbol depends not only on the current transmitted symbol but also on $L-1$ previous transmitted symbols. When the symbols are transmitted block-by-block over the channel, the term inter-block interference refers to the problem that the current received block depends not only on the current transmitted block but also on the previous transmitted block. To avoid this problem, many communication systems such as the mobile communication system GSM clear the channel memory after transmission of each block by appending to each block a sequence of $L-1$ zeros. This sequence of zeros is called a guard interval.

Guard intervals consume transmission bandwidth, however, they offer many advantages. Originally, the use of guard intervals was to prevent inter-block interference. It is now known that guard intervals allow the transmitted symbols to be always recovered if the channel is known and non-zero [1], and they ensure the channel deconvolution is always a stable operation [2, 3]. Another advantage of guard intervals is that they help blindly identify the channel [4, 5, 6]. Note that the cyclic prefix in OFDM systems is also a guard sequence, but it can only prevent inter-block interference and does not guarantee recovering the transmitted symbols when there is a zero sub-channel [7].

To recover the source symbols, the receiver requires (either explicit or implicit) knowledge of the channel coefficients. The simplest way to identify the channel is to send a training sequence. However, the disadvantage of this method is that there is a latency delay of $2L-1$ symbols while the training sequence is being transmitted. When guard intervals are present, the $L-1$ zeros at the end of the previous block can serve as part of the training sequence, hence the latency delay is reduced to L symbols. The original motivation for this paper was the desire to reduce this latency delay to just a single symbol.

The key observation is the following. If L known symbols $b_1, \cdots, b_L$ are transmitted consecutively over a channel with impulse response $h_0, \cdots, h_{L-1}$, the last received symbol is $y_L = b_L h_0 + b_{L-1} h_1 + \cdots + b_1 h_0$ and is *a known linear combination of the channel coefficients*. In other words, if L known symbols are appended to a transmitted block, then it is possible to determine directly a particular linear combination of the channel coefficients given just the last received symbol corresponding to that block. By using different sequences after each block, different linear combinations of the channel coefficients can be determined. Clearly, if L linearly independent sequences are used, one per block, then after L received blocks all the channel coefficients can be determined.

It is candidly stated that to achieve identical performance (over a constant channel) to a simple training sequence method, the total power used must be increased, as explained by example below. However, the peak power per symbol can remain constant, and since most systems transmit symbols from a finite alphabet, this increase in total power is not an issue. Let $L=2$. If the training sequence $0,1,0$ of length $2L-1$ is transmitted, the received symbols are $y_i = h_i + n_i$ for $i = 0, 1$, where n_i represents noise and the h_i are the channel coefficients. The first equation can also be obtained by transmitting the L symbols $0, 1$ and observing the last received symbol, namely $y = h_0 + n$. Similary, the second equation can be obtained by transmitting the L symbols $1, 0$. Therefore, to achieve the same performance as the training sequence $0, 1, 0$, it is necessary to use the two short sequences $1, 0$ and $0, 1$, which means the total required power in the known symbols has doubled. Note though that the total increase in power of the whole communication system is negligible because most of the power will go into transmitting the source symbols, not the known symbols. Note too that the added redundancy in both cases is the same; the

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training sequence method adds L consecutive symbols right at the start while the proposed method adds one symbol to each of L blocks.

By effectively spreading the training sequence over L blocks, not only has the latency delay been reduced to a minimum[1], but it can be anticipated that the performance of the system will improve if the channel varies over time. Preliminary simulation results in Section 3 show that this is indeed the case.

In fact, the idea of using known symbol guard intervals is not new; they were used in [8], for example. However, the key observation stated earlier about being able to determine directly the channel by solving a system of linear equations appears to have gone unnoticed. For instance, a subspace method is proposed in [8] to identify the channel, which is significantly more computationally involved than the simple approach proposed in the present paper. (It is noted though that the scheme in [8] appears to work even if only $L-1$ known symbols are inserted between blocks, although the identifiability proof, namely Theorem 3 in [8], requires L known symbols per block, the same as considered here.) Another advantage over the algorithm in [8] is that our scheme requires only L received blocks, while the algorithm in [8] can only estimate the channel after receiving p blocks, where p is block length and is usually much larger than L. Furthermore, simulations show that our scheme outperforms the algorithm in [8] in terms of both the channel estimation error and bit error rate.

