Improved Iterative EM Receiver for Space Time Coded Systems in Frequency Selective Fading Channel with Channel Gain and Order Estimation†

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Abstract - Recently, research on space-time trellis coded system in frequency selective fading channels have received increased attention because of its achievable capacity and diversity. It has been shown that the maximum likelihood (ML) detector can achieve spatial, temporal and frequency diversity in such channels. However, it assumes the channel parameters are known perfectly at the receiver. Moreover, as the ML detector complexity grows exponentially with the number of channel taps (channel order), estimation of the channel order must be performed to reduce unnecessary computations. In [1], we proposed an iterative receiver derived from the Expectation-Maximization (EM) algorithm, which performs channel order, channel gain and sequence estimation. The conditional model order estimator is employed for channel order estimation and is shown to have good performance. In this paper, we have 3 major contributions in improving the performance of this receiver: 1) a generalized CME criterion for MIMO systems, 2) a modified CME criterion for MMSE based EM receiver, and 3) an order estimate adjustment scheme to avoid overestimation. Simulation results show that the new modifications improve the order estimate significantly; hence reducing unnecessary computation due to overestimation.

I. INTRODUCTION

Space-time trellis code [2] attempts to achieve the capacity of a multiple transmit and receive antenna system. It provides good performance in frequency flat fading channels by capitalizing both spatial and temporal diversity. Numerous research works have been focused on enhancing its performance and practical usage. As the data rate increases, broadband wireless channels exhibit frequency selective fading. Recently, various works on transmission of space-time code in those channels had emerged, and we showed in [3] that it can achieve frequency diversity in addition to spatial and temporal diversity. However, it assumes that the receiver knows the channel parameters perfectly, and thus a channel estimator must be used in practise.

In single-input single-output (SISO) ML equalization, the estimation of channel order is mostly ignored because in traditional communication systems, long tap length receivers are used instead. Those receivers have more than enough taps to model a realistic channel such that the redundant taps will be close to zero after adaptation. However, for multiple transmit antenna systems, the receiver complexity grows exponentially with the number of channel taps and transmit antennas. Thus it is highly inefficient (or even impractical) to use long tap length receivers. Hence, a reliable channel order estimator must be used to avoid unnecessarily large amount of computation.

In [1], we have proposed an iterative receiver for channel gain and order estimation, with sequence detection in quasi-static frequency selective fading channels. The receiver is EM [4] based where it jointly performs channel gain estimation and sequence detection. For channel order estimation, the conditional model order estimator (CME) [5] is generalized for multiple-input single-output (MISO) system and used.

In this paper, we aim to improve the order estimation accuracy and robustness of the previously proposed receiver. First, the MISO CME criterion proposed in [1] is generalized for MIMO systems. Secondly, as the original CME criterion uses least-square estimates, a new MMSE based CME criterion is proposed for the MMSE based receiver. Thirdly, although the CME criterion provides highly accurate estimates, we observed that it is vulnerable in overestimating the channel order. Moreover in practical channels, where the channel gains at long delay tap will not be zero, the CME will provide an estimate including those residue taps. This is highly undesirable as those residual taps will have negligible performance improvement, but increased the complexity exponentially. To make the CME more robust, we proposed an order estimate adjustment scheme to avoid such overestimation, and hence reducing unnecessary computations.

This paper is organised as follows. In Section II, the signal model and space-time trellis code is described. Section III briefly revisits the proposed the EM based iterative receiver in [1], and Section IV presents the proposed improvement schemes. Simulation results are presented in Section V and Section VI concludes this paper.

II. SIGNAL MODEL

Consider a (N, M) space-time coded system with N transmit and M receive antennas transmitted over a quasi-static frequency selective fading channel. The data are encoded and mapped by the space-time encoder to N streams of symbols, which are then transmitted simultaneously at

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different transmit antennas. All $N\times M$ wireless channels are independent and possess frequency selective fading. With proper pulse shaping and matched filtering, these channels can be modelled as a symbol-spaced tap delay line. The tap lengths for all $N\times M$ channels are assumed to be the same and denoted as L. This assumption is made because in wave propagation, the delay profiles of wireless channels are mainly due to reflection off large objects. Hence, as the antennas are not separated very far apart (adequate for independent fading), these channels should have similar delay spread.

