Frame-Based Iterative Channel Estimation Using Data Symbols of Space-Time Block Codes

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Abstract

In this paper, a novel approach using frame-based iterative channel fading parameters estimation technique from the received data sequence exploiting orthogonal property of the space-time block (STB) code is proposed. For practical implementation of STB code, the receiver requires to estimate these parameters. Regarding this type of estimation, the inherent orthogonal nature of STB code can be exploited to simplify multiple-input-multiple-output (MIMO) channel estimation technique. While modified decision-directed iterative channel estimation updates estimated parameters throughout the frame, proposed frame-based iterative channel estimation technique updates estimated channel parameters once in each iteration after decoding the whole frame. This modification reduces the effect of incorrect detection significantly. Simulation results show about 1 dB gain of bit error rate over the state-of-the-art method. The proposed scheme uses few pilot symbols to provide near perfect lower-bound performance at the cost of increased receiver complexity.

1. Introduction

One of the widely applied approaches to reduce the detrimental effects of multi-path fading is antenna diversity. Due to the difficulty of efficiently using receive antenna diversity at the remote units, since they should remain relatively simple, inexpensive and small, receive diversity has been nearly exclusively used at the base station [2]. A new approach of transmit diversity, namely STB Code, has recently been proposed by S. M. Alamouti [1] and later analyzed in detail by V. Tarokh [9, 10] *et al.* This scheme can provide the best theoretical tradeoff between diversity gain, transmission rate, constellation size, signal space dimension and trellis complexity [10].

One of the advantages of Space-Time Code is that it can be used in concatenation with other channel codes. Two layer channel coding offers increased reliability of data transmission for very noisy channels. An example is Turbo code as outer code and STB code as inner code [2]. The decoding complexity of STB code for practical implementation is that it requires knowledge of the MIMO channel fading parameter at the receiver end. Performance degradation due to mismatch in the channel parameters has been addressed in standard literature [11]. It was shown in [3] that STB code is more sensitive to channel estimation error than straightforward two branch diversity scheme, because of its dependency on the removal of cross-terms in the decision rule. This dependency on the channel estimation error increases as the number of transmitter and receiver antennas increases to achieve same error performance [5].

Techniques to overcome performance degradation due to this type of channel estimation error are extensively being studied. The decision-directed channel tracking method has been proposed in [4, 7, 12]. An improved method of the channel tracking, called the modified decision-directed algorithm, has recently been proposed in [6]. In this paper, a frame-based iterative channel estimator is proposed that shows even better performance than the modified decision-directed approach.

The organization of this paper is as follows. The system model is described in Section 2. Section 3 contains mathematical explanation showing simplicity of MIMO channel fading parameter estimation algorithms using data symbols of STB codes, compared to the conventional orthogonal pilot sequence insertion (O-PSI) method proposed in [8]. Section 4 describes proposed iterative channel estimation algorithm. Section 5 focuses on the analytical reasoning for improved performance. Section 6 presents simulation results and the conclusion is given in Section 7.

2. System Model

A wireless communication system is considered with n transmitter antennas at the base station and one

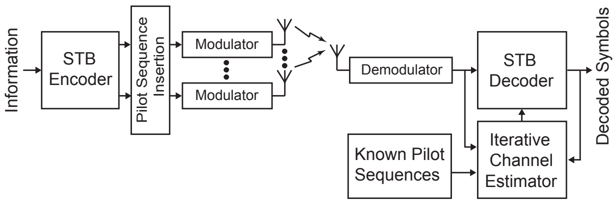

Figure 1. Block diagram for iterative channel estimation of STB coded system.

receiver antenna at the remote station. A simplified block diagram is given in Figure 1. Extension of formulations for m receiver antennas is straightforward. The STB encoder takes p symbols in one block of data from the information source and uses the generator matrix to produce q symbols for each transmitter antenna [1, 9]. Hence the generator matrix has dimension of $q \times n$. One frame of data symbols contains L blocks. If $p = q$, then the encoder is called full rate and if $p < q$, the encoder is partial rate. At each time slot t, one symbol $s_{i,t}$, $i = 1,2,\ldots,n$ is transmitted simultaneously from the n transmit antennas. The channel is assumed to be flat fading and quasi-static, i.e., the path gains are constant over a frame and vary from one frame to another. The path gain from the ith transmitter antenna to the receiver antenna is denoted by h_i. The Rayleigh fading channel is modelled as samples of independent complex Gaussian random variables with variance of 0.5 per real dimension.