This paper is organized as follows. Section 2 describes the proposed channel identification method. Section 3 presents simulation results while Section 4 concludes the paper.

Notation: Superscript T denotes transpose and $\mathbf{I}$ denotes the identity matrix. The Matlab notation $\mathbf{A}(:, m:n)$ is used to denote the sub-matrix of $\mathbf{A}$ that contain the columns m to n and $\mathbf{A}(m:n, :)$ the sub-matrix of $\mathbf{A}$ that contain the rows m to n.

2. SEMI BLIND CHANNEL IDENTIFICATION AND SOURCE RECOVERY

2.1. Semi Blind Channel Identification

We propose to insert known symbols between blocks before transmitting them over an FIR channel of length at most L, as now described. The source sequence is broken into blocks of fixed length p. We consider groups of L blocks. Then the mth source block is denoted by $\mathbf{s}_m = [s_m(1), \dots, s_m(p)]^T \in \mathbb{C}^p$, where $m = 1, \dots, L$. Each block is then appended with a sequence of L guard symbols denoted by $\mathbf{b}_m \in \mathbb{C}^L$. The mth source block is appended with the sequence in which the mth element is non zero and all other elements are zero, namely $\mathbf{b}_m = [0, \dots, b, 0, \dots, 0]^T$. The mth transmitted block is then $\mathbf{x}_m = [\mathbf{s}_m^T, \mathbf{b}_m^T]^T$. Let $\mathbf{a}_m$ be the last $L-1$ elements of $\mathbf{b}_m$, i.e. $\mathbf{a}_m = \mathbf{b}_m(2:L)$. The the mth received block $\mathbf{y}_m \in \mathbb{C}^{p+L}$ is mathematically related to the mth transmitted block and the channel by

$$\mathbf{y}_m = \mathbf{H}\begin{bmatrix} \mathbf{a}_k \\ \mathbf{x}_m \end{bmatrix} + \mathbf{n}_m \qquad \begin{array}{ll} k = m-1 & \text{if} \quad m \geq 2 \\ k = L & \text{if} \quad m = 1 \end{array} \tag{1}$$

[1] A latency delay of zero corresponds to using just $L-1$ known symbols per block. It has been proved recently in [5, 6] that with just $L-1$ known symbols per block, the channel can be identified deterministically, but doing so requires non-linear (actually, polynomial) equations to be solved. Hence, the minimum latency delay for which the channel can be identified by solving a linear set of equations is one, as claimed.

where $\mathbf{H} \in \mathbb{C}^{(p+L)\times(p+2L-1)}$ is the Toeplitz matrix constructed from $\mathbf{h}$, namely

$$\mathbf{H} = \begin{bmatrix} h(L-1) & \dots & h(0) & & \\ & \ddots & & \ddots & \\ & & h(L-1) & \dots & h(0) \end{bmatrix} \tag{2}$$

and $\mathbf{n}_m \in \mathbb{C}^{(p+L)\times L}$ is additive Gaussian noise. Stacking L successive received blocks, we obtain

$$\mathbf{Y} = \mathbf{H}\mathbf{X} + \mathbf{N} \tag{3}$$

where

$$\mathbf{X} := [\mathbf{x}_1, \dots, \mathbf{x}_L] = \begin{bmatrix} \mathbf{A} \\ \mathbf{S} \\ \mathbf{B} \end{bmatrix}, \tag{4}$$

$$\mathbf{S} := [\mathbf{s}_1, \dots, \mathbf{s}_L], \tag{5}$$

$$\mathbf{B} = b\mathbf{I} \in \mathbb{C}^{L\times L}, \tag{6}$$

$$\mathbf{A} = [\mathbf{B}(:, 3:L), \mathbf{B}(:, 1)]^T, \tag{7}$$

$$\mathbf{N} := [\mathbf{n}_1, \dots, \mathbf{n}_L]. \tag{8}$$

At the receiver, the channel coefficients are obtained simply by

$$\hat{h}(n) = \frac{1}{b}\mathbf{y}_{L-n}(p+L), \quad n = 0, \dots, L-1, \tag{9}$$

or in the Matlab notation

$$\hat{\mathbf{h}} = \frac{1}{b}\mathbf{Y}(p+L, L:-1:1). \tag{10}$$

The variance of the channel estimation error is as

$$\mathcal{E} = E\{\|\mathbf{h} - \hat{\mathbf{h}}\|^2\} = \frac{L\sigma_n^2}{b^2}. \tag{11}$$