Let $c_i(t)$ be the coded symbol transmitted in transmit antenna i at time t (with a frame length of K) and $\mathbf{c}_i = [c_i(1), c_i(2), \ldots, c_i(K+L-1)]$ be its coded symbol vector. Also, let $h_{i,j}(l)$ be the l-th channel tap gain from transmit antenna i to receive antenna j, and $\mathbf{h}_{i,j} = [h_{i,j}(0), h_{i,j}(1), \ldots, h_{i,j}(L-1)]$ be the channel vector from transmit antenna i to receive antenna j. The additive white Gaussian noise at the receive antenna j in time t is denoted as $n_j(t)$ with variance σ_n^2, and let $\mathbf{N}_j = [n_j(1), n_j(2), \ldots, n_j(K+L-1)]$ be the noise vector. Thus the received signal at antenna j is

$$\mathbf{R}_j = \mathbf{C}\mathbf{H}_j + \mathbf{N}_j \tag{1}$$

where
$$\mathbf{H}_j = [\mathbf{h}_{1,j}, \mathbf{h}_{2,j}, \ldots, \mathbf{h}_{N,j}]^T$$
$$\mathbf{C} = \left[\tilde{\mathbf{c}}_1^{(0)}, \tilde{\mathbf{c}}_1^{(1)}, \ldots, \tilde{\mathbf{c}}_1^{(L)}, \tilde{\mathbf{c}}_2^{(0)}, \ldots, \tilde{\mathbf{c}}_N^{(L)}\right]$$
$$\tilde{\mathbf{c}}_i^{(l)} = \left[\mathbf{0}_{\langle l\rangle}, \mathbf{c}_i, \mathbf{0}_{\langle L-l-1\rangle}\right]^T .$$

The entire transmitted symbol matrix is denoted as $\mathbf{C}$ with $\tilde{\mathbf{c}}_i^{(l)}$ being the symbols transmitted by the i-th antenna at the l-th tap, and $\mathbf{0}_{<k>}$ is the all zero row vector with length k. The superscript T denotes matrix transposition. The tap gains $h_{i,j}(l)$ are modelled as independent and identically distributed complex Gaussian random variables, with zero mean and total variance for each channel normalized to one. That is, $\sum_{l=0}^{L} Var(h_{i,j}(l)) = 1$, for all i, j where $Var(.)$ is the variance operator. The symbol energy is normalised to one.

III. Iterative Receiver

It is known that the ML solution is optimal but with enormous complexity, especially for the current problem. EM algorithm [4] is remarkable in producing the ML estimates of the parameters through iterative computation with lesser complexity than direct ML estimation. In this section, we briefly revisit our proposed EM-based iterative receiver in [1]. Interested readers are referred to that publication for detailed derivations.

The expectation step of the EM algorithm provides the MMSE conditional mean and second moment estimates at k-th iteration as

$$\hat{\mathbf{H}}_j^{(k)} = \left(\mathbf{C}^{*(k)}\mathbf{C}^{(k)} + \sigma_n^2\mathbf{I}\right)^{-1}\mathbf{C}^{*(k)}\mathbf{R}_j \tag{2}$$

$$\hat{\xi}_j^{(k)} = \mathbf{I} - \left(\mathbf{C}^{*(k)}\mathbf{C}^{(k)} + \sigma_n^2\mathbf{I}\right)^{-1}\mathbf{C}^{*(k)}\mathbf{C}^{(k)} + \hat{\mathbf{H}}_j^{(k)}\hat{\mathbf{H}}_j^{*(k)} \cong \hat{\mathbf{H}}_j^{(k)}\hat{\mathbf{H}}_j^{*(k)} \tag{3}$$

where $\mathbf{I}$ is the identity matrix and the superscript * denotes the matrix complex conjugate transposition. The maximization step is given by