A sample of the received signal at time t is the superposition of all signals sent from different transmitter antennas and is given by [9]

$$r_t = \sum_{i=1}^{n} h_i \cdot s_{i,t} + n_t \tag{1}$$

where n_t is a zero-mean complex Gaussian random variable with single-sided power spectral density N_0.

Assuming perfect channel state information (CSI) is available, the STB decoder computes the decision metric

$$\sum_{t=1}^{q} \left| r_t - \sum_{i=1}^{n} h_i \cdot s_{i,t} \right|^2 \tag{2}$$

over all possible combinations of transmitted symbol sequences ($s_i = [s_{i,1}\ s_{i,2}\ \ldots\ s_{i,q}]^T$), for $i = 1,\ldots,n$, and decides in favor of the symbol sequences that minimizes the sum. In practical cases, as the receiver does not have access to the actual channel fading parameter h_i, it tries to estimate the h_i's using a channel estimation technique. Let the estimated channel parameter be $\hat{h}_i$, which has a certain estimation error. Hence in (2), h_i is to be replaced by estimated channel parameter $\hat{h}_i$, which causes degradation of performance compared to perfect channel knowledge [10]. A better estimate of fading parameter improves performance but higher number of overhead symbols are required for this purpose. An efficient iterative channel estimator reduces the number of pilot symbols needed to achieve the same or even better performance.

3. Channel Estimation

Among different types of channel estimation techniques, O-PSI method and STB coded data based channel estimation are of interest.

3.1 O-PSI method

O-PSI is a simple but powerful technique for channel estimation. In this method, some pilot sequences are inserted at the beginning (or middle) of a data frame. The receiver has perfect knowledge of the positions and magnitudes of the pilot sequences. For multiple transmit antennas, the pilot sequence of any transmitter must be orthogonal to other pilot sequences from other transmitter antennas to simplify channel estimator structure. For a system with n transmit antennas, n different pilot sequences $P_1, P_2, ..., P_n$ with the same length are needed. Let k is the length of the pilot sequences, i.e., $P_i = [P_{i,1}\ P_{i,2}\ ...\ P_{i,k}]^T$ for the ith transmitter. To satisfy the orthogonality property, the pilot sequence of the ith transmitter has to satisfy the condition

$$P_i^T \cdot P_j^* = \begin{cases} 0 & \text{for } i \neq j \\ \|P_i\|^2 & \text{for } i = j \end{cases}$$

where j is any other transmitter antenna. Here $(\cdot)^T$ denotes transpose and $(\cdot)^*$ denotes complex conjugate.

The receiver isolates the received signals due to the pilot symbols and sends those to the channel estimator for initial estimation of channel before decoding of the received signals due to data symbols.

During the channel estimation, the received signal at the the receiver antenna and time t can be represented by

$$r_t = \sum_{i=1}^{n} h_i \cdot P_{i,t} + n_t. \tag{3}$$

The received signal and noise sequence at the antenna can be represented as

$$r_p = [r_1\ r_2\ ...\ r_k]^T, \tag{4}$$
$$n_p = [n_1\ n_2\ ...\ n_k]^T. \tag{5}$$