Note that for preventing inter block interference, $L-1$ guard symbols per block are sufficient. However, our method consumes an extra symbol per block for the purpose of channel identification. In terms of redundancy, it is equivalent to transmission of a training sequence before every L blocks. That is, after appending $L-1$ zeros to each source block, the mth transmitted block is $\tilde{\mathbf{x}}_m = [\mathbf{s}_m^T, 0, \dots, 0]^T \in \mathbb{C}^{p+L-1}$. If we insert the sequence $\tilde{\mathbf{b}} = [b, 0, \dots, 0]^T$ between every L blocks $\tilde{\mathbf{x}}_m$, then a group of the transmitted signal is then described by the vector $\tilde{\mathbf{x}} = [b, 0, \dots, 0, \tilde{\mathbf{x}}_1^T, \dots, \tilde{\mathbf{x}}_L^T]^T$. Since the previous group ends in $L-1$ zeros, for every group we have the training sequence $[0, \dots, 0, b, 0, \dots, 0,]^T$. However, as will be presented in Section 3, when the channel is time varying block-by-block, our proposed scheme results in less bit error rate than this scheme does.

Remark: Significantly better performance is obtained if instead of choosing $\mathbf{b}_m$ as above, with all but one element zero, sequences with all elements having modulus one are used. For simplicity of presentation, this more general scheme is not discussed here.

2.2. Source Recovery

Since the guard sequences are known at the receiver, inter-block interference can easily be removed by constructing the matrix $\mathbf{R}$ as follows.

$$\mathbf{R} = \begin{bmatrix} \mathbf{U} \\ \mathbf{O} \\ \mathbf{V} \end{bmatrix} \tag{12}$$

where $\mathbf{O}$ is the zero matrix having L columns and $p-L+1$ rows, $\mathbf{V} \in \mathbb{C}^{L\times L}$ is the lower triangular Toeplitz matrix having $\hat{\mathbf{h}}$ as the first column and $[\hat{h}(0), 0, \ldots, 0]^T$ as the first row and

$$\mathbf{U} = [\hat{\mathbf{h}}(1:L-1), \mathcal{H}] \tag{13}$$

where $\mathcal{H} \in \mathbb{C}^{(L-1)\times(L-1)}$ is the Toeplitz matrix having $[0, \ldots, 0]^T$ as the first column and $[0, \hat{h}(L-1), \ldots, \hat{h}(2)]^T$ as the first row.

The received blocks after removing inter block interference is mathematically described by

$$\mathbf{Z} = \mathbf{Y} - b\mathbf{R}. \tag{14}$$

Let $\mathcal{Z}$ be the matrix obtained from the matrix $\mathbf{Z}$ by removing its last row, i.e. $\mathcal{Z} = \mathbf{Z}(1:p+L-1, :)$. Let $\mathbf{G} \in \mathbb{C}^{(p+L-1)\times p}$ be the lower triangular Toeplitz matrix constructed from $\hat{\mathbf{h}}$, having the vector $[\hat{h}(0), \ldots, \hat{h}(L-1), 0, \ldots, 0]^T$ as the first column and $[\hat{h}(0), 0, \ldots, 0]^T$ as the first row, namely

$$\mathbf{G} = \begin{bmatrix} \hat{h}(0) & & \\ \vdots & \ddots & \hat{h}(0) \\ \hat{h}(L-1) & & \vdots \\ & \ddots & \hat{h}(L-1) \end{bmatrix}. \tag{15}$$

Then the L source blocks can be recovered using the zero forcing (ZF) equalizer

$$\hat{\mathbf{S}} = (\mathbf{G}^H\mathbf{G})^{-1}\mathbf{G}^H\mathcal{Z} \tag{16}$$

or using the minimum mean squared error (MMSE) equalizer (provided that the noise variance σ_n^2 is known at the receiver)

$$\hat{\mathbf{S}} = \sigma_s^2\mathbf{G}^H(\sigma_s^2\mathbf{G}\mathbf{G}^H + \sigma_n^2\mathbf{I})^{-1}\mathcal{Z} \tag{17}$$

where σ_s^2 is the source symbol power and superscript H denotes Hermitian transpose. It is clear that as long as $\hat{\mathbf{h}} \neq \mathbf{0}$ the matrix $\hat{\mathbf{G}}$ is always full column rank. This guarantees the source symbols always be recovered.