$$\mathbf{C}^{(k+1)} = \arg\max_{\mathbf{C}} \sum_{t=1}^{K+L-1}\sum_{j=1}^{M} \left(\mathbf{R}_j^*\right)_t (\mathbf{C})_t \hat{\mathbf{H}}^{(k)} - \frac{1}{2}(\mathbf{C})_t \hat{\xi}^{(k)} \left(\mathbf{C}^*\right)_t \tag{4}$$

which can be implemented using the combined trellis ML detector [6] through the Viterbi algorithm for non-interleaved systems, or the iterative MAP equalizer and decoder [7] for interleaved systems.

For channel order estimation in reducing unnecessary computations, we proposed the use of the conditional model order estimator (CME) [5] in the EM receiver. It has better performance than the well-known minimum description length (MDL) approach [8]. Moreover, the derivation of the CME is based on ML rule and aims at minimizing the probability of error, while the MDL criterion is derived based on asymptotic arguments. Hence, the CME shares the same principle with the EM algorithm and incorporating it into the EM receiver is more reasonable.

The CME rule chooses the hypothesis H_i that maximizes

$$L_{Y|T_i}(\mathbf{y}) = \frac{p_Y(\mathbf{y};\boldsymbol{\theta}_i \mid H_i)}{p_{T_i}(\mathbf{T}_i(\mathbf{y});\boldsymbol{\theta}_i \mid H_i)} \tag{5}$$

where $\mathbf{y}$ is the observed vector, $\mathbf{T}_i(\mathbf{y})$ is the sufficient statistic of $\mathbf{y}$, and θ_i is the parameter vector. In MISO case, we derived the CME criterion at iteration k to find the order $l \in \{1, \ldots, L_{max}\}$ that minimizes

$$CME_j^{(k)}(l) = \frac{\mathbf{R}_j^*\left(I - \mathbf{C}_l^{(k)}\left(\mathbf{C}_l^{*(k)}\mathbf{C}_l^{(k)}\right)^{-1}\mathbf{C}_l^{*(k)}\right)\mathbf{R}_j}{2\sigma^2} + \frac{1}{2}\ln\left|\mathbf{C}_l^{*(k)}\mathbf{C}_l^{(k)}\right| \tag{6}$$

where l denotes the number of taps for the transmitted code matrix $\mathbf{C}$ such that it contains l delayed versions of the transmitted code vectors and |.| represents the matrix determinant.

IV. Proposed Modifications

In this section, we present our three new modification schemes to our proposed receiver [1]. For ease of presentation, the iteration number is omitted in the following equations, and the codeword matrix $\mathbf{C}$ is obtained from the detector output in the previous iteration.

A. Generalized CME Criterion for MIMO System

The proposed CME criterion in (6) is for MISO systems. Our first proposed modification scheme is to generalize it to MIMO systems.

Using the symbols defined in Section II, the numerator of (5) can be written for the MIMO case as

$$p(\mathbf{R};\mathbf{H}) = \left(2\pi\sigma^2\right)^{-K/2} \exp\sum_{j=1}^{M}\left[-\frac{1}{2\sigma^2}\left(\mathbf{R}_j - \mathbf{C}\mathbf{H}_j\right)^*\left(\mathbf{R}_j - \mathbf{C}\mathbf{H}_j\right)\right]$$
$$= \left(2\pi\sigma^2\right)^{-K/2} \exp\sum_{j=1}^{M}\left[-\frac{1}{2\sigma^2}\left(\mathbf{R}_j - \mathbf{C}\hat{\mathbf{H}}_j\right)^*\left(\mathbf{R}_j - \mathbf{C}\hat{\mathbf{H}}_j\right)\right]$$
$$\exp\sum_{j=1}^{M}\left[-\frac{1}{2\sigma^2}\left(\hat{\mathbf{H}}_j - \mathbf{H}_j\right)^*\left(\mathbf{C}^*\mathbf{C}\right)\left(\hat{\mathbf{H}}_j - \mathbf{H}_j\right)\right]. \quad (7)$$