The receiver estimates the channel fading parameter h_i using the observed sequences r_p. Since the pilot sequences $P_1, ..., P_n$ are orthogonal, the minimum mean square error (MMSE) estimate of h_i is given by [10]

$$\hat{h}_i = r_p^T \cdot P_i^* / \|P_i\|^2$$

$$
\begin{aligned}
&= (h_i P_i + \sum_{j=1, j\neq i}^{n} h_j P_j + n_p)^T \cdot P_i^* / \|P_i\|^2 \\
&= [h_i (P_i^T \cdot P_i^*) + \sum_{j=1, j\neq i}^{n} h_j (P_j^T \cdot P_i^*) \\
&\qquad + (n_p^T \cdot P_i^*)] / \|P_i\|^2 \\
&= h_i + (n_p^T \cdot P_i^*) / \|P_i\|^2 \\
&= h_i + e_i
\end{aligned} \tag{6}
$$

where e_i is the estimation error due to noise, given by

$$
e_i = (n_p^T \cdot P_i^*) / \|P_i\|^2. \tag{7}
$$

Since n_p is a zero-mean complex Gaussian random variable with single-sided power spectral density N_0, the estimation error e_i has a zero mean and single-sided power spectral density N_0/k [10].

3.2 STB Coded data

The generator matrices of all STB codes (either full rate or partial rate) are formed so that, for a block, the data symbol sequence of any transmitter antenna is orthogonal to the sequences of other transmitter antennas [1, 9]. For example, with two transmitter antennas, the full rate generator matrix is

$$
G = \begin{bmatrix} x_1 & x_2 \\ -x_2^* & x_1^* \end{bmatrix} \tag{8}
$$

where each column, which represents the signals sent from an antenna, is orthogonal to other column. Here x denotes data symbols. The transmitted signal sequences, in this case, are $s_1 = [s_{1,1}\ s_{1,2}]^T = [x_1\ -x_2^*]^T$ and $s_2 = [s_{2,1}\ s_{2,2}]^T = [x_2\ x_1^*]^T$. In general, if s_i is the transmitted signal sequence of the ith transmitter for a block, then

$$
s_i^T \cdot s_j^* = \begin{cases} 0 & \text{for } i \neq j \\ \|s_i\|^2 & \text{for } i = j \end{cases}
$$

where s_j is the transmitted signal sequence from any other transmitter antenna for the same block. This orthogonality of the transmitted symbol sequences is guaranteed due to the inherent orthogonal property of the generator matrices.

The inherent orthogonal property of the generator matrix makes the channel estimator simpler using MMSE criterion. When a block of the transmitted symbol sequence of the ith transmitter antenna is multiplied with the corresponding received signal, fading parameter of other paths vanish. This property enables one to easily obtain the channel fading parameter of the corresponding transmission path. Let the received signal vector for a block be $r_s = [r_1\ r_2\ ...\ r_q]^T$. As transmitted symbol sequence is not known to the receiver, a previous estimate of the channel fading parameter has to be used to decode the received signal of the block. The detected symbol sequence of a transmitter antenna is then utilized to estimate corresponding channel fading parameter. As for quasi-static channel, the fading parameter of any block is the same during the whole frame, so this estimated fading parameter using data block can be used for the next iteration of the received signal of the same frame. Now, if the detected symbol sequence is correct, i. e. $\hat{s}_i = s_i$, then the estimate of desired channel parameter is the same as O-PSI method. The estimated channel fading parameter becomes

$$
\begin{aligned}
\hat{h}_i &= r_s^T \cdot \hat{s}_i^* / \|\hat{s}_i\|^2 \\
&= (h_i s_i + \sum_{j=1, j\neq i}^{n} h_j s_j + n_s)^T \cdot s_i^* / \|s_i\|^2 \ [\text{as } \hat{s}_i = s_i] \\
&= [h_i (s_i^T \cdot s_i^*) + \sum_{j=1, j\neq i}^{n} h_j (s_j^T \cdot s_i^*) \\
&\qquad + (n_s^T \cdot s_i^*)] / \|s_i\|^2 \\
&= h_i + (n_s^T \cdot s_i^*) / \|s_i\|^2 \\
&= h_i + e_i
\end{aligned} \tag{9}
$$

where $n_s = [n_1\ n_2\ ...\ n_q]^T$ and e_i is again the estimation error due to the AWGN noise.