3. SIMULATIONS AND COMPARISONS

In this section, our proposed channel identification and source recovery scheme is tested and compared with the case of transmitting training sequences and with the method in [8] which we denote by LM.

Rayleigh fading channels of length $L = 8$ were used. The transmitter breaks the sequence of QAM source symbols $\{\pm 1 \pm j\}$ into blocks of $p = 64$ symbols each and appends a guard sequence to each block according to the scheme described in Section 2.1 before transmitting them over the channel. The known symbol b in the guard sequences is $b = 1 + j$. The normalized least squared channel error (NLSCE), denoted as E_{ch}, is used as the figure of merit for channel identification and is defined as follows.

$$E_{ch} = \|\hat{\mathbf{h}} - \mathbf{h}\|^2/\|\mathbf{h}\|^2 \tag{18}$$

where $\hat{\mathbf{h}}$ and $\mathbf{h}$ are the estimated and the true channel vectors respectively. The estimated channel is used to recover the source symbols using the MMSE equalizer (17) follow by a symbol-by-symbol quantization scheme. Bit Error Rate (BER) is the figure of merit for source recovery.

3.1. Comparison with Training Sequence Case

We compare our scheme with the case of transmitting a training sequence for every L blocks described in Section 2.1. The same parameters $L = 8$, $p = 64$ and $b = 1 + j$ are used for both methods. The simulated NLSCE is shown in Figure 1 and the corresponding BER is presented in Figure 2. It can be observed that the performance of our scheme is as good as that of the training sequence case.

We now consider the case when the channel varies from block to block according to

$$\mathbf{h}_m = \alpha\mathbf{h}_{m-1} + (1-\alpha)\mathbf{w} \tag{19}$$

where α was chosen to be 0.98 and $\mathbf{w}$ is a Gaussian random vector with zero mean and unit variance. It can be seen from Figure 3 that our scheme outperforms the training sequence case.

Remark: Significantly better performance can be obtained if the receiver knows the model (19) and applies a Kalman filter. This is not considered here though.

3.2. Comparison with LM Method

Since the LM method can only estimate the channels after receiving as many as p blocks, both the our scheme and the LM scheme use $M = 64$ received blocks to estimate the channel. The same parameters $p = 64$ and $L = 8$ were used for both schemes. The guard sequence of length L in the LM scheme is $[0, \ldots, 0, b, 0, \ldots, 0]^T$ and $b = 1 + j$. Since in our scheme the channel estimate can be obtained for every $L = 8$ blocks, we average channel estimates by $\hat{\mathbf{h}} = \frac{1}{8}\sum_{i=1}^{8}\hat{\mathbf{h}}_i$. The simulated NLSCE and BER are presented in Figures 4 and 5 respectively. These results show that our method outperforms the LM method.

4. CONCLUSION

Guard intervals are inserted between blocks of symbols to prevent inter-block interference in a number of block transmission systems. This paper proposes a known symbol guard insertion scheme to help estimate the channel. The scheme has a very low computational complexity and simulation results show that the performance of our proposed method is as good as or better than a training sequence method, depending on whether or not the channel is constant or time-varying.

5. REFERENCES

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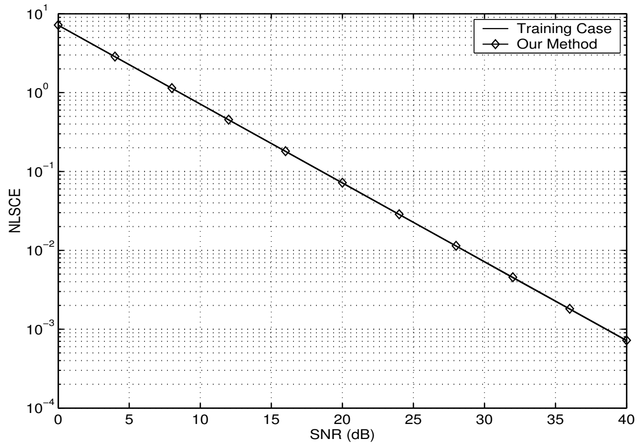