From [5] the sufficient statistics is $\mathbf{T}(\mathbf{r}) = \hat{\mathbf{H}}$, which is complex Gaussian with distribution $N\left(\mathbf{H}, \sigma^2\left(\mathbf{C}^*\mathbf{C}\right)^{-1}\right)$. Hence its joint probability density function is given by

$$p(\mathbf{T}(\mathbf{r});\mathbf{H}) = \frac{\exp\sum_{j=1}^{M}\left[-\frac{1}{2\sigma^2}\left(\hat{\mathbf{H}}_j - \mathbf{H}_j\right)^*\left(\mathbf{C}^*\mathbf{C}\right)\left(\hat{\mathbf{H}}_j - \mathbf{H}_j\right)\right]}{\left(2\pi\sigma^2\left|\left(\mathbf{C}^*\mathbf{C}\right)^{-1}\right|\right)^{M/2}}.$$

Then the CME criterion is to minimize

$$CME(l) = \sum_{j=1}^{M}\frac{1}{2\sigma^2}\left(\mathbf{R}_j - \mathbf{C}_l\hat{\mathbf{H}}_{j,l}\right)^*\left(\mathbf{R}_j - \mathbf{C}_l\hat{\mathbf{H}}_{j,l}\right) + \frac{M}{2}\ln\left|\mathbf{C}_l^*\mathbf{C}_l\right|. \quad (8)$$

Thus, the MIMO CME criterion chooses the tap length l that minimizes (8), and uses that as the channel length for all $N\times M$ channels.

B. CME Criterion for EM Receiver

The original CME criterion and the proposed MISO one are derived based on Least Square estimation of the channel gains. However for the derived EM receiver, the channel gain estimation is MMSE based. Hence, to incorporate the channel order estimator into the EM receiver, the CME criterion should be modified for the MMSE estimate. Moreover with MMSE estimation, the order estimates should be more accurate.

Using the MMSE approach, the sufficient statistics is distributed as $N\left(\mathbf{H}, \sigma^2\left(\mathbf{C}^*\mathbf{C} + \sigma^2\mathbf{I}\right)^{-1}\right)$, with probability density function

$$p(\mathbf{T}(\mathbf{r});\mathbf{H}) = \frac{\exp\sum_{j=1}^{M}\left[-\frac{1}{2\sigma^2}\left(\hat{\mathbf{H}}_j - \mathbf{H}_j\right)^*\left(\mathbf{C}^*\mathbf{C} + \sigma^2\mathbf{I}\right)\left(\hat{\mathbf{H}}_j - \mathbf{H}_j\right)\right]}{\left(2\pi\sigma^2\left|\left(\mathbf{C}^*\mathbf{C} + \sigma^2\mathbf{I}\right)^{-1}\right|\right)^{M/2}}. \quad (9)$$

The new CME criterion is obtained by dividing (7) by (9). As SNR increases, $\mathbf{C}^*\mathbf{C} + \sigma^2\mathbf{I}$ inside the exponential function of (9) can be approximated as $\mathbf{C}^*\mathbf{C}$. Moreover, as the MMSE estimator has small estimation error, the elements of $\hat{\mathbf{H}}_j - \mathbf{H}_j$ are very close to zero. Hence approximating $\mathbf{C}^*\mathbf{C} + \sigma^2\mathbf{I} = \mathbf{C}^*\mathbf{C}$ will have negligible performance degradation in the order estimation. Therefore, the CME criterion can be simplified as to minimize

$$CME(l) = \sum_{j=1}^{M}\frac{1}{2\sigma^2}\left(\mathbf{R}_j - \mathbf{C}_l\hat{\mathbf{H}}_{j,l}\right)^*\left(\mathbf{R}_j - \mathbf{C}_l\hat{\mathbf{H}}_{j,l}\right) + \frac{M}{2}\ln\left|\mathbf{C}_l^*\mathbf{C}_l + \sigma^2\mathbf{I}\right| \quad (10)$$

where $\hat{\mathbf{H}}_{j,l}$ is given by the MMSE estimate in (2) with a channel tap length l.