On the other hand, if an incorrect detection of a block of data occurs, i. e. $\hat{s}_i \neq s_i$, then the estimated channel fading parameter using that block also becomes incorrect. Assuming that the channel fading parameter of wireless path from the ith transmitter antenna to the receiver antenna is to be found. Also assuming that due to incorrect detection, the detected block of data is the sequence sent from the kth transmitter antenna (i.e. $\hat{s}_i = s_k$). Then the obtained channel parameter becomes

$$
\begin{aligned}
\hat{h}_i &= r_s^T \cdot \hat{s}_i^* / \|\hat{s}_i\|^2 \\
&= (h_i s_i + h_k s_k + \sum_{j=1, j\neq i,k}^{n} h_j s_j + n_s)^T \cdot s_k^* / \|s_k\|^2 \\
&= [h_i (s_i^T \cdot s_k^*) + h_k (s_k^T \cdot s_k^*) \\
&\qquad + \sum_{j=1, j\neq i,k}^{n} h_j (s_j^T \cdot s_k^*) + (n_s^T \cdot s_k^*)] / \|s_k\|^2 \\
&= h_k + (n_s^T \cdot s_k^*) / \|s_k\|^2 \\
&= h_k + e_k
\end{aligned} \tag{10}
$$

where e_k is the corresponding estimation error due to the AWGN noise. If the kth sequence is not produced by any transmitter antenna, then the estimated channel parameter does not even exist.

4. Iterative Channel Estimation

For iterative channel estimation, an initial estimate of channel fading parameters is done using O-PSI pilot sequences, known data symbols or some other methods. The initial estimate is given to the detector for detecting the received signal. This initial estimate can be updated exploiting the orthogonal property of STB code using either the modified decision directed (tracking) mode or the frame-based approach proposed in this paper.

The need for pilot symbols can be reduced if some known data from the transmitter can produce the same effect of transmitting the pilot sequence. For example, if 2 bits of a transmitted data are known, it is equivalent to 2 pilot symbols inserted within the frame when modulated using BPSK modulation scheme. Considering space-time Turbo codes as a specific example, the Turbo code is concatenated with the space-time code for higher performance gain [2]. With the coding rate of 1/3, two data from the two recursive systematic convolution (RSC) encoders are sent with one bit of systematic data. As both encoders are initially at all zero state, the first outputs from two RSC encoders are always zero irrespective of data. If these two data are sent before the systematic bit in the frame, then 2 known bits per frame are found. This is an example of reducing the need of pilot symbols on an ad hoc basis.

Whatever method is used, the obtained initial estimate during the training process has certain estimation error due to noise in the receiver. The initial estimate of the channel fading parameter of the ith path can be expressed as

$$\hat{h}_i^0 = h_i + e_i^0 \tag{11}$$

where e_i^0 is the initial estimation error. Here the superscript indicates the index number of iterative estimation process.

4.1 Modified Decision-Directed Channel Estimation

In this method, the initial estimation of the channel fading parameter is changed after the detection of every block of data throughout the entire frame as decoding progresses [6]. The estimated channel parameter for block l with a received signal vector $r_s^l = [r_1^l \; r_2^l \; ... \; r_q^l]^T$ and a detected signal sequence $\hat{s}_i^l = [\hat{s}_{i,1}^l \; \hat{s}_{i,2}^l \; \ldots \; \hat{s}_{i,q}^l]^T$ is

$$\hat{h}_i^l = \frac{(r_s^l)^T \cdot (\hat{s}_i^l)^*}{\left\|\hat{s}_i^l\right\|^2} = h_i + \frac{(n_s^l)^T \cdot (s_i^l)^*}{\left\|s_i^l\right\|^2} = h_i + e_i^l \tag{12}$$

where n_s^l is AWGN noise and e_i^l is the corresponding estimation error. Note that (12) holds only when the detected signal sequence is correct ($\hat{s}_i^l = s_i^l$). This estimated fading parameter $\hat{h}_i$ is then time averaged over previous estimations to get the averaged estimate for the next iteration. Thus the averaged parameter for iteration $m = 1, 2, ..., M-1$ is

$$\begin{aligned}
\hat{h}_i^1 &= (\hat{h}_i^0 + h_i + e_i^1)/2 = h_i + \frac{1}{2}(e_i^0 + e_i^1) \\
\hat{h}_i^2 &= (\hat{h}_i^1 + h_i + e_i^2)/3 = h_i + \frac{1}{3}(e_i^0 + e_i^1 + e_i^2) \\
&\quad ... \qquad ... \qquad ... \\
\hat{h}_i^{M-1} &= h_i + \frac{1}{M}\sum_{m=0}^{M-1} e_i^m.
\end{aligned} \tag{13}$$