Fig. 1. NLSCE: our method vs. training case

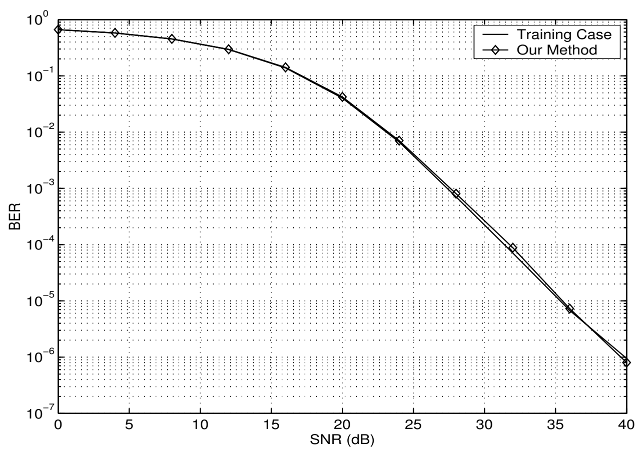

Fig. 2. BER: our method vs. training case

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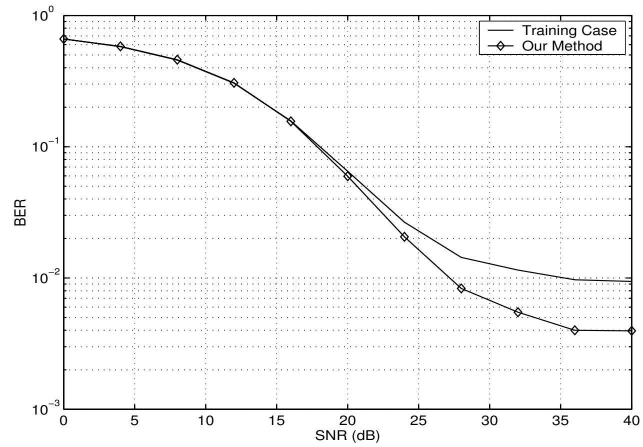

Fig. 3. BER: our method vs. training case when the channel is slowly varying

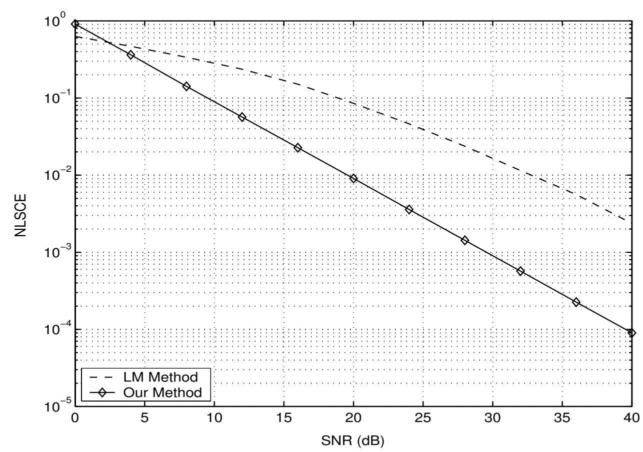

Fig. 4. NLSCE: our method vs. LM method

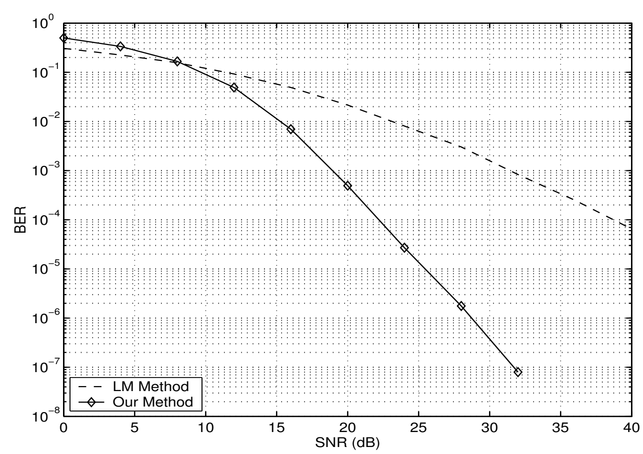

Fig. 5. BER: our method vs. LM method