C. Order Estimate Adjustment Scheme

It is noticed from simulation that the CME tends to overestimate the channel order. We observed in (10) that when l is less than the original tap length, the first term will have a large value, prohibiting underestimation. When l is larger than the original tap length, the second term increases, which tries to prevent overestimation. However, as the increase by the second term is small, the CME criterion is more vulnerable to overestimation. This will lead to unnecessary extra computations that grow exponentially. Moreover, in practical channel environment where the residue taps are not exactly zero, i.e., $h_{i,j}(l) \neq 0, \forall l > L$, the highly accurate CME will provide an estimate that includes these taps in high SNR environment. It has been tested that with SNR at 40dB, the CME will even include the taps with strength 50dB lower than the strongest power tap. This is highly unfavourable in practise, and hence an order estimate adjustment scheme is required to avoid overestimation.

Our idea is to compute a threshold such that discarding a tap will not cause any detection error. In other words, this tap gain has a very small value such that it is redundant to the detection process, and thus should be discarded to avoid unnecessary computation. Since trellis detection is used in the receiver, we consider the path metric in computing the threshold. When a tap is discarded, the path metric will be different to the original non-discarded one. If this difference of path metric is larger than the path metric caused by one symbol error (assuming noiseless environment), a detection error will occur. Hence to avoid incorrectly discarding a significant tap, the threshold must be set to be the minimum path metric caused by one symbol error in the trellis. A tap will only be discarded if the maximum path metric induced by it is less than the threshold.

To compute the threshold, the path metric caused by one symbol error in space-time trellis code is given by

$$PM_1(\mathbf{C})=\sum_{t=t_e}^{t_e+v}\sum_{j=1}^{M}\left|\sum_{i=1}^{N}\sum_{l=0}^{L-1}\hat{h}_{i,j}(l)\big(c(t-l)-e(t-l)\big)\right|^2 \qquad (11)$$

where t_e is the first symbol error instance, v is the code constraint length, and $e(t)$ is the error symbol. Considering the 4-states QPSK delay diversity code (DD), its minimum path metric is less than many other codes, and hence can be used to compute this minimum threshold. From the structure of delay diversity code with symbol energies normalized to one, the minimum path metric caused by one symbol error is

$$\min_{DD}(PM_1)=2\sum_{j=1}^{M}\sum_{i=1}^{N}\sum_{l=0}^{L-1}\left|\hat{h}_{i,j}(l)\right|^2 .$$

On the other hand, the path metric caused by discarding a tap is given by

$$PM_2(\mathbf{C})=\sum_{t=1}^{K}\sum_{j=1}^{M}\left|\sum_{i=1}^{N}\sum_{l=\hat{L}-2}^{\hat{L}-1}\hat{h}_{i,j}(l)c(t-l)\right|^2=\sum_{t=1}^{K}\sum_{j=1}^{M}\left|\hat{\mathbf{H}}'_j\mathbf{C}(t)\right|^2$$

where $\hat{L}$ is the estimated tap length by CME, and $\hat{\mathbf{H}}'_j$ is the estimated channel vector at receive antenna j from $\hat{L}-1$ to $\hat{L}$ tap. By Cauchy-Schwartz inequality $|v_1\cdot v_2|\le\|v_1\|\|v_2\|$, the path metric can be upper bounded by

$$PM_2(\mathbf{C})<\sum_{t=1}^{K}\sum_{j=1}^{M}\left|\hat{\mathbf{H}}_j\right|^2\left|\mathbf{C}(t)\right|^2<NK\sum_{j=1}^{M}\sum_{i=1}^{N}\sum_{l=\hat{L}-2}^{\hat{L}-1}\left|\hat{h}_{i,j}(l)\right|^2 . \qquad (12)$$

The adjustment scheme is to discard the last tap only if $PM_2<PM_1$. This scheme is applied until the criterion is not satisfied, thus avoiding overestimation by more than 1 tap.