Now, let the first incorrect detection of block ($\hat{s}_i^l = s_k^l$) occurs at the Mth iteration. Using (10) in (13), the averaged estimated channel fading parameter becomes

$$\hat{h}_i^M \approx \frac{M}{M+1}h_i + \frac{1}{M+1}h_j + \frac{1}{M+1}\sum_{m=0}^{M} e_i^m. \tag{14}$$

The approximation is used to simplify the estimation error term. Iteration continues until the end of the frame. The algorithm can be summarized as follows:

Find the initial estimate
For data block 1 to L
  Detect data block using present estimate
  Use detected data block to find new estimate
  Time average new estimate to get present estimate
End

4.2 Proposed Frame-Based Iterative Channel Estimation

The proposed method is a simple extension of the state-of-the-art method, but the performance gain is substantial. The analytical reasoning is given in the next section. Here the mathematical modelling of the proposed scheme is described. The proposed scheme uses the property that, if a transmitted symbol sequence of a particular antenna is orthogonal to other transmitted symbol sequences for several blocks of data, then the combined transmitted symbol sequence for multiple blocks of data of that antenna will still be orthogonal to the combined transmitted symbol sequences of the other antennas. Let the transmitted signal sequence for a frame from the ith transmitter antenna be $S_i^T = [(s_i^1)^T \; (s_i^2)^T \; ... \; (s_i^L)^T]$, where one data frame contains L blocks of data. According to this orthogonality property

$$S_i^T \cdot S_j^* = \begin{cases} 0 & for\ i \neq j \\ \|S_i\|^2 & for\ i = j \end{cases}$$

where S_j is the transmitted symbol sequence from any other transmitter antenna for that frame.

In the frame-based iterative method, the initially estimated channel fading parameter is used to decode the whole frame similar to non-iterative methods. Then the whole decoded frame of data is used to find a new channel estimation parameter. For example, an estimate of h_i using the received signal vector of the frame ($R_s^T = [(r_s^1)^T \ (r_s^2)^T \ ... \ (r_s^L)^T]$) and the detected data frame ($\hat{S}_i^T = [(\hat{s}_i^1)^T \ (\hat{s}_i^2)^T \ ... \ (\hat{s}_i^L)^T]$) can be obtained as follows:

$$\hat{h}_i^z = R_s^T \cdot (\hat{S}_i^{z-1})*/\left\|\hat{S}_i^{z-1}\right\|^2 \qquad (15)$$

where z denotes number of iteration. Noting that $\left\|s_i^1\right\|^2 = \left\|s_i^2\right\|^2 = ... = \left\|s_i^L\right\|^2$ and assuming a blocks are correctly detected and other $L-a$ blocks produce symbol sequences of the kth transmitter antenna in one frame of data during detection process of the last iteration, (15) can be rewritten as follows:

$$\begin{aligned}\hat{h}_i^z &= [a \cdot h_i(s_i^T \cdot s_i^*) + (L-a)h_k(s_k^T \cdot s_k^*) \\ &\qquad + N^T \cdot (\hat{S}_i^{z-1})^*]/[L \left\|(\hat{s}_i)^{z-1}\right\|^2] \\ &= \frac{a}{L}h_i + \frac{L-a}{L}h_k + \frac{1}{L}N^T \cdot (\hat{S}_i^{z-1})^*/\left\|\hat{s}_i^{z-1}\right\|^2 .\end{aligned} \qquad (16)$$

This new estimated channel fading parameter is used for the next iteration, and the process is repeated for a desired number of iterations. The proposed algorithm can be summarized as follows:

```
Find the initial estimate
For number of iterations 1 to Z
        Detect whole frame of data using present estimate
        Use all data in the frame to find new estimate
        Set new estimate to present estimate, discard previous
End
```