V. Simulation Results

The performance of the proposed EM-based receiver is evaluated for 4-state space-time trellis coded system with QPSK transmission under various environments. The code is full rank and it generates coded symbols using

$$\left(x_1^k,x_2^k\right)=b_{k-1}(0,2)+a_{k-1}(1,1)+b_k(2,0)+a_k(1,2)$$

where b_k, a_k are the binary inputs at time k and x_i^k is the code symbols transmitted by antenna i at time k. The channel is quasi-static and frequency selective, where each tap is independently Rayleigh faded. All channel tap gains have equal variance per dimension. Each frame consists of 128 simultaneous transmissions of data and three iterations are performed upon reception of a frame. The channel order is unknown to the receiver and the maximum possible tap length L_{max} is set to 4.

The first set of simulation is performed for a 2-transmit and 1-receive antenna (2,1) system using the proposed EM receiver. The channel is 2 tap and the tap gains have average equal energy (i.e., [0.5, 0.5]). Figure 1 plots the frame error rate of the EM receiver with the modified CME estimator and order adjustment scheme (EM CME OAS) at different iterations. For comparison, the performance of the EM receiver with original CME at third iteration (EM O-CME #3) and the long tap EM receiver that uses a fixed 4 taps equalizer (EM LT #3) are also plotted. The performance of combined trellis ML detector with known channel gain and order (CT-MLD) using the same code is also shown for reference. The number of training symbols used for initial estimation is eight, which is determined by simulation.

It can be seen that the modified EM receiver with OAS at third iteration has negligible performance degradation comparing to the original proposed EM receiver. Moreover, it has only slight degradation when compared to the known channel CT-MLD. It is important to note that the EM receiver with CME performs better than the conventional long tap EM receiver. This is because the long tap receiver always increases the mean squared error, and hence degrades the performance. Thus channel order estimation not only reduces complexity but also improves the performance.

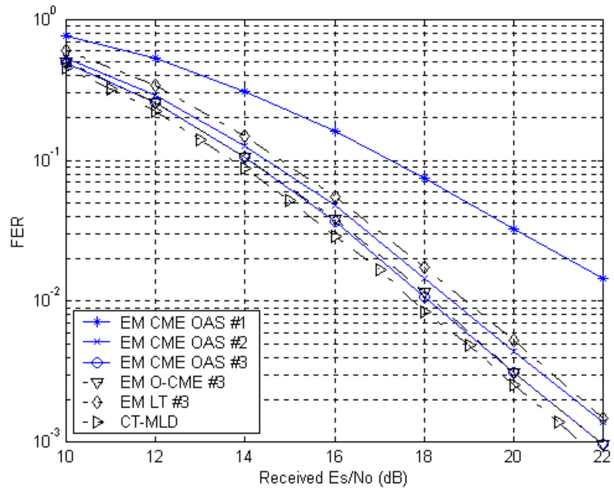

Figure 1: Performance of EM receiver for (2,1) STC system with modified channel order estimator over 2-tap channel.

Next, we consider the reliability of the modified CME estimator with the order adjustment scheme (EM CME OAS) in this EM receiver. This reliability is measured as the percentages of frames with correct order estimate (i.e. $\hat{L}=2$), and is plotted in Figure 2 versus the SNR at different iterations. The reliability of the original CME (EM O-CME) criterion that generalized to MISO system in (6) is also plotted for comparison. It can be seen that the reliability of the modified CME has significant improvement over the original CME. This improvement is most significant in the first iteration (the training part) and in low SNR region. It must be noted that most of the incorrect order estimate are being overestimated, which leads to excessive unnecessary computations. This shows that the proposed modified CME criterion with order estimate adjustment scheme has a very reliable performance in unknown channel order and channel gain scenario.

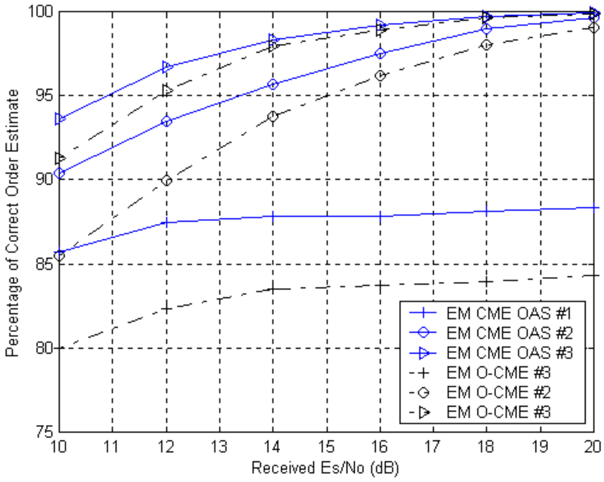

Figure 2: Reliability of modified CME with order adjustment scheme (OAS) in (2,1) system over 2 taps channel with EM-based receiver.

The second set of simulation is to investigate the performance of order estimate adjustment scheme in channel with residue taps. The channel has 3 taps with the residue tap having an average energy 20dB less than the first tap, i.e. [0.5, 0.495, 0.005]. In practise, a tap is considered as residue when its energy is 20dB less than the highest one. Hence, the desired order estimate in this set of simulation should be $\hat{L} = 2$. The frame error performance shows similar results as in Figure 1, where the receiver with CME has negligible performance degradation. Hence the plot is omitted. The reliability of the channel order estimate shows interesting results and is plotted in Figure 3. Both reliability plots on the modified CME criterion with (EM CME OAS) and without (EM CME) the order estimate adjustment scheme are shown.

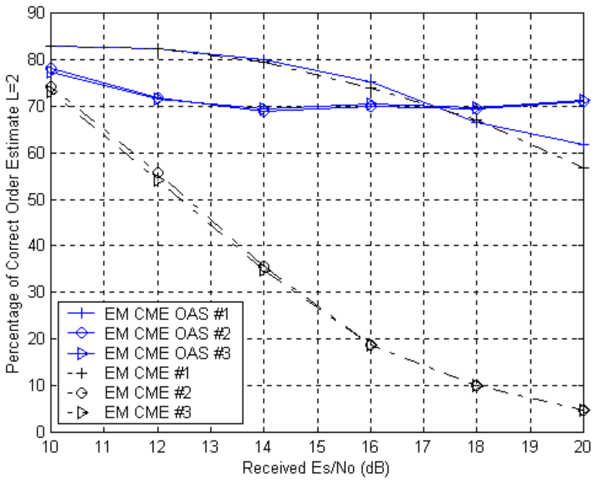

Figure 3: Reliability of modified CME with and without OAS in (2,1) system over a 2-tap channel with 1 extra residue tap.

The modified CME criterion without order adjustment scheme has a poor reliability as the SNR increases. It includes the residue tap into the order estimate and favours the output of 3. Hence, excessive computation is wasted. On the other hand, the modified CME with order adjustment showed a good performance, with an average of reliability at 70%. Notice that the residue tap has a 20dB less average energy than the highest one, but instantaneously it might be significant enough to be included in the estimate. Thus, the scheme successfully adjusts the order estimate according to the environment. Therefore, the order adjustment scheme improves the robustness of the CME estimator to channels with residue taps.

To verify the MIMO CME criterion, a 2 transmit and 2 receive antenna system is simulated with 2 channel taps. Simulation result shows similar trends as for (2,1) system, and is thus omitted due to the length constraint of this paper.

VI. Conclusions

The EM-based iterative receiver for space-time trellis coded systems over frequency selective fading channels with channel order and gain estimation in [1] is modified. The CME criterion is generalized for MIMO systems and incorporated into the EM receiver. Moreover, an order adjustment scheme is also proposed to avoid overestimation, hence reducing unnecessary large amount of computations. Simulation results show that the modifications do not degrade the frame error rate performance, but significantly improve the channel order estimation reliability. Moreover, the modified CME estimator is more robust to realistic channel with the aid of the proposed order adjustment scheme.

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