5. Analysis of Performance

The difference of performance observed between the modified decision-directed estimation and the proposed frame-based iterative estimation is mainly based on the effect of incorrect detection within the frame. In the modified decision-directed estimation, one incorrect detection of a data block changes the channel estimation substantially, leading to a higher probability of incorrect detection of subsequent data blocks. However, in the frame-based estimation method, the effect of incorrect detection of a particular block is less. Because the effect of the incorrect fading parameter due to incorrect detection of a data block blends with other correct fading parameters of the same frame. From (16), as the value of a reduces in each iteration, so $a \approx L$ and $L - a \approx 0$, leading to $\hat{h}_i^z \approx h_i$. This ensures better estimation of channel fading parameter in each iteration of the frame under consideration.

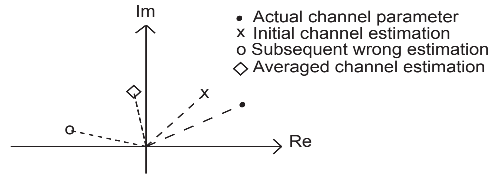

Figure 2. Effect of drastic channel estimation error if error occurs in the first block of data detection using modified decision directed method.

To have a better understanding of the difference in performance, let us study a particular case. With average bit error rate (BER) of $7.7{\times}10^{-3}$, one block of data might be incorrect among 65 blocks of data. For the frame-based iterative method, from (16) with $a = 64$ and $L = 65$, the effect of the incorrect channel fading parameter is 1/64 compared to the correct parameter. But for the modified decision-directed method, the effect depends on the number of blocks correctly detected before that error actually occurred. Suppose if the incorrect block happens before detecting half of the frame, from (14) with $M = L/2$, the effect of incorrect channel fading parameter is 2/65 compared to the correct parameter. If an incorrect block is encountered within the first quarter of the frame ($M = L/4$), the effect is 4/65 . The worst case is when an incorrect detection occurs just after the initial estimation ($M = L/65$) and the effect is equal to the correct parameter. This case is shown in Figure 2, where the initial estimate of the channel fading parameter is close to the actual parameter, but the detection of the first data block is incorrect. Subsequently the channel parameter estimated using this data block might be away from the actual fading parameter of that channel, be-

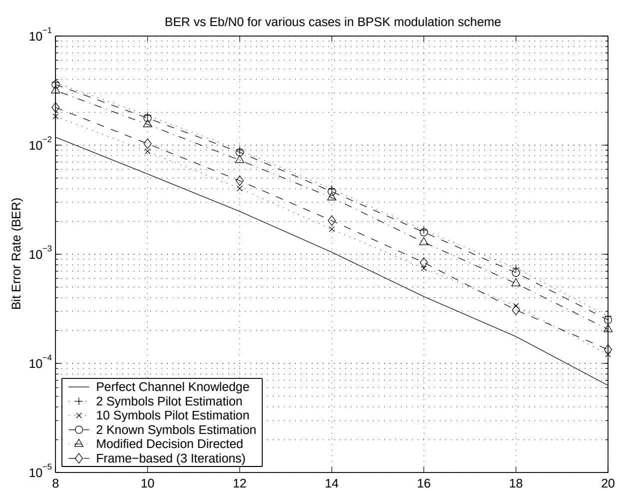

Figure 3. BER vs Eb/N0 (BPSK modulation).

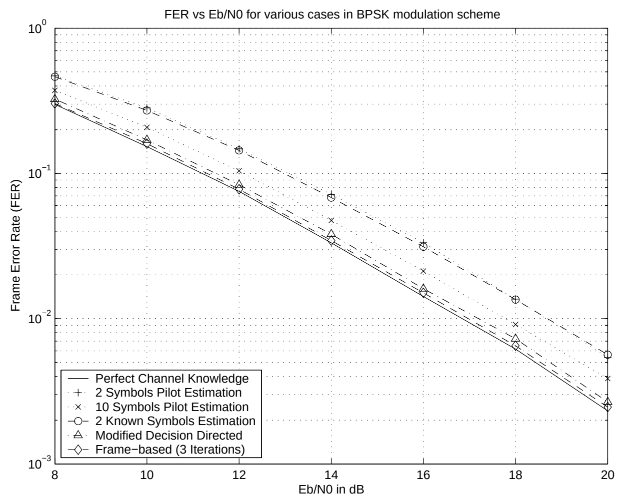

Figure 4. FER vs Eb/N0 (BPSK modulation).

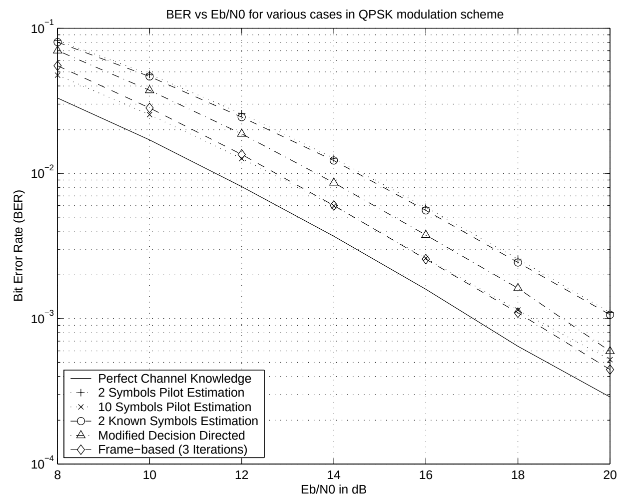

Figure 5. BER vs Eb/N0 (QPSK modulation).

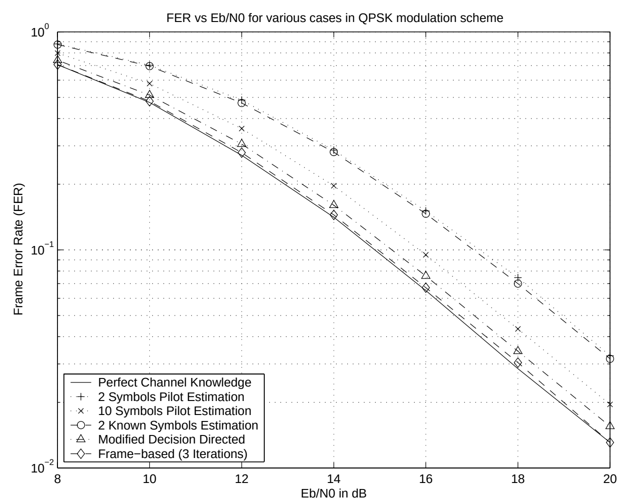

Figure 6. FER vs Eb/N0 (QPSK modulation).

cause this is a channel parameter of some other path as indicated in (10). As a result, the time averaged channel parameter diverts greatly from the actual channel parameter, increasing the probability of incorrect detection for subsequent data blocks. Further incorrect detection of data blocks will make the estimated channel parameter divert further away from the actual channel parameter.

From the analysis of performance for the case of incorrect detection of data block, it is clear that the proposed frame-based iterative algorithm is robust against this type of error compared to the modified decision-directed algorithm. The simulation results are also in agreement with this analysis.

6. Simulation Results

The simulations have been done for Alamouti's STB codes having 1 receiver and 2 transmitter antennas with generator matrix given by (8) over the BPSK and QPSK modulation schemes. The initial estimation is done assuming only 2 known symbols per frame.

Figure 3 shows the bit error rate (BER) for the modified decision-directed and frame-based iteration methods for BPSK modulation scheme with the frame length of 130 bits. The performance of the conventional pilot signal estimation (using 2 and 10 symbols) and also the performance of the system with perfect channel knowledge (as a lower bound) are given for comparison purposes. It is seen that a substantial gain is achieved using the proposed algorithm, which almost supersedes performance achieved even by 10 pilot symbols. For instance, to achieve the error rate of 3×10^{-4}, the gain is 1.2 dB with 3 iterations using the frame-based channel estimation method over the modified decision-directed method.

In Figure 4, the frame error rate (FER) of the corresponding cases are given. Both the modified decision-directed and frame-based iterative channel estimation methods outperform the conventional method using 10 pilots. The performance of the frame-based channel estimation (with 3 iterations) is near to the lower bound. For example, to achieve the frame error rate of 10^{-2}, compared to the case with perfect channel knowledge, the proposed method requires 0.04 dB additional signal power, whereas the modified decision-directed method requires 0.17 dB. Further iterations of the frame-based iterative approach have marginal additional gain in terms of BER or FER.

In Figure 5 and 6, BER and FER for various cases are given using QPSK modulation and with the same frame length. BER of the proposed method is found

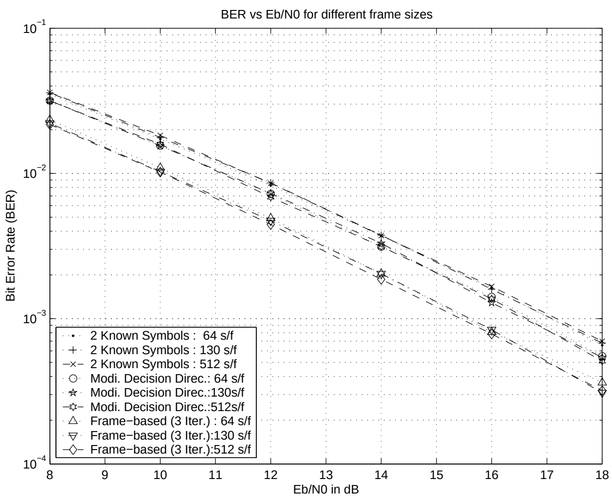

Figure 7. BER vs Eb/N0 for different frame sizes for the considered cases (BPSK modulation).

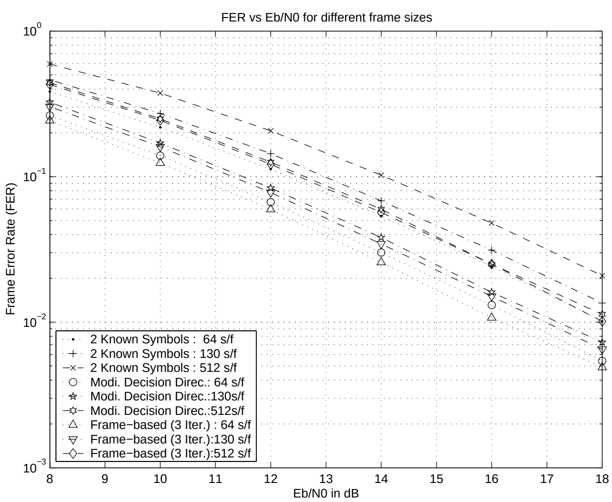

Figure 8. FER vs Eb/N0 for different frame sizes for the considered cases (BPSK modulation).

to reach 10 symbols pilot estimation for high SNR, and even better in the case of FER performance. Substantial improvement of error rate is observed over the modified decision-directed method.

Finally, in Figure 7 and 8, a comparison is made for different frame lengths. It is seen that, BER is independent of the frame length in all the case. For FER, better performance is found with a shorter frame length. One interesting point to notice is that, to achieve the same FER using the proposed scheme compared to the modified decision-directed scheme, shorter frame length provides higher performance gain over longer frame length.

7. Conclusion

The frame-based iterative algorithm for channel fading parameter estimation of STB coded system, proposed in this paper, is found to outperform state-of-the-art modified decision directed scheme. The BER and FER of the proposed scheme with 2 pilot symbol supersedes the performance of the conventional pilot signal estimation even with 10 pilot symbols in high SNR. The algorithm is applicable in space-time Turbo coded systems with very little modification. The improved CSI can be utilized in decoding of a Turbo decoder for even better performance gain. The simulations show that high performance gain can be achieved with fewer iterations. The proposed method significantly reduces the number of pilot symbols needed to achieve the same or even better performance, but requires higher processing complexity.